



11th International IUFRO Wood Drying Conference
Recent Advances in the Field of Wood Drying
Skellefteå Sweden, January 18-22, 2010

PROCEEDINGS

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Proceedings of the

11th International IUFRO Wood Drying Conference

Recent Advances in the Field of Wood Drying

January 18-22, 2010, Skellefteå, Sweden

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FOREWORD

The 11th IUFRO Wood Drying Conference is now arranged for the second time at Luleå University of Technology, LTU in Skellefteå. This series of IUFRO conferences in fact started here back in 1987, one year after the 18th IUFRO World Congress in Yugoslavia 1986. The first meeting in Skellefteå however started with not more than 32 participants and 17 oral presentations. Things have changed ...

From that first Drying Conference Sept 28 to Oct 2, I remember that we were fortunate to have a very nice weather period (like an Indian summer) with clear sky and calm winds. This time, we hope to offer you something rather different, but more exclusive: A harsh Nordic winter weather! At our latitude 65° north you will find yourself only some 250 kilometres away from the Arctic Circle. This means you will have a good chance to experience northern lights, blistering cold weather, a sun hardly rising above the horizon or even visit the world famous ice hotel in Jukkasjärvi (the only threat is the global warming).

On behalf of the organiser, LTU Skellefteå, it is my pleasure to invite more than 40 oral presentations and round 80 participants to this conference. We will share almost one week time updating each other in this, as it seems ever green field of research. Posters will be exposed all week close by our session room, coffee and lunch served in the nearby cafeteria. For those of you who need warmer clothes, we can provide that if you notify us!

The in-conference excursion tour will take us to Martinsons, the most modern sawmill in Europe and later the same day to Svanselse Wilderness Centre for an exotic dinner and a quick look at the wild life exhibition.

Finally, my special thanks to our key note speakers Mike Milota, Mihaela Campean and Jarl-Gunnar Salin, who by the way is the only member of this IUFRO action that has visited all conferences from the start in 1987!

You are all very welcome to the 11th International IUFRO Wood Drying conference for exchange of ideas on recent advances in the field of wood drying. Hope you enjoy the arrangements, the posters, the presentations the social activities and even the Nordic winter!

Tom Morén
November 2009

Skellefteå, December 2009

The Editors

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KEYNOTE ADDRESS

I

Timber Drying Methods – Passing Through History Into The Future

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ABSTRACT

Wood was present in the humans' life since the very beginning and it accompanied mankind through all stages of development. The necessity of drying wood before using it to manufacture various objects was early recognised, in the antiquity already. Air drying and sand drying were the only drying techniques used until the early modern period. The possibility to use solar panels to accelerate drying seems to have been discovered at the end of the 17th century, when conservatories (greenhouses) at the Court of the French King Louis the XIVth (1638-1715) were used not only for growing vegetables, but also for wood drying purposes. However, the beginnings of kiln-drying as such are referred to only at the beginning of the 18th century, when the first dryers were built in the proximity of shipyards, metal-processing industries and machine-building industries. The first kilns were simple heating chambers, with direct firing, using the flue gases resulted from burning wood wastes as drying agent. As soon as the benefits of forced air circulation were acknowledged (around 1850), kiln-drying shifted to a new stage, that of “artificial drying”. During the first World War, the classical drying method with hot moist air and air exchange with the outer atmosphere was perfected in the USA, then introduced and further developed in Europe as well, after the Second World War. Alternative, unconventional methods were continuously patented, tested, abandoned, re-discovered and re-launched within the timespan of the last 100 years. Although none managed to conquer the market and interest of users as much as the conventional drying method, it is the merit of active researchers worldwide that answers regarding faster...better...with less energy...less polluting drying of wood were found and developed as viable alternatives. It was the author's intention to provide within this paper a historical review of timber drying methods out of two reasons: on one hand, in order to praise the efforts of the precursors, by bringing forward their achievements, and on the other hand, with hope that some of the past, maybe forgotten, ideas may raise again the interest of today's researchers. The historical research performed within this work concluded with two original illustrations: one consists in a timeline of the main milestones within the evolution of timber drying methods from antiquity until today, and the other is a “family-tree” of timber drying methods, presenting not only their timing, but also emphasising several cases of succession, where an idea or principle was re-considered and re-launched once or several times over the years, promoting thus the idea that:

“The distinction between past, present and future is only a stubbornly persistent illusion”
Albert Einstein

HISTORICAL DEVELOPMENT

Wood was present in the humans' life since the very beginning and it accompanied mankind through all stages of development. The primitive man used wood as fuel and for manufacturing his first weapons, instruments and shelters. Then he discovered the floating ability of wood, which made it suitable to create

means for water transportation. The solar cedar boat of Keops, dating from 2690 BC and presently displayed at the Museum in Gizeh, still stands as a proof of the wood processing means and techniques available at that time.

The necessity of drying wood before using it to manufacture various objects was early recognised. Surviving objects – such as furniture master-pieces from

Ancient Egyptian graves – sustain this statement: after being preserved for over 5,000 years in hermetic chambers under the dessert sand, wooden objects found in Tuthankhamon's grave (statues, chests, wardrobes) showed absolutely no tendency for fissuring, veneer delamination or joint failures.

Written proofs of that time's knowledge on how to stack and dry wood are offered by Hesiod (750 BC), Vitruvius (50 BC) and Plinius (50 AD) (acc. to Hildebrand 1969, Milota 1999).

Since then, over forty different drying methods were developed in time. Based on the historical research performed within this paper, a timeline comprising the main milestones of the evolution of timber drying methods was conceived and is presented in Fig. 1.

Air drying, sand drying and smoke drying were the only drying techniques used until the early modern period. The first patent (1636) was issued in England and refers to drying shipcraft wood. The possibility to use solar panels for wood drying purposes seems to have been recognized at the end of the 17th century, when conservatories (greenhouses) at the Court of the French King Louis the XIVth (1638-1715) were also employed as wood dryers. An other patent (1720) known as the Cumberland method (acc. to Milota 1999) is a re-discovering of sand drying, dealing with simultaneous drying and heat treatment to attain increased suppleness of wood prior to bending, by placing it into wet sand.

However, the beginnings of kiln-drying as such are referred to only at the beginning of the 18th century, when the first dryers (heating chambers) were built in the proximity of shipyards, metal-processing industries and machine-building industries. The first kilns were simple, with no fans, with direct firing, using the flue gases resulted from burning wood wastes as drying agent.

The poor quality of the dried material became soon an inconvenience: part of the wooden material (the one placed on the side where smoke entered the stack) was over-dried, while the rest remained moist. The additional darkening and even superficial carbonisation made it unsuitable for many uses and the high risk for fire accelerated the shift to a further stage of progress: the introduction of indirect firing by means of heat exchangers.

The first dryers using hot air as drying agent and being equipped with air chimneys and a heat exchanger, placed at the bottom of the kiln, below the timber stack, were built at the end of the 18th century. They used the principle of drying by natural convection. At first, the heat carrier used were still flue gases, but these were gradually replaced by steam, superheated water and thermal oils. Being economic, safe and easy to operate, this kind of heating chambers were very popular in Europe for a long time. Endowed with automatic kiln

control devices, such kilns are still in use even today, in small enterprises.

As soon as the benefits of forced air circulation were acknowledged (around 1850), kiln-drying shifted to a new stage, that of "artificial drying". The drying performances of the fan-endowed kilns increased significantly both in terms of time and quality. Various kiln designs, with centrifugal fans built onto the drying kiln, or, the improved solution, with axial fans placed inside the kiln, were tested.

During the first World War (1914-1918), the classical drying in hot moist air was perfected in the USA. The importance of spraying was also acknowledged at that time and spraying systems were added as compulsory components of a drying kiln. Thus the domination era of **conventional drying** began.

In 1927, in the US there already existed 5,000 kilns and half of the timber amount was kiln-dried (Tiemann 1956). In Europe, the development began with some delay, but after the Second World War (1939-1945) conventional kiln-drying experienced a quick spread and continuous efforts for improvement were done.

Parallel to the development of this classical drying method, several alternatives were developed. The end of the 19th century and beginning of the 20th century was a prolific period in terms of innovation:

- in 1865, Robbins filed with a patent for **drying in vapours of organic liquids**, where the wood is heated to approximately 150°C in an ordinary pressure-treating cylinder with hot vapours of an organic chemical, which has the boiling point above 100°C, such as xylene (135°C) or toluene (110°C). The mixed vapours of solvent and water are continuously drawn off and condensed. Since the solvent is not miscible with water, the two can be separated and the solvent can be recirculated afterwards. At the end of the process, a vacuum is drawn, to remove the chemicals adsorbed by the wood and to complete the drying as well. Although patented that early, the method was applied at industrial scale only in 1942 in the USA (Taylor-Colquitt process) and in Poland, and it proved to be efficient for oak and gum crossties, as well as southern pine poles;

- in 1867, **high-temperature drying** by means of superheated steam was patented by Allen & Campbell. In 1908 Uphus and Shapman applied for a patent to dry and treat structural lumber with temperatures up to 163°C and Tiemann (1944) used the principle in a patented superheated steam kiln, in which circulation was forced by means of four pairs of steam-spray lines and could be reversed. The advantage of time reduction was soon shadowed by the rapid deterioration of the kilns and poor drying quality even with softwoods, and so, the principle was soon abandoned, but only for few decades;

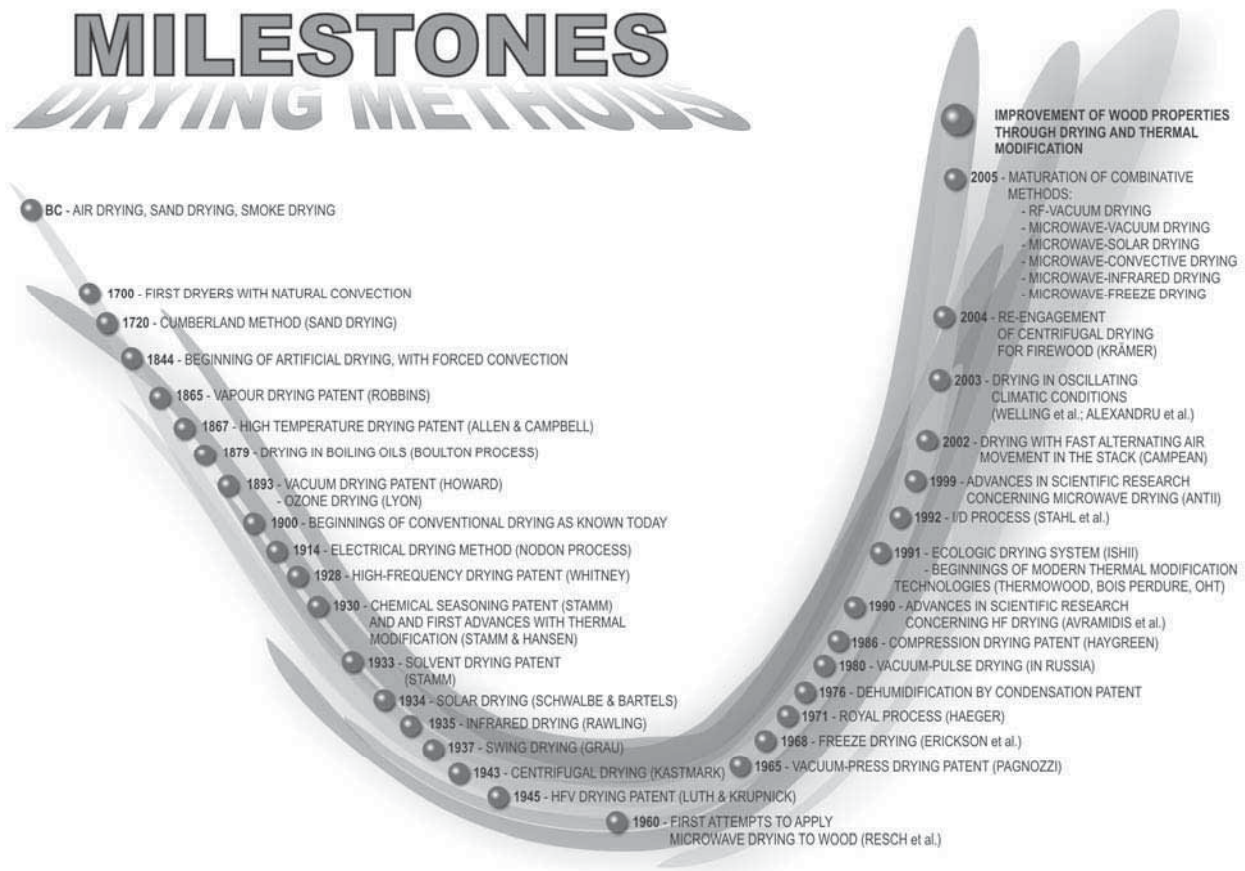


FIGURE 1. Timber drying methods - timeline

- in 1879, the Boulton process, consisting of **drying by boiling in oily liquids**, was patented in England and in 1881 in the USA. The principle of this method consists in dipping logs into a water-repellent liquid, which has the boiling point considerably above that of water (e.g. coal-tar oil) and which is maintained at a temperature of ca. 120°C, high enough to vaporise water. Other patents on timber drying as a first step in treating it with hot preservatives was granted to Curtis and Isaacs (1895) and Zuhlsdorff (1908) (acc. to Kollmann 1968);

- in 1893, Howard was granted a patent for the first **vacuum dryer** for timber. At the beginning, discontinuous vacuum drying was tested, but soon it was abandoned because of not so spectacular results as expected. Only half decade later, scientific research will enhance further development of this principle;

- also in 1893, Lyon was granted a patent for **ozone drying** of wood (Villiere 1966); the presence of ozone in hot, moist air seems to determine a condensation of the water vapours contained by the drying agent (air), maintaining the superficial layers humid and preventing thus casehardening; a second advantage of using ozone in wood drying processes is the oxidation of the

secondary substances (gums, resins etc.) contained in wood, so that during drying an “artificial ageing” effect is obtained. Though successfully promoted in France between 1925-1930, when experimented years later in India (Kapur 1934) with local species, the method did not confirm the same good results;

- in 1914, an **electrical drying method**, called Nodon process was proposed and tested in France, as a “rapid drying and preservation method for wood” (Villiere 1966). The process is based on the heat transmission from wire-mesh electrodes, placed between the timber rows during stacking and connected to a CC or AC power source. The treatment lasts 1-2 days and is suitable as an air-drying accelerating solution. A further development of this method, known under the name of **induction drying** was proposed and tested in Russia by S.G. Romanovski (acc. to Marinescu 1980) and it consisted in introducing the whole stack-wire-mesh assembly in a solenoid. Heat transmission occurred both by conduction and convection, the drying times being two times lower than in conventional drying;

- in 1928, **high-frequency drying** was apparently patented by W.R. Whitney in the USA and one year

later by John Gray in Great Britain (acc. to Resch 2006). In 1934, Abramenko published his experiments, carried out during the previous years, to dry wood by this method. In the same year, Matsumoto filed for a Japanese patent, then Stephen and Holmquest (1936) followed up with drying studies on timber and Voigt et al. (1940) provided a technological overview;

- in 1930, the US Forest Products Laboratory began investigations on the possibility to use chemicals in order to improve timber drying. The basic consideration of **chemical seasoning** is as follows: if green wood is treated with a hygroscopic chemical, such as common salt, invert sugar, molasses or urea solutions, the outer zone of the lumber will be impregnated to a depth of about 1/10th of the thickness, with the highest concentration near the surface. The consequence is a reduction of shrinkage and surface checking. Some chemicals produce a permanent anti-shrink effect. The presence of the chemicals does not impede drying. The water molecules from the untreated core pass through the impregnated shell and evaporate at the surface. A further development of this method (after 1960) was the application of polyethylene glycol (PEG)(Moren 1965). PEG is more hygroscopic than wood, so it absorbs the water and takes its place within the cell wall cavities. This way, dimensional stability is much improved, as the treated wood does not shrink during the water removal. This process is well-known as a preservation possibility for wooden objects and artifacts stored for a long time under water (*e.g.* Swedish warship Vasa, sunken in 1928 was restored through PEG treatment and is presently displayed at the Vasa Museum in Stockholm). Belmadur™, based on the same drying&preservation principle by means of a hygroscopic chemical, is the most recent successor of chemical seasoning;

- in 1933, Stamm was granted a patent for **solvent drying** of timber, consisting of the exposure of green wood to a hot solvent, maintained at a temperature nearby its boiling point (the solvent is chosen so as to have lower boiling temperature than water). Stamm (1933) originally used molten paraffin as solvent, but soon this was replaced by acetone ($t_f=56.2^\circ\text{C}$). The solvent is heated up to a temperature of ca. 55°C , and then it is continuously sprayed over the timber. The resulting mixture, containing acetone, water and pitch from wood, recirculates to the sprayer. When the mixture contains too much water it is recovered by distillation. Good results were obtained for ponderosa pine: 24h drying time from 150% to 12% m.c., at an extractive yield of 12kg/m^3 ;

- in 1934, Schwalbe&Bartels proposed an original **solar drying** plant to improve the heat-economy of air-drying round logs; the first recorded solar kilns for drying timber were designed by Johnson (1961) and Peck (1962). Since then, several designs were

developed, especially in areas with warm climate (South America, Australia, Africa, South Asia etc.), where this method proved maximum efficiency. An excellent overview is provided by Wengert & Oliveira (www.woodweb.com);

- in 1935, Rawling published his results concerning the penetration depth of **infrared radiation** into different wood species. Later experiments by Keylwerth (1951) showed that infrared radiation is not suitable for drying timber, but only for thin materials;

- in 1937, Grau advanced the idea of **swing-drying** as a way to accelerate air drying. His idea was continued by Egner and Sinn (1941) and Piest (1941);

- in 1943, Kastmark launched the idea of **centrifugal drying**, by building the first timber drying centrifuge in Sweden. His kiln design was improved later on by Eisenmann (1950) and Fessel (1952);

- in 1945, the first patent for drying timber in **vacuum with high-frequency heating (HFV)** was granted to Luth and Krupnick. HF heating for seasoning wood was also suggested by Miller (1948) in Canada and studied by Murata and Iso (1949) in Japan. Its economic aspects were considered by Birjukow in Russia in 1950.

Some of these early special methods were temporarily abandoned, because of insufficient understanding and re-launched successfully later on. This is the case of high-temperature drying, chemical seasoning, vacuum drying, high-frequency drying. Others maintained the limited field of application, being only rarely applied nowadays.

The only kiln-drying method which resisted with no interruption to the time test was the conventional drying. After World War II, this technique was continuously improved and developed.

During the 50's and 60's, beside continuous improvement in terms of construction and endowment of conventional dryers, considerable work and research was devoted to **high-temperature (HT) drying**. This was the time when it was recognised that, depending on the value of the wet-bulb temperature, the environment created within the HT dryer may be superheated steam (when $t_{wet\ bulb}=100^\circ\text{C}$) or an air-steam mixture (when $t_{wet\ bulb}<100^\circ\text{C}$). An essential step was the determination of the hygroscopic equilibrium curves of wood in superheated steam at atmospheric pressure (Keylwerth 1949, Eisenmann 1949, Czepek 1952), at temperatures up to 120°C , as basic tool for the HT kiln control.

Within the same period, many advances were made in the field of **HF drying**. At that time, the best known tunnel dryer using radio-frequency (RF)-current for heating and drying short pieces of European beech had been designed by Brown, Boverly & CIE in 1963 (Czepek and Sporkman 1968). The first industrial RFV dryers were also built in the 1960s, by the Russian Academy of Science in Moskow and their main use was

for drying furniture stock from Russian hardwood species (Djakonov and Gorjaev 1981). Both types of kilns used a 13.56MHz generator with adjustable power.

Two new developments in terms of wood drying methods during this period are:

- **microwave drying**, which seemed logically to be applied in the field of forest products, as well, after the appearance of the magnetrons in the 1940s. The first applications refer to thin materials, such as thin timber, pencil slats and veneers (Resch 2006);

- **freeze drying**, investigated as a possibility to reduce shrinkage in wood (Erickson et al. 1968).

The period of the 70's and 80's is characterised by very active improvement of the existing methods, especially in terms of construction, through the shifting from brick-laid kilns to the more flexible modular metallic construction and with regard to kiln control systems and related measuring and adjusting devices, which become more and more complex, but user-friendly, following up the general trend concerning the automatisisation of technological processes.

New developments in terms of wood drying methods during this period are:

- **vacuum-press drying**, patented by Vincenzo Pagnozzi in 1965 and strongly promoted since then by the Italian firm he developed. The method is based on the concept of accelerating vacuum drying in an autoclave by continuous conductive heat supply from hot platens, placed alternatively between the timber rows;

- **the Royal process**, patented by Bror Häger in 1971 as a process for drying and treating timber by means of boiling oils under vacuum. The method is a modern successor of drying in boiling oils, applicable to wet timber, which is placed in a treatment vessel and then flooded with an oil having a relatively high boiling point (150-400°C). The oil is heated to 60-90°C and at the same time, a vacuum is applied (0.03-0.16bar) (Powell 2003). The reduced pressure caused by the vacuum leads to the reduction of the boiling point of water and its evaporation. The drying time is of the order 4-6 hours for 25mm thick timber and 6-8 hours for 50mm thickness. A similar, yet distinctive method was developed in Germany (Sailer 2000), under the name Oil Heat Treatment (OHT™), using crude vegetable oils as treating agent. However, OHT uses vegetable oils heated at higher temperatures (180-220°C), which cause chemical changes in timber;

- **dehumidification by condensation**, based on a patent dated 1976, promotes a different air dehydration modality than the conventional exchange with outer atmosphere: the heated and excessively moisturised air from the kiln is sucked into an attached humidifier (which can be placed inside or outside the kiln), where it is cooled so that the vapours it contains are condensed and evacuated; the initially used cooling agent (freon)

was replaced in the 1990s with the more ecological propane or butane, which also allows higher temperatures (up to 70°C) than freon. A slightly different variant, where the air dehydration is performed by absorption instead of adsorption, and using an organic absorbent (TEG) was reported by Chrusciel et al (1999). The advantages offered by such a system compared to adsorptive dehumidification refer to higher life-time of the apparatus (made of HDPE) and on temperature-independence: the circulated air has not to be cooled down in order to dehydrate;

- **vacuum-pulse drying**, developed in the early 80's in Russia, was originally intended for use in a military-industrial complex for drying thermo-unstable substances. Later, it received wide development in joint Korean and Siberian research works for several uses in food industry, but also for wood drying;

- **compression drying**, based on a patent dated 1986 by Haygreen, consists in mechanical water removal from wood during passage through a roller press. This method was further developed by Adachi et al. (2003);

The end of the 20th and beginning of the 21st century are dominated by the “combination trend”. Two different principles are combined within the same process, so as to maximise the advantages and minimise the shortcomings of each method, as individual. The most popular “**hybride**” methods resulted by combining microwave heating or RF heating with vacuum drying or several other drying methods, obtaining thus spectacular drying time reduction and significant improvement of drying quality, especially in case of difficult species.

During the last two decades, dictated by present market trends in the wood sector and the significant increase of wood demand for construction purposes, the innovation in wood drying seems to shift into a related field, namely that of **thermal wood modification**. The process of thermal modification involves changing the chemical properties of wood by heating it at 160-245°C within an oxygen-controlled atmosphere. This results in the chemical modification of the wood structure including degrading the hemicelluloses and lignin.

Distinction can be made between technologies where the modification occurs only due to the high temperature, with no addition of chemical substances (i.e. ThermoWood™, Bois Perdure™, PlatoWood™ etc.) and other processes, where the modification occurs as a consequence of temperature and impregnation of wood with certain preservatives (Belmadur™, OHT™ etc.).

Same as in the case of drying treatments, thermal modification and its effect upon wood properties, are known since ancient times (primitive men subjected the tips of their wood lances to a flame in order to harden them and get better durability). A historical overview is provided in ThermoWood® Handbook (2003).

As a conclusion to the historical research performed within this work, an original illustration of the evolution of timber drying methods was conceived, under the shape of a “family-tree”, as presented in Fig. 2. Thus, not only time references, but also several cases of

succession could be emphasised, where an idea or principle was patented impressively early, but then re-considered and re-launched once or several times over the years, with certain modifications / improvements and under different names.

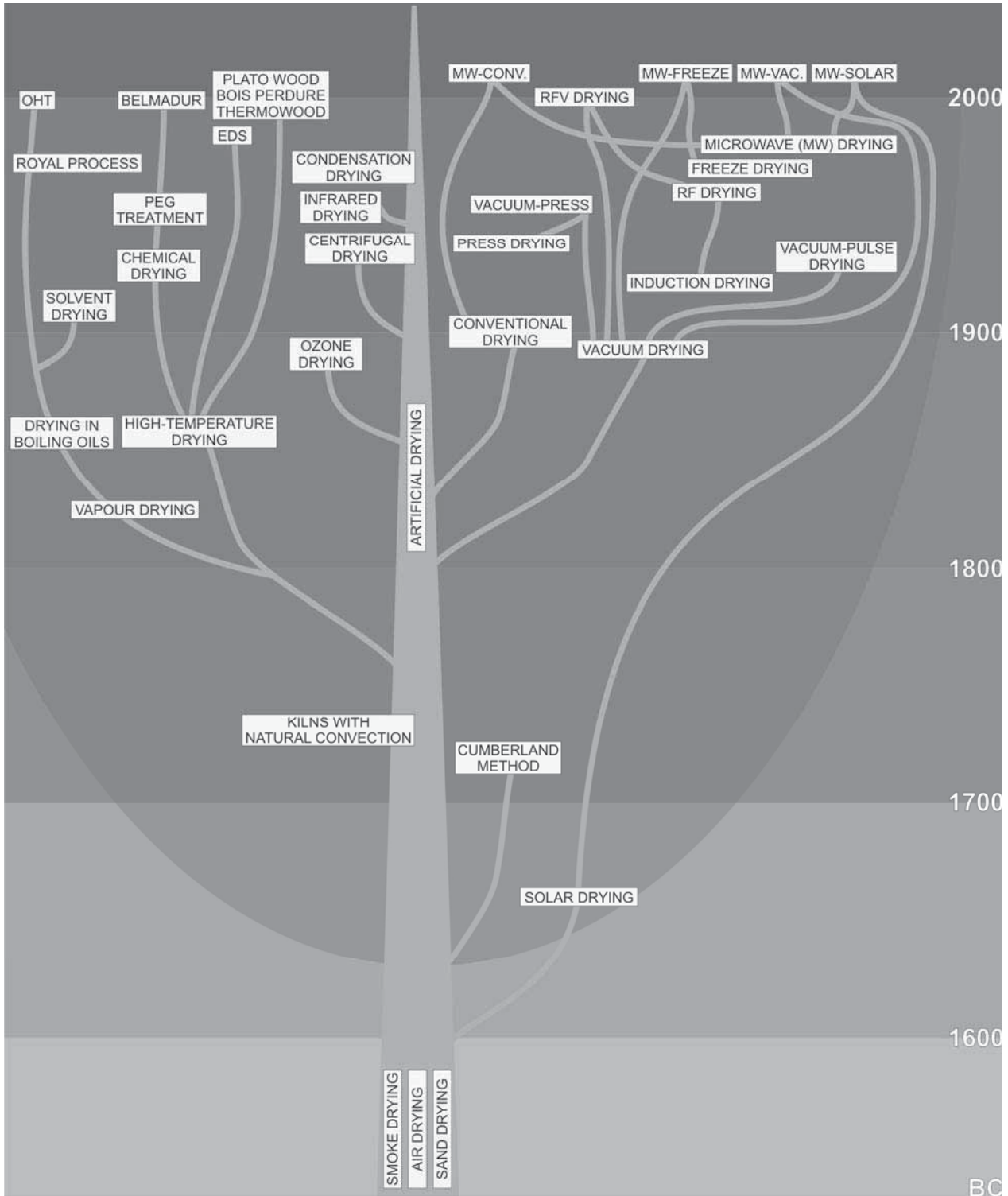


FIGURE 2. The “family-tree” of timber drying methods

CLASSIFICATION OF DRYING METHODS

Drying methods can be classified according to various criteria. Thus,

1) According to the **form of heat transfer** between the surrounding environment and wood (Fig. 3), drying methods can be:

- by convection (e.g. conventional drying, condensation drying, solar drying etc.);
- by conduction (e.g. press drying);
- by radiation (e.g. high-frequency drying, microwave drying, drying with infrared radiation).

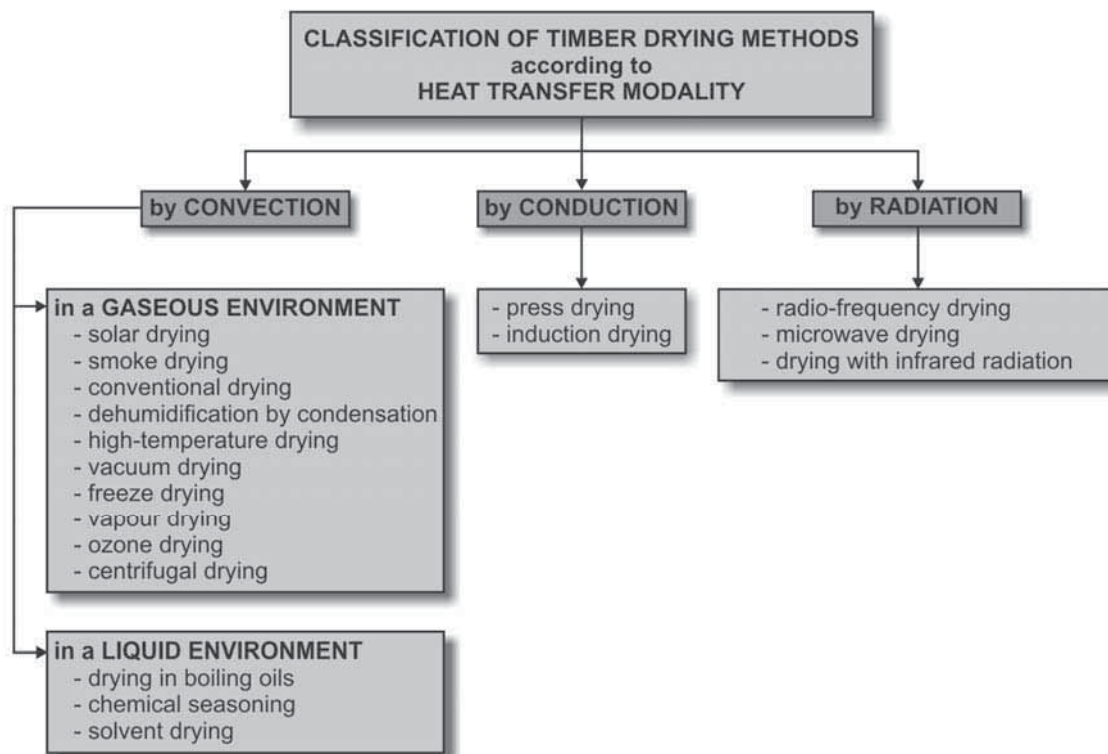


FIGURE 3. Classification of timber drying methods according to the form of heat transfer

2) According to the **drying agent** involved, we distinguish between:

- drying in a gaseous environment, which can be air (e.g. conventional drying), superheated steam (e.g. high-temperature drying), flue gases (e.g. Ecologic Drying System) or vapours of organic solvents;
- drying in a liquid environment, which can be boiling oils, organic solvents miscible with water (e.g. acetone) or other chemicals (e.g. PEG).

3) According to the **temperature of the drying agent**, we distinguish between drying methods:

- at temperatures above 100°C (e.g. high-temperature drying, drying in boiling oils etc.);
- at temperatures below 100°C (e.g. conventional drying, condensation drying, vacuum drying etc.);
- at temperatures below 0°C (e.g. freeze drying).

4) According to the **pressure of the drying agent**, we can distinguish between:

- drying at atmospheric pressure: $p=1\text{bar}$ (e.g. conventional drying);
- drying at low pressures: $p<1\text{bar}$ (e.g. vacuum drying);
- drying at overpressures: $p>1\text{bar}$ (e.g. press drying, solvent drying);
- drying under pressure variation, with the possibility of applying a single pressure change (e.g. freeze drying, vapour drying) or of applying variable pressure cycles (e.g. vacuum-pulse drying, I/D drying).

5) According to the way in which **air circulation** is achieved within the kiln, we distinguish between:

- drying with longitudinal air flow through the stacks;
- drying with transversal air flow through the stacks, both being possible to be achieved by means of centrifugal fans, axial fans or other mechanical means (e.g. swings, centrifuges, oscillating plates etc.).

However, inspite the impressive number of drying methods developed so far, only few are actually applied at industrial scale. Among these, conventional drying keeps a meritorious pole-position with an overwhelming percentage of over 85% for 60 years now. This is why, conventional drying is considered a “classic” method, while all others are usually referred to as “special” drying methods.

SPECIAL DRYING METHODS

Alternatives to conventional drying, which is an almost universal method with average performances in terms of time, energy consumption and quality, were born according to temporary priorities, like: faster...better...with less energy...less polluting...etc.

Thus, several drying methods with limited application, but interesting character were developed. Among these, some were re-considered and re-launched several times in history, which hints towards a certain advantage which incited again and again the interest of several generations of researchers. Selectively, a few of these special methods are refreshed as follows.

One of the most courageous attempts to accelerate air drying was the idea of **mechanical drying**. Low energy consumption and reduced drying time are the strengths which promoted the idea of mechanical water extraction throughout a period of no less than 70 years:

- in 1937, in Chemnitz (Germany) Grau constructed a heavy swing, on which the boards - in an amount corresponding to a total weight of ca. 10t - were piled vertically and balanced at 20° to the vertical at a speed of 15 balances/minute, corresponding to 4-7m/s at mid stack height (acc. to Eichler 1961). The electric drive of the swing was similar to that of a bell-ringing apparatus; that is electric current was supplied to the motor only when the amplitude of the swing decreased. The consumption of energy was kept very low by this feeding system (0.25 kWh/m³ with the big swing and 0.10 kWh/m³ with smaller swings). Compared to air-drying, the pre-drying time (from green state to fibre saturation point) was reduced by 33-66%;
- four years later, Piest (1941) obtained similar results for smaller workshop-swings, having a capacity of 2-2.5cbm of boards;
- the idea of using the centrifugal force was continued and developed by Kastmark (1943), who built the first timber drying centrifuge in Sweden, replacing thus the oscillating motion of the swing with a rotation motion (at 58rpm), much easier to achieve. The most noticeable result obtained by Kastmark is the moisture decrease of resinous timber pre-heated at 40°C from 55% to 35% in 4 hours. Kastmark is also one of the first who performed experiments concerning the influence of the air speed (through variation of the rotation speed) upon the drying time for different wood species. The method showed no perspective of applicability below fibre saturation point

and it also turned deficitary in terms of moisture uniformity, as the final moisture content was higher at the timber ends, presumably due to the formation between the stack and the carcass of a vapour-saturated air “mantle” keeping the timber ends moist;

- in order to avoid this shortcoming, Eisenmann (1950) tried to improve technically Kastmark’s design and changed the carcass shape into a square one, provided with air-directing baffles;
- although it never really attained industrial importance, centrifugal drying was “re-discovered” in recent years and proposed as an efficient method for drying firewood in a carussell-type grid-box (Krämer 2004).

Other methods which seem to be efficient in accelerating especially the free water removal from wood rely on the principle of creating a pressure gradient within the kiln or within the timber parts.

The first variant refers to the possibility to improve conventional drying by **fast alternating air movement within the stacks** (Campean 2002) or by **oscillating climate conditions** (Riehl&Welling 2003; Alexandru 2003) at atmospheric pressure.

The second variant refers to drying processes characterised by pressure cycles, as within the so-called **I/D process**, meaning drying by incubation and decompression (Schill et al 1992, Stahl 2000, Seegmueller 2004). The drying process takes place in an autoclave. During the incubation phase, a pressure of 20-40 bar is created, followed by a decompression phase when pressure is lowered again to normal value (1 bar). The alternation cycle lasts several minutes. The method is efficient in terms of free water removal, and thus able to be employed for rapid pre-drying. In spite high investment costs, amortissement is evaluated at less than two years (Schill et al 1992).

A similar drying method was developed in the early 80’s in Altai (Southern Siberia) under the name of **vacuum-pulse drying or impulse drying**, but it was patented only in 2002 (NPO VISIP). Wood heats up in a vacuum kiln in a superheated steam environment, up to a fixed temperature. After this stage, a sharp pressure release (impulse) is created. As a result, moisture from capillaries is “squeezed out” as fine water drops and the forced air stream removes them from wood surface proximity. Most of the moisture removal occurs thus without transformation of the fluid water into vapours (without phase change). Thus, the technology allows to increase several times productivity, and simultaneously, to lower power consumption and to improve drying quality, due to the absence of liquid water removal from wood.

A similar effect, using the avoidance of phase transition is obtained within **freeze drying** - an other special vacuum drying method, tested in the 60’s-70’s, where the moist wood (preferably above FSP) is first frozen at $t=-30^{\circ}\text{C}$, transforming thus the free water from

the cell lumina into ice. A vacuum of 0.27-2.7mbar is applied hereinafter, transforming thus the ice directly into vapours (sublimation). The main effect consists in less internal stresses, which launched the idea of using this drying method for temperature-sensitive and fragile wood (e.g. archeological wooden products).

The end of the 20th century brings a new prevailing trend in drying: sustainability. Reduction of energy consumption, kiln endowment with energy recovery systems, use of alternative energy sources (e.g. solar energy), capitalization of wood wastes as fuel to produce drying energy become the new priorities.

The Japanese **Ecologic Drying System (EDS)**, based on a Japanese patent (Ishii 1991) is a characteristic development for this period and also one of the pioneers in the development of thermal wood modification technologies. EDS is a modern smoke drying process, using wood wastes to produce the necessary heat energy, which is admitted through a controller into the actual drying chamber, where unbarked logs or cut timber may be treated. Whilst exposed for 3-5 days to this hot drying environment ($t=70\dots200^{\circ}\text{C}$), green logs may reduce their moisture content to 40-50%. The bark prevents checking and it is much easier removed after the treatment. After cutting the logs into timber parts, these may be introduced within the same chamber, for final drying down to 8-10%, which may last 3-7 more days, depending on wood species. The main benefit is the change of the chemical composition of wood, which improves significantly its dimensional stability and workability. Colour darkening and specific (smoke) smell less desired secondary effects, which must be mentioned.

A drying method characteristic to veneer industry, but which was also extended to timber drying by a Danish company is **press drying** (acc. to Trübswetter 2006). The main characteristic of this method is the conductive heat transfer from the hot platens of a multi-deck press towards the wood strips placed between each pair of decks (strict observance of uniform wood thickness is compulsory in order to attain good results). The method was tested with steamed beech parquet strips, placed right after steaming at 100°C onto the platens of a 20-deck hot press and pressed at $t=165^{\circ}\text{C}$ with $p=12\text{bar}$ for ca. 2 hours. During this time, they dried from 80% to 1...3% and were re-conditioned up to 8-9% afterwards. The drying in pressed state determines a thickness loss of ca. 6mm, density increase, and also higher swelling. The high temperature determines significant darkening. It is suitable only for diffuse-porous wood species.

Adachi et al. (2003) showed that compression by roller pressing prior to conventional kiln-drying of flat sawn, thin sheets of Sugi timber, reduces their moisture content from 270% to ca. 100% (pre-drying) and it also reduces the kiln-drying time at $t=60^{\circ}\text{C}$ to 15% final m.c.

from 400 minutes (without precompression) to 220 minutes.

Maintaining the advantage of time reduction through direct contact between wood and hot platen surfaces, **vacuum-press drying** is a further development of this method, with better results in terms of drying quality: good homogeneity of final wood moisture and absence of deformations, at 5-20 shorter drying times than in traditional dryers. Experimental tests performed with 50mm thick beech parts (Cividini et al. 2003) showed that the average m.c. decreases almost linear until 20-25%, the removal rate of free water being as high as ca. 20%/h; when bound water removal begins, the drying speed decreases down to 3.5-4.5%/h, in average, with a total drying time of less than 20 hours. The vacuum-press dryer is considered an effective system for the fast drying of permeable species, from green to low final m.c. (max. 7%).

STATE-OF-THE-ART AND PRESENT TRENDS

As already stated, **conventional drying** still holds the leading position within the range of drying methods applied at industrial scale. Kiln design was and still is continuously improved, in terms of materials used for the thermal insulation of the kiln walls and fixing solutions, also in terms of fan design, baffles with aerodynamic shapes, improved (atomising) vaporisation solutions etc. Adaptive control systems with user-friendly touch screen operation and more and more accurate measuring and adjusting equipment, allowing effective climate control or even creation of different climate zones in kiln length, air flow adjustment, ongoing optimisation of energy consumption etc. are other current developments which allowed this classical method to be catalogued as a modern method as well.

When we refer to modern drying methods, we necessarily have to mention vacuum drying, microwave drying and high-frequency drying, in various combinations, and also thermal wood modification technologies.

Microwave heating is nowadays one of the most popular modalities to achieve rapid drying. Intense fundamental and applicative research on wood (Antti 1999, Perre and Turner 1999, Hannson and Antti 2003, Jia and Afzal 2005) enhanced understanding and control over the physical phenomena, enabled development of simulation programs, promoting thus microwave heating as a reliable way to reduce drying time and to attain good drying quality.

There are only few combinations which were not tried out. Here are some recent results obtained by such combinations:

- **microwave treatment combined with solar drying** (Brodie 2008) enables a 17% reduction of solar drying time for 30mm thick *Eucalyptus regnans* samples and a 33% reduction of solar drying time for 30mm thick

Populus alba samples, without causing any change in the visible quality of the dried timber. This acceleration is attributed to a 9% reduction in wood density and a substantial increase in moisture permeability associated with the microscopic internal fractures created in wood by the microwave treatment, which was achieved by heating the wood samples placed along the diameter of the turntable of a microwave oven, operating at 2.45GHz for 6 minutes on full power. The energy requirement for the microwave treatment was approx. 104kWh/m³ (Brodie 2008). Based on the results obtained, this combination is recommended for drying hardwoods with low permeability and medium or high density, cut to thickness of 30mm or above;

- **microwave heating combined with vacuum drying** (Seyfarth et al 2003, Leiker et al. 2004, Leiker 2007) enables several advantages compared to conventional drying: significant time reduction (at a drying rate of ca. 7%/minute for beech under a 40mbar vacuum), no discoloration, no crack formation, no deformation, energy efficiency up to 80%; the principle is suitable for continuous processes;

- **combined microwave and convective drying** tested on Korean red pine (Lee 2003) revealed the possibility to speed-up conventional drying considerably by adding stepwise microwave control: from ca. 60h to 90' in case of 25mm thick parts and from 400h to 190' for 50mm thick parts, within similar moisture decrease intervals (100% down to 8-12%). An other example is given by Dedic et al (2001) for red oak, which is sensitive to powerful microwave drying, whilst the combination with hot air, especially around the FSP provides a safer drying;

- **combined infrared and microwave drying** (Haghi and Ghanadzadeh 2006);

- **combined microwave heating and freeze drying** (Wang and Shi 2008), a recent development proposed for drying unsaturated porous media.

Radio-frequency (RF) heating relies on the same principle as microwave heating – that of dipole rotation. In contrast to microwave heating, RF heating provides lower heating intensity, but heating is more uniform and deeper (order of meters) due to the lower frequency spectrum.

Although being revolutionary in terms of drying time reduction, simple RF drying was never really a “hit”, but in the 1990s, the interest in dielectric heating as possibility to dry wood was renewed, and the idea of combining RF heating with other drying methods came up.

- **HF heating combined with hot air at atmospheric pressure** reduces drying time to ca. one third compared to conventional drying, without raising the drying costs as much as RFV drying (Kobayashi et al. 1999), and being thus a viable alternative for drying housing members;

- **RF heating combined with vacuum drying** is up to date the fastest and most quality-efficient drying method known so far, applicable to the most difficult to dry wood species and thick assortments. Understanding of the drying mechanism in this specific case, development of drying schedules and kiln construction improvement are all due to assiduous research performed mainly in Canada, the USA and Japan (Avramidis et al 1996a, 1996b, 1997, Farkas 1993, Koumoutsakos et al 2002, Noji et al 2001, Resch and Gautsch 2000, Resch and Hansmann 2002, Resch 2003). The impressive kiln facilities available today and the record of drying totally defect free 100mm thick red oak furniture squares in 1.5 days from 80% to 8% m.c., witness the opportunities offered by the present level of technology.

As already specified, it is not possible to talk at present about modern drying methods without mentioning the **thermal wood modification technologies** developed during the last decade in Europe (Finland, France, The Netherlands, Germany), but which already caught the interest overseas as well.

Such processes always include a drying stage: ThermoWood uses HT-drying in a superheated steam environment, PlatoWood uses a combination of steam and heated air for drying, Bois Perdure uses an inert gas, and OHT uses heated vegetable oils. Beside the modification of the chemical structure of wood and thus the reduction of wood hygroscopicity, the high temperatures also determine a plasticity increase: wood becomes elastic at high temperatures, its resistance to deformation is better, reducing thus warping tendency and increasing the bending strength.

Here is a short description of some of the most significant thermal wood treatment technologies applied at this stage at industrial scale, using no chemicals, but only the influence of temperature upon the chemical structure of wood, in order to improve some of its properties (shape and dimensional stability, weather resistance, bending strength, wear resistance, colour, durability etc.).

The Finnforest **ThermoWood™** process, patented by VTT Technical Research Centre of Finland (EP0695408) and licensed to the members of the Finnish ThermoWood Association, is an industrial-scale heat-treatment process comprising three main phases:

- heating and drying phase: rapid temperature increase at ca. 100°C, followed by steadily increase of temperature to 130°C, HT drying of wood down to a nearly zero moisture content. When the temperature is raised, a special adjustment system is used to prevent splitting and checking. Customised values are used for different wood species and dimensions. This is the most time-consuming phase of the process;

- heat treatment phase: temperature increase inside the kiln up to 185°C and then 215°C; when the target level is reached, temperature remains constant for 2-3

hours, depending on end-use application; due to thermic degradation of hemicelluloses at these high temperatures, wood structure is re-formed;

- cooling and moisture conditioning phase: temperature lowering by using water spray systems; when temperature reaches 80-90°C, re-moisturising takes place, to bring wood up to a useable level of 5-7% in moisture content. Depending on temperature and wood species, this phase may take 5-15 hours.

An other example is the **PlatoWood™** process developed in The Netherlands, consisting in a two-step process with intermediate drying (Tjeerdsma et al 1998):

- in the first stage of the process, the conversion of hemicelluloses and activation of lignin is carried out hydro-thermally, by immersing the wood planks into water at high temperature (155-190°C) in an autoclave;

- then drying is performed in a climate controlled drying chamber;

- finally, the curing (condensation) is carried out in a vacuum chamber by flushing with N₂ gas at 160-190°C.

La Bois Perdure™, developed in France, consists in subjecting the wood to high temperature by a unique pyrolysis process under controlled atmosphere. The treatment cycle consists of three phases:

- pre-drying: at the beginning of the process, the wood pieces are dried at a temperature of 100-120°C, which is maintained for 4-8 hours, depending on species, dimensions, initial moisture content; this step ends when wood reaches 10-20%, best 12% m.c;

- drying: temperature is kept at the same level for 2-3 hours under constant air circulation of air inside the chamber;

- actual treatment: modification of the macromolecular structure of wood occurs by raising temperature to 200-230°C, whereby alcohols, tars and resins migrate into the cell walls. They form a protective layer that stops or slows down rotting when wood is exposed; this step takes 1-5 hours;

- moisture conditioning: temperature is lowered to 80-100°C and steam is injected into the kiln for 15-45 minutes.

The total duration of the process may vary between 7-16 hours. Throughout the process, the temperature difference between the core and the surface is kept constant.

The **Oil Heat Treatment (OHT™)** patented in Germany (Sailer 2000, Militz 2002) is a modern successor of drying in boiling oils. The process is performed in a closed vessel. After loading it with wood, hot oil is pumped into the process vessel, where it is kept at high temperature and circulated around wood. The heating medium is crude vegetable oil, like rapeseed oil, linseed oil or sunflower oil and it serves

for both fast and equal heat transfer towards wood, and perfect separation of oxygene from wood (Rapp and Sailer).

Depending on envisaged upgrading, temperatures up to maximum 220°C may be applied.

The process includes three phases:

- heating-up phase, when the hot oil is expected to reach the middle of the wooden parts to be treated; this lasts at least 4 hours;

- actual treatment phase, which lasts about 2-4 hours;

- cooling phase, when the oil is evacuated.

The typical process duration for the whole treatment cycle is ca. 18 hours.

CONCLUSIONS

It is in the man's nature to seek always to improve and innovate. This explains the great variety of drying methods experimented over the years, according to each period's priorities. Some of them focussed on drying time reduction, others on drying without any energy supply, others pursued finding and using environment-friendlier energy sources, others followed the reduction of energy consumptions, or the improvement of drying quality etc.

Although at the time of their appearance, some innovative proposals did not prove the expected efficiency, when they were re-considered years afterwards they turned into major sensations.

It was the author's intention to provide within this paper a historical review of wood drying methods, out of two reasons: on one hand, in order to praise the efforts of the precursors, by bringing forward their achievements, and on the other hand, with hope that some of the past, forgotten, ideas may raise again the interest of today's researchers. Having in view new IT and advanced software and equipment available, a new approach may lead to surprising results, as history has shown before that new ideas mainly arise from old ideas.

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SESSION 1

DRYING QUALITY AND WOOD PROPERTIES

The Role of Liquid Water Flow in the Formation of Discolouration in Silver Birch and Scots Pine Sawn Timber

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ABSTRACT

Discolouration is an unfavorable property in dried wood, because it makes the wood look like stripy and unattractive. The formation of discolouration can be connected to migration and precipitation of wood extractives during the drying process. The precipitate of extractives is then discoloured at adequate moisture content and temperature as the drying proceeds. The chemical precursors of wood discoloration seem to develop during the capillary phase of drying and the movement of liquid water is probably the most important transportation mechanism for the chemicals involved in discolouration. The objective of this study was to investigate the role of liquid water flow in the development of discoloured layers in sawn timber during drying.

Liquid water flow in silver birch (*Betula pendula*) and Scots pine (*Pinus sylvestris*) sawn timber during drying was investigated using a dye solution in order to describe the pathways of extractive migration and precipitation. The dye solution migrated along with the liquid water during the drying process and left a trace which was seen in the samples cut from the dried sawn timber. The trace of the dye solution differed between silver birch and Scots pine sawn timber and also between Scots pine sapwood and heartwood sawn timber. Especially, in the Scots pine sawn timber, the dye precipitated below the surface in a layer where the evaporation took place. It was in accordance with the earlier findings from the migration of wood extractives from the interior of boards to the surface layer, and from the location of evaporation front. The results from the dye tracing experiment were compared with the results of colorimetric measurements. The migration and precipitation of the dye can be used to illustrate the layers in wood, where the discolouration can be expected.

Destabilization of Wood Caused by Drying -Effects of Drying History on Physical Properties of Wood-

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ABSTRACT

Recently it has been reported that wood components were destabilized by drying and physical properties of wood were affected by drying histories. To obtain new information about destabilization of wood caused by drying, effects of drying history on physical properties of wood were studied using the measurements of dynamic viscoelastic properties and gas adsorption.

Firstly, dynamic viscoelastic properties of dry wood in the radial direction were measured between 100 °C and 200 °C. Unstable states of dry wood still existed after heating at 105 °C for 30 min. and were modified by activated molecular motion in the first heating process to higher temperatures above 105 °C, and dry wood subjected to higher temperatures showed larger dynamic elastic modulus (E') and smaller $\tan \delta$. The phenomena thought to be caused by the unstable states reappeared after wetting and drying again. These results indicated that the unstable states of dry wood components were gradually modified with higher temperature and/or time at constant temperatures.

Secondly, CO₂ adsorptions onto dry wood at ice-water temperature (273K) were measured, and micro-pore size distributions were obtained using HK method. Micropores smaller than 0.6 nm exist in dry wood. They decreased with elevating drying temperatures from 50 °C to 160 °C and increased again after re-wetting and drying.

In conclusion, a larger amount of micropores smaller than 0.6 nm exist in the microstructure of dry wood in more unstable states, corresponding to smaller E' and larger $\tan \delta$ than in the stable state; consequently, unstable states are considered to result from the destabilization of dry wood components in the microstructures. It was clarified that physical properties of dry wood changed with drying histories.

Characterisation of Wood Properties and Transverse Anatomy for Vacuum Drying Modelling of Commercially Important Australian Hardwood Species

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ABSTRACT

Characterisation of a number of key wood properties utilising ‘state of the art’ equipment at AgroParisTech – ENGREF, France, was achieved for four commercially important Australian hardwood species. The species investigated were: *Corymbia citriodora* (spotted gum), *Eucalyptus pilularis* (blackbutt), *Eucalyptus marginata* (jarrah) and *Eucalyptus obliqua* (messmate). The species were chosen for this study based on their large range of drying characteristics. The wood properties were measured for input into microscopic (cellular level) and macroscopic (board level) vacuum drying models currently under development. Morphological characterisation, in terms of fibre cell wall thickness and porosity, was completed using a combination of ESEM microscopy and image analysis software. A clear difference in fibre porosity, size, wall thickness and orientation was evident between species. Viscoelastic properties were measured in the tangential and radial directions using dynamic mechanical analysis (DMA) instrumentation. The glass transition temperature was markedly different for each species due to anatomical and chemical variations. The radial direction showed higher stiffness, internal friction and glass transition temperature than the tangential directions. The loss of stiffness over the measured temperature range was greater in the tangential direction than the radial direction. Due to time dependant molecular relaxation, the storage modulus and glass transition temperature decreased with decreasing test frequency, approaching an asymptotic limit. A highly sensitive microbalance and laser technology were used to measure loss of moisture content in conjunction with directional shrinkage on micro-samples. The device generated data that varied between species but were repeatable within a species. Collapse shrinkage was clearly evident with this method for *E. obliqua*, but not with other species, which is consistent with industrial seasoning experience. To characterise the wood-water relations of *E. obliqua*, free of collapse, thinner sample sections (in the R-T plane) are recommended.

Measurement of Dynamic Sorption Behaviour of Radiata Pine - Influence of Wood Type and Moisture Content on Diffusion Rate

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ABSTRACT

Sorption behaviour of radiata pine has been investigated by weighing small samples continuously during isothermal step changes in relative humidity. The Dynamic Sorption Platform, which measures mass changes (~ 0.0001g) in small (~ 4mm cubes) wood samples, has previously been developed by Scion. The use of small wood samples ensures that all tracheids in a specimen are exposed, removing the effect of wood structure on bound water transport. The small size also allows samples to be prepared from a single band of earlywood or latewood.

Using this equipment, a number of sorption experiments were undertaken comparing dynamic sorption behaviour of individual bands of earlywood and latewood, which had been heat treated to mimic the chemical changes that occur during high temperature drying.

Diffusion coefficients and surface emission coefficients have been calculated from the sorption data, and are presented here. Earlywood and latewood had different sorption behaviour, but no measurable changes in sorption behaviour was seen with the different heat treatments. Diffusion coefficients were strongly dependent on moisture content.

Measurement of Wood Thermal Properties

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ABSTRACT

Correct predicting of the thermal behaviour of wood is a part of a successful control of its processing, e.g. drying, steaming, plasticization, combustion and others. The optimization of such processes provides the possibility of energy saving. The energy saving is evenly important in the life cycle of the product.

In this article we concentrated our focus on determining the values of mass specific heat capacity, thermal conductivity, thermal diffusivity and heat transfer coefficient of thin ash thermowood parquet slabs. These four quantities are useful in solving several problems concerning the relationship between wood and heat. Furthermore, we devote special attention to the method used in the measurement of the thermal properties, especially to the apparatus and the technique which determines the values of the mentioned thermal quantities of thin slabs. The method is based on an analytical solution to the heat conduction equation with constant coefficients. The solution was derived under the boundary condition of the third kind containing heat transfer coefficient. The values of thermal quantities were computed in Excel and the function which represents the solution was programmed in Visual Basic for Applications to simplify the computing process. Also the method enables to determine the change of thermal quantities as a function of measured time.

INTRODUCTION

We expect a larger utilization of wood as a renewable material in the future. As the energy will become more important the processes involving heat will attain more attention. Optimization is crucial for such processes, so the answers to the questions like how much heat is required to increase the temperature or how much heat flows out through the wall or how fast the temperatures equilibrate at the surface are important. The proper answers to these questions require the knowledge of values of thermal properties or quantities dealing with heat such as specific heat capacity, thermal conductivity, thermal diffusivity and heat transfer coefficient.

The aim of the article is the evaluation of these thermal properties and heat transfer coefficient of thin thermowood parquet slabs made of ash.

Introduction to measurement methods

The following data are valid for all methods used in this work. The dimensions of specimens are 100x100x4mm³ and their shape was parallelepiped. We used 18 of these specimens made of thermowood ash. The thickness of the samples was in radial direction. The experiment took place in a moist air environment with temperature of 20°C and 65% relative humidity. The specimens' equilibrium moisture content was 6.5 % in average. The temperature increase during the

measurement is no more than 10°C. The duration of the measurement is less than 10min. All the methods utilize the least square method. The code for evaluation of experimental temperatures was written in Visual Basic for Applications.

METHOD OF MEASUREMENT WITH DEVICE ISOMET 104 AND 2104

The method utilizes the Isomet device which is semi-automatic. The measurement can be divided into three parts. During the first part, after putting the probe on the surface of the specimen it explores and waits for the specimen's surface to reach constant temperature. During the second part, the probe provides heat and the specimen surface temperature is rising. Approximately in the middle of the measurement there is a third part during which the decrease of temperature occurs because heat is not delivered by the probe any more. Surface temperature is measured during the whole process. According to these measurements the device is able to provide the values of thermal conductivity, thermal diffusivity and volume specific heat capacity. Isomet 104 is older than the new generation of the device - 2104.

QUASI-STATIONARY METHOD

This method is based on solution of heat conduction equation under the following initial and boundary conditions (Babiak 1976).

Let us suppose constant temperature throughout the specimen at the beginning of the experiment:

$$t(x,0) = t_0 \quad (1)$$

$$t(x, \tau) = \frac{\varphi s}{\lambda} \left(\frac{a\tau}{s^2} + \frac{3x^2 - s^2}{6s^2} - \frac{2}{\pi^2} \sum_{n=1}^{\infty} \frac{(-1)^n}{n^2} e^{-\frac{a\tau}{s^2} n^2 \pi^2} \cos\left(\frac{n\pi x}{s}\right) \right) \quad (3)$$

where x is space coordinate and τ is time.

The thin nickel-chrome foil (0,01mm) can be used as heat source. It is necessary to know its properties (area S, electric resistance R) owing to the fact that all of the three thermal properties of wood are determined simultaneously. The arrangement of experiment is illustrated in fig.1.

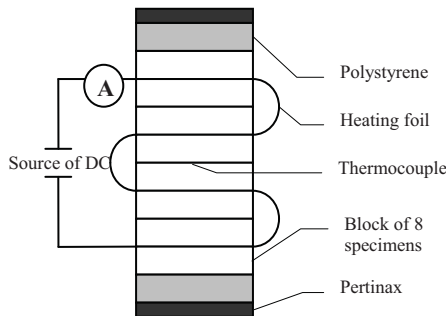


Figure 1. Scheme of quasi-stationary apparatus.

We suppose that heat is symmetrically distributed to both adjacent specimens and so heat flux is given by the equation:

$$\varphi = \frac{RI^2}{2S} \quad (4)$$

I is the direct current flowing through the foil. Thin thermocouple is in the centre of the specimen block, x=0.

$$t(x, y, z, \tau) - t_0 = \frac{8\varphi}{c\rho L} \sum_{r=1}^{\infty} \sum_{p=1}^{\infty} \sum_{m=1}^{\infty} \left(\frac{(\sin \mu_r)(\cos \frac{\mu_r}{T} z)}{(\mu_r + (\sin \mu_r)(\cos \mu_r))} \frac{(\sin \mu_p)(\cos \frac{\mu_p}{R} y)}{(\mu_p + (\sin \mu_p)(\cos \mu_p))} \frac{\mu_m (\cos \frac{\mu_m}{L} x)}{(\mu_m + (\sin \mu_m)(\cos \mu_m))} \right) \frac{1 - e^{-\left(\mu_m^2 \frac{a_x}{L^2} + \mu_p^2 \frac{a_y}{R^2} + \mu_r^2 \frac{a_z}{T^2}\right)\tau}}{\left(\mu_m^2 \frac{a_x}{L^2} + \mu_p^2 \frac{a_y}{R^2} + \mu_r^2 \frac{a_z}{T^2}\right)} \quad (10)$$

We assume constant heat flux φ at the surface of the specimen along the direction of thickness L=2s:

$$\lambda \frac{\partial t}{\partial x} \Big|_{x=s} = \varphi \quad (2)$$

In the centre of the specimen there is no heat flux. Then the solution is of the form:

METHOD OF MEASUREMENT WITH AIR CONTACTING WOOD AT ITS SURFACE

The method is based on the solution of heat conduction equation under the following initial and boundary conditions.

Let us suppose constant temperature throughout the specimen at the beginning of the experiment:

$$t(x, y, z, 0) = t_0 \quad (5)$$

We assumed constant heat flux φ at the centre of the specimen along the direction of thickness:

$$-\lambda_x \frac{\partial t}{\partial x} \Big|_{x=0} = \varphi \quad (6)$$

The opposite surface is assumed to obey the boundary condition of the III. kind in the form:

$$-\lambda_x \frac{\partial t}{\partial x} \Big|_{x=L} = \alpha_x (t(L, y, z, \tau) - t_0) \quad (7)$$

where α_x is the heat transfer coefficient in the thickness direction.

The lateral surfaces fulfil the boundary condition:

$$-\lambda_y \frac{\partial t}{\partial y} \Big|_{y=R} = \alpha_y (t(x, R, z, \tau) - t_0) \quad (8)$$

$$-\lambda_z \frac{\partial t}{\partial z} \Big|_{z=T} = \alpha_z (t(x, y, T, \tau) - t_0) \quad (9)$$

where α_y, α_z are the heat transfer coefficients in y and z directions.

The fluxes in the centre of specimen in y or z direction are zero due to symmetry of the experiment. Then the solution is of the form:

where μ_m, μ_p, μ_r are nonnegative roots of the equations:

$$\mu_m(tg\mu_m) = \frac{\alpha_x L}{\lambda_x} = Bi \quad (11)$$

$$\mu_p(tg\mu_p) = \frac{\alpha_y R}{\lambda_y} \quad (12)$$

$$\mu_r(tg\mu_r) = \frac{\alpha_z T}{\lambda_z} \quad (13)$$

The same circumferences about heat source must be fulfilled in this method as in quasi-stationary method. Fig.2 depicts the apparatus.

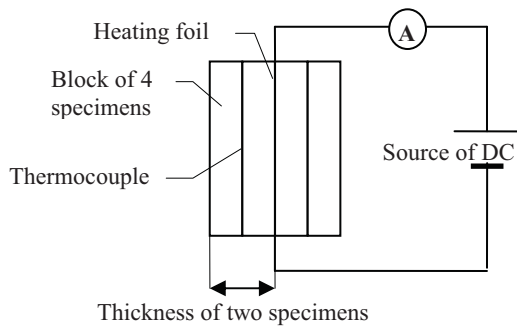


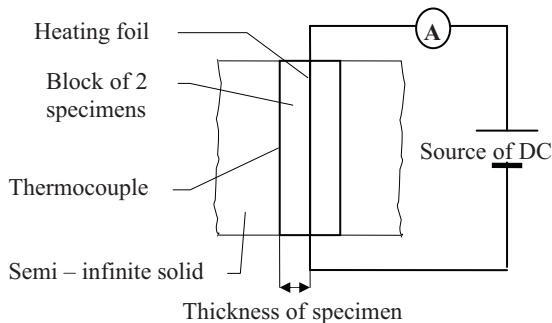
Figure 2. Scheme of apparatus for method of measurement with air contacting wood at its surface.

We used four specimens to ensure the thermocouple be inside the block at coordinates $[L/2, 0, 0]$.

$$t_2(x, \tau) - t_0 = \frac{4\varphi\sqrt{a_1\tau}}{\lambda_1(1 + \frac{\lambda_2}{\lambda_1}\sqrt{\frac{a_1}{a_2}})} \sum_{n=1}^{\infty} \left(\frac{1 - \frac{\lambda_2}{\lambda_1}\sqrt{\frac{a_1}{a_2}}}{1 + \frac{\lambda_2}{\lambda_1}\sqrt{\frac{a_1}{a_2}}} \right)^{n-1} \text{ierfc}\left(\frac{L}{2\sqrt{\tau a_1}}((2n-1) - \sqrt{\frac{a_1}{a_2}}(1 - \frac{x}{L}))\right) \quad (18)$$

where a_2 is thermal diffusivity of adjacent solid body.

The same circumferences about heat source must be fulfilled in this method as in the quasi-stationary method. Fig.3 depicts the apparatus.



METHOD OF MEASUREMENT WITH OTHER INFINITELY THICK SOLID BODY CONTACTING WOOD AT ITS SURFACE

The method is based on the solution of heat conduction equation under the following initial and boundary conditions.

Suppose constant temperature throughout the specimen at the beginning of the experiment:

$$t_1(x,0) = t_2(x,0) = t_0 \quad (14)$$

Constant heat flux ϕ is supposed at the centre of the specimen along the direction of thickness:

$$-\lambda_1 \frac{\partial t}{\partial x} \Big|_{x=0} = \phi \quad (15)$$

The opposite surface is assumed to fulfil the boundary condition of the I. kind and II. kind in the form:

$$t_1(x,L) = t_2(x,L) \quad (16)$$

$$-\lambda_1 \frac{\partial t_1}{\partial x} \Big|_{x=L} = -\lambda_2 \frac{\partial t_2}{\partial x} \Big|_{x=L} \quad (17)$$

where λ_2 is thermal diffusivity of the adjacent solid body.

Then temperature in adjacent semi-infinite body is described as follows:

Figure 3. Scheme of apparatus for method with solid body contacting wood at its surface.

We placed the thermocouple on the surface of wood sample. The point, where the temperature is measured, is $x=L$.

RESULTS

The results are in the tab.1.

Table 1. Values of thickness L, density ρ and thermal quantities of thermowood ash provided by various methods.

Isomet 104 – slab						
Quantity	$L \cdot 10^3$ [m]	ρ [kg.m ⁻³]	λ [W.m ⁻¹ .K ⁻¹]	c [J.kg ⁻¹ .K ⁻¹]	a [m ² .s ⁻¹]	$c \cdot \rho$ [J.m ⁻³ .K ⁻¹]
number of obs.	18	18	18	18	18	18
Average	6,56	567,0	0,095	1384	1,17E-07	8,18E+05
var.coefficient[%]	142	4,1	6,23	7	5,25	7,79

Isomet 2104 - slab						
Quantity	$L \cdot 10^3$ [m]	ρ [kg.m ⁻³]	λ [W.m ⁻¹ .K ⁻¹]	c [J.kg ⁻¹ .K ⁻¹]	a [m ² .s ⁻¹]	$c \cdot \rho$ [J.m ⁻³ .K ⁻¹]
number of obs.	18	18	18	18	18	18
Average	6,56	567,0	0,060	1295	8,13E-08	7,34E+05
var.coefficient[%]	142	4,1	4,75	6	4,48	7,12

Isomet 2104 - semi-infinite body						
Quantity	$L \cdot 10^3$ [m]	ρ [kg.m ⁻³]	λ [W.m ⁻¹ .K ⁻¹]	c [J.kg ⁻¹ .K ⁻¹]	a [m ² .s ⁻¹]	$c \cdot \rho$ [J.m ⁻³ .K ⁻¹]
number of obs.	4	4	4	4	4	4
Average	7,86E-02	567,0	0,091	1280	1,26E-07	7,26E+05
var.coefficient[%]			7,73	8	6,05	7,58

Quasi-stationary method					
Quantity	$L \cdot 10^3$ [m]	ρ [kg.m ⁻³]	λ [W.m ⁻¹ .K ⁻¹]	c [J.kg ⁻¹ .K ⁻¹]	a [m ² .s ⁻¹]
number of obs.	4	4	4	4	4
Average	4,28	607,2	0,101	1247	1,33E-07
var.coefficient[%]	2	4,3	25,85	12	19,85

Method of measurement with fast moving air contacting wood at its surface							
Quantity	$L \cdot 10^3$ [m]	ρ [kg.m ⁻³]	λ [W.m ⁻¹ .K ⁻¹]	c [J.kg ⁻¹ .K ⁻¹]	a [m ² .s ⁻¹]	α [W.m ⁻² .K ⁻¹]	Bi
number of obs.	4	4	4	4	4	4	4
Average	8,71	567,1	0,120	1341	1,58E-07	49	3,61
var.coefficient[%]	2	2,7	9,62	3	6,08	10	20,5

Method of measurement with almost stationary air contacting wood at its surface							
Quantity	$L \cdot 10^3$ [m]	ρ [kg.m ⁻³]	λ [W.m ⁻¹ .K ⁻¹]	c [J.kg ⁻¹ .K ⁻¹]	a [m ² .s ⁻¹]	α [W.m ⁻² .K ⁻¹]	Bi
	8,50	583,1	0,15	1354	1,9E-07	12	0,68

Method of measurement with other infinitely thick solid body contacting wood at its surface					
Quantity	$L \cdot 10^3$ [m]	ρ [kg.m ⁻³]	λ [W.m ⁻¹ .K ⁻¹]	c [J.kg ⁻¹ .K ⁻¹]	a_1 [m ² .s ⁻¹]
number of obs.	9	9	9	9	9
Average	4,37	567,0	0,090	1181	1,36E-07
var.coefficient[%]	2	3,3	3,79	3	5,36

DISCUSSION

The results for specific heat capacity indicate measurement stability of this property. Even, without the data from Isomet, it attains the smallest variability among thermal quantities. Its average value is $1305 \text{ J.kg}^{-1}.\text{K}^{-1}$. This value is lower than the value published in *Kollmann and Côte (1968)* with difference around $100 \text{ J.kg}^{-1}.\text{K}^{-1}$ and it is lower than value published in *Perelygin (1965)* with difference $500 \text{ J.kg}^{-1}.\text{K}^{-1}$ at given moisture content.

Among measurement methods thermal conductivity attains larger variability than specific heat capacity. Isomet 2104 provided the smallest average value. We overcame this problem by replacing the slab with a semi-infinite body. Such procedure is reasonable because Isomet does not need the specimen thickness for computing thermal properties. The method with air contacting the wood surface delivered the largest values. We speculated if the presence of coupled phenomena is responsible for this fact. But this fact needs further investigation. For the rest of the data its average is $0.095 \text{ W.m}^{-1}.\text{K}^{-1}$. This value is smaller than the value published in the available literature - for ash $0,173 \text{ W.m}^{-1}.\text{K}^{-1}$ (*Požgaj 1993*) probably due to lower amount of water in wood in the equilibrium state.

The values of thermal diffusivity are not as known as the previous quantities. It can be obtained from the ratio of those quantities and the measurement of density or determined by non-steady methods. There is no necessity to know the value of heat flux at the surface of specimen to determine the value of thermal diffusivity. The average value of this property for thermowood ash is $1,25.10^{-7} \text{ m}^2.\text{s}^{-1}$.

In general the heat transfer coefficient is not solely a wood property. But its value can be determined, for example with the non-steady method with air contacting the wood surface. If the air is forced to move this coefficient is larger than without it as the measurements indicate. The same is true for dimensionless Biot number Bi .

All the presented measurement methods are remarkably similar. All methods utilized a planar source of heat and solutions of heat conduction equation. If the Biot number is going to zero or solid body contacting wood at its surface is a good insulator and lightweight material then from the mathematical point of view the mentioned methods are equal to quasi-stationary method. The equation (10) is much more complex than we utilized in this work. It enables to determine axial quantities as well as the radial ones from measurement with one thermocouple in the specimen symmetry axis. The equation (10) was utilized for determining region of validity or measurement time for methods. A specific method is measurement with device Isomet which is a commercially produced machine. The older one (type 104) is also suitable for thin samples but the new one

(type 2104) is more suitable only for thicker, semi-infinite samples as our results indicate. The advantage of Isomet consists in easy operating and consequently measurements do not require special skills.

Conclusion

Most of the presented methods provided similar results of thermal properties – thermal conductivity, thermal diffusivity, specific heat capacity. We determined the averages of these properties for thin thermowood slabs made of ash. We also determined the values of heat transfer coefficient for wood – air interface depending on the speed of air. We tried to explain some discrepancies with thickness of the specimens. Others are difficult to explain or they are beyond the scope of this article.

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Comparison Between Physical Properties and Drying Behaviour of White Wood and Red Heart of European Beech

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ABSTRACT

The paper presents the results of an experimental study performed with European beech wood (*Fagus sylvatica* L.) containing red heart. From the same log, test pieces were cut both from the white wood area, and from the red heart area. Some of them were used to cut samples for the determination of the main physical properties (moisture content, density, shrinkage) of the two wood types, other specimens were dried under different conditions, in order to assess the drying behaviour of white beech wood and red heart, compared both from the quantitative viewpoint (drying rate) and from the qualitative viewpoint (percentage and severity of cracks, deformations, discoloration). Thus it was possible to link the premises (raw material properties) with the results (drying behaviour) and formulate some recommendations for optimising the drying of beech wood with red heart in practice.

INTRODUCTION

Beech wood (*Fagus sylvatica* L.) is one of the main wood species in Europe and in Romania. At present, beech forests cover a total surface of 1.39mil.ha in Romania, which represents 32% of the hardwoods forest area and 22% of the total forest area in Romania (ASFOR 2008). The annual cuts exceed 4mil.m³, most of the logged wood being converted into timber for export and own use for furniture manufacturing.

One of the main characteristics of Romanian beech is the prevailing presence of red heart, which has repercussions upon the drying quality, both in terms of drying stresses and colour.

Previous researches regarding comparisons between the properties and drying behaviour of white wood and red heart of beech refer to the drying at high temperatures (Marinescu 2002), the influence of steaming upon physical and mechanical properties (Nemeth *et al.*), and the influence of climate parameters upon the shrinkage coefficients (Bajraktari 2007).

But, although it represents a topic of major interest for industrials, no previous study approached the improvement of drying schedules for beech with red

heart, starting from the different material characteristics between the white wood and the red heart.

OBJECTIVE

The main aim of the present study was to assist industrials with this optimization, respectively to formulate some recommendations for the industry regarding peculiarities to be taken into account when drying beech wood with red heart.

The research focussed on two set of tests, both being performed on white wood samples and healthy red heart samples cut from the same logs.

One test envisaged the determination of the main physical properties (moisture content, density and shrinkage coefficients), while the second test pursued the drying behaviour (time and quality) of the two wood types, as well as of “mixed” wood parts, from the border area, containing both white wood and red heart.

In the end, it was possible to link the premises (raw material properties) with the results (drying behaviour) and formulate some practical recommendations in order to enhance improvement of industrial drying of beech wood.

METHOD AND MATERIALS

Wooden Material

The samples for the experiments were cut from two trees with average diameter of 60cm, selected so as to have a significant amount of red heart (red heart diameter was ca. 24cm). Two 1.5m long logs were cut from each tree, at $H_1=1.3\text{m}$ from ground and at $H_2=2.5\text{m}$ from ground. Each log was cut by means of a band saw, so as to obtain test pieces containing either only white wood, or only red heart. Some "mixed" test pieces, containing both white wood and red heart, were also cut from the limit area (Fig. 1).

Forty-six test pieces with 1.5m length, ca. 60mm width and 30mm thickness (in strictly radial direction) were thus obtained for each log, out of which: 20 pcs. containing only white wood, 20 pcs. containing only healthy red heart and 6 pcs. were "mixed".

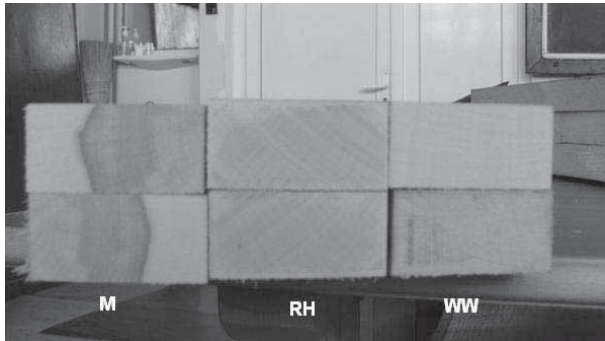


FIGURE 1. Test pieces of beech wood used within the experiments: M-"mixed"; RH-red heart; WW-white wood.

Determination of Physical Properties

The following physical properties were selected to be determined comparatively for the white wood and the red heart samples cut from each log: initial moisture content, oven-dry density, total linear and volumic shrinkage coefficients, as well as the coefficient of anisotropy.

All properties were determined according to the Romanian standards in force, most of them being presently aligned to international standards (EN and ISO).

First, the initial moisture content of wood (in green state) was determined by the oven-dry method (SR EN 13183-1:2003), by means of 10mm wide slices, cut at a distance of 500mm from both board ends of each test piece. The length of the 46 test pieces was thus reduced to 0.5m.

Two of the test pieces containing only white wood, and respectively only red heart, were destined to cut the samples for determination of density and shrinkage coefficients. These were air-dried for 1 month and then introduced in a climate chamber for 2 weeks conditioning at constant parameters: $t=20^\circ\text{C}$ and

$\text{RH}=65\%$ ($\text{EMC}=12\%$), so as to comply with SR ISO 3129-93 requirements concerning preparation of wood samples to be tested for physical properties. The moisture content before cutting the samples were measured in three positions along each test piece by means of an ultrasound moisture meter type MERLIN PM-1 E. All values fitted within the interval $12\pm 2\%$.

The oven-dry density (ρ_0) was determined according to STAS 84-87 (identical with ISO 3131:1975), by means of $20 \times 20 \times 20\text{mm}$ cubic samples. A total number of 20 samples for each wood assortment were used.

The total shrinkage coefficients (β_l , β_r , β_t and β_v) were determined according to STAS 85/2-91 (identical to ISO 4469:1981), by means of the same twelve cubic samples as used for the oven-dry density determination.

The coefficient of anisotropy, as indicator of shape stability, was determined as the ratio between the total tangential and radial shrinkage coefficients (β_t/β_r).

Drying Trials

Three drying trials were conducted, with six white wood specimens, six red heart specimens and two "mixed" specimens from each log. A classical conventional kiln was used to this purpose, the test specimens being introduced within a complete stack, always in the same positions.

The drying conditions for each test are presented in Table 1.

Table 1. Drying conditions

Period	MC, %	T, °C	RH, %
Warming-up	MC_i	45	90
Actual drying	$\text{MC}_i \dots 30$	45	82
	$30 \dots 25$	50	78
	$25 \dots 20$	60	70
	$20 \dots 15$	70	60
	$15 \dots \text{MC}_f$		
	Test I	70	50
	Test II	80	50
	Test III	90	50
Cooling	MC_f	30	-

After 84 hours, the moisture content of all test pieces was determined by weighing. Afterwards, the test pieces were weighed individually at different time intervals, pursuing the moment when each attained the final moisture content of 10%. The drying time was recorded at this moment.

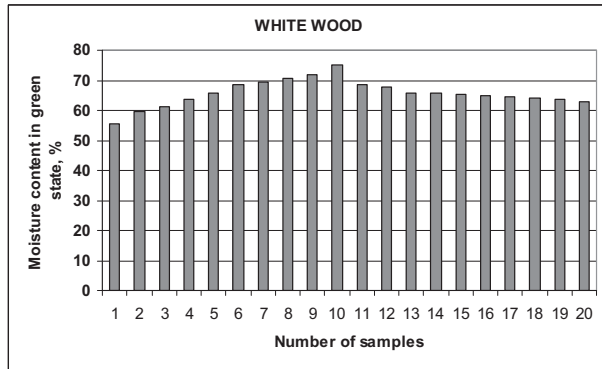
After being evacuated from the drying kiln, the test pieces were stored within the laboratory for 48h and then a quality control was performed by naked-eye observation, concerning the appearance and severity of cracks, discoloration and deformations.

RESULTS AND DISCUSSION

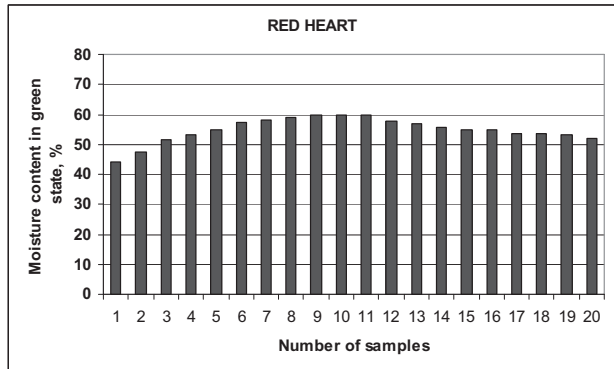
Physical Properties

The results concerning, comparatively, the main physical parameters of white wood and red heart originating from the same log are illustrated in Fig. 2, 3,

4 and 5 for one of the tested logs, while Table 2 presents some statistical data, including the average values, obtained by processing the results for all 4 tested logs.

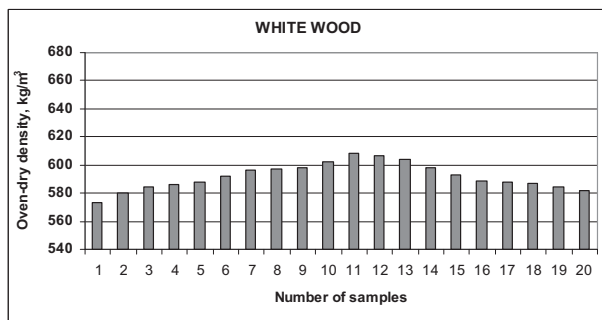


a.

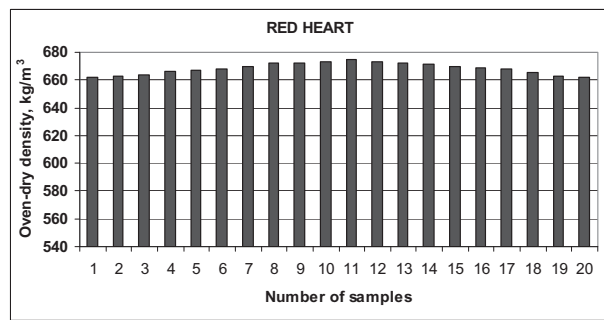


b.

FIGURE 2. Comparative values of initial moisture content of white wood (a) and red heart (b) originating from the same beech log.

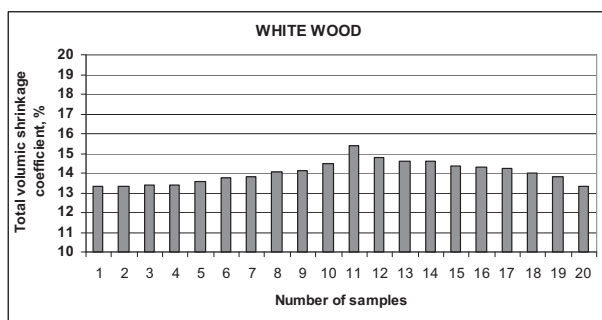


a.

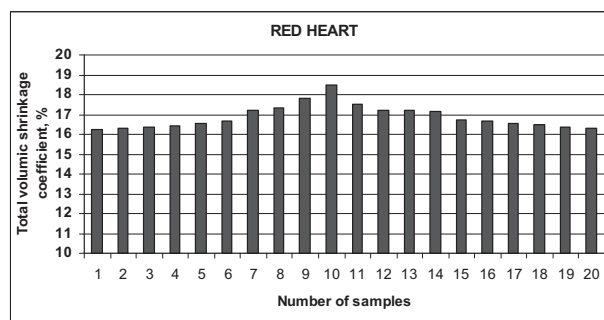


b.

FIGURE 3. Comparative values of oven-dry density of white wood (a) and red heart (b) originating from the same beech log.



a.



b.

FIGURE 4. Comparative values of total volumic shrinkage coefficient of white wood (a) and red heart (b) originating from the same beech log.

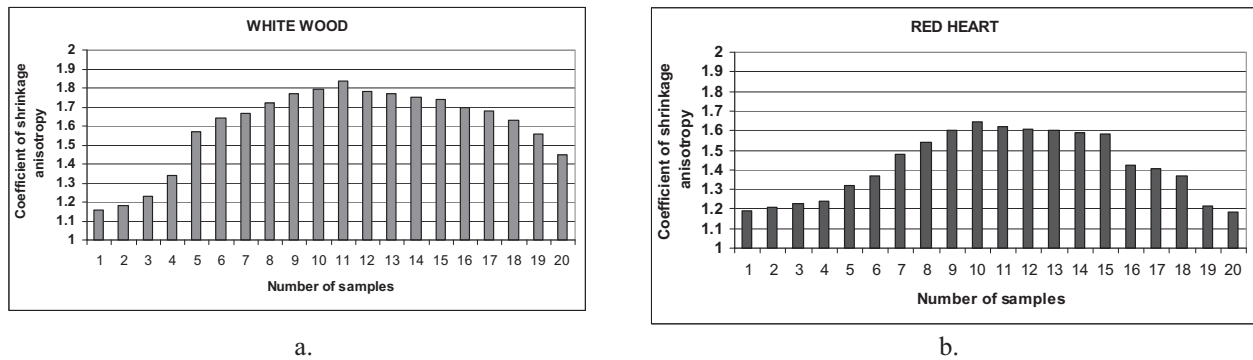


FIGURE 5. Comparative values of the coefficient of anisotropy for white wood (a) and red heart (b) originating from the same beech log.

Table 2. Experimental results (average values) concerning the physical and properties of white wood and red heart of beech

Property	Specimen UM	WHITE WOOD				RED HEART			
		Min.	Avg.	Max.	Std.	Min.	Avg.	Max.	Std.
Moisture content in green state	%	55.4	65.7	75.1	4.94	44.0	54.9	60.0	4.40
Oven-dry density (ρ_0)	kg/m ³	573	592	608	9.82	662	668	675	4.05
Total longitudinal shrinkage (β_l)	%	0.1	0.6	1.2	0.59	0.1	0.6	1.0	0.28
Total radial shrinkage (β_r)	%	4.7	5.5	6.5	0.64	6.1	7.1	7.9	0.63
Total tangential shrinkage (β_t)	%	8.2	8.5	9.0	0.52	9.1	10.0	11.0	0.60
Total volumic shrinkage (β_v)	%	13.3	14.0	15.4	0.70	16.3	16.7	18.5	0.80
Coefficient of anisotropy (β_t / β_r)	-	1.16	1.60	1.84	0.24	1.19	1.42	1.64	0.17

Based on these results, the following can be concluded:

- the moisture content in green state varies within the cross section of fresh logged tree, being different in the outer white wood area than in the inner red heart area: with an average value of 55%, the moisture content of red heart wood is by 10% lower than the moisture content of the surrounding white wood (whose average moisture content is 65%);
- both the oven-dry density of white wood and red heart fits within the generally accepted range of values for European beech (*Fagus sylvatica* L.), which is 490...680...880kg/m³ (Lohmann 1998), but the density of red heart is ca. 10% higher than that of the surrounding white wood;
- no significant differences could be noticed between the longitudinal shrinkage coefficients of the two beech wood assortments;
- both radial and tangential shrinkage are lower in case of white wood: 1.3 times lower in radial direction and

- the volumic shrinkage of red heart is 1.2 times higher than that of white wood;
- because of the greater difference between radial shrinkages of the two assortments compared to the differences between tangential shrinkages, the coefficient of anisotropy is by ca. 10% lower in the case of red heart, which hints toward a better shape stability of this wood assortment during drying.

Drying Behaviour

The results concerning the drying time from initial moisture content down to 10% of white wood test pieces, red heart test pieces and “mixed” test pieces within the three drying tests are given in Table 3.

Considering the different values of initial moisture content, a more eloquent interpretation of the results is provided by the drying rate values, which are presented in Table 4.

Table 3. Experimental results concerning the drying time (in hours) of white wood, red heart and “mixed” test samples

Test N°	WHITE WOOD			RED HEART			MIXED		
	Initial MC	Final MC	Drying time, h	Initial MC	Final MC	Drying time, h	Initial MC	Final MC	Drying time, h
I	72.6	23.5	84	53.8	16.3	84	67.5	22.2	84
	23.5	10.0	84	16.3	10.0	56	22.2	10.0	96
			168			140			180
II	68.5	18.6	84	56.8	18.0	84	58.9	15.2	84
	18.6	10.0	30	18.0	10.0	36	15.2	10.0	22
			114			120			106
III	70.5	20.3	84	57.8	18.8	84	65.7	21.3	84
	20.3	10.0	30	18.8	10.0	26	21.3	10.0	32
			114			110			116

Table 4. Drying rate (in %/h) of white wood, red heart and “mixed” test samples of beech wood

Test N°	Stage of actual drying	Drying rate, %/h		
		WHITE WOOD	RED HEART	“MIXED”
I (<i>t</i> =45...70°C)	Above 15%	0.58	0.44	0.54
	Below 15%	0.16	0.11	0.13
	Average	0.37	0.31	0.32
II (<i>t</i> =45...70°C)	Above 15%	0.59	0.46	0.52
	Below 15%	0.29	0.22	0.24
	Average	0.51	0.39	0.46
III (<i>t</i> =45...70°C)	Above 15%	0.59	0.46	0.52
	Below 15%	0.40	0.34	0.35
	Average	0.53	0.43	0.48

According to expectations, white wood dried the fastest, followed by the “mixed” parts, while the red heart parts were slower. According to the drying rate values obtained, a board containing only white wood dries from an initial m.c. of 60% down to a final m.c. of 10% in ca. 135h (5.6 days), while a board containing only red heart needs 161h (6.7 days) for the same moisture decrease interval, assuming the application of drying schedule I (*t*=70°C) in both cases. But, considering also that the initial moisture content of the two boards would be different, even if they originate from the same log, with a higher value for the white

wood board, the situation may be very well reversed (as can be seen in tests I and III from Table 3).

Increasing temperature during the last stage of actual drying (below 15%) accelerates drying, especially in case of white wood, which means that, higher temperature leads to more severe differences between the drying rates within a mixed load, and the internal stresses within the “mixed” parts will be also higher.

The latter was already confirmed within the present research, as the quality control showed that all “mixed” test pieces suffered major cracks and deformations, their severity increasing with increasing temperature (Fig. 6).

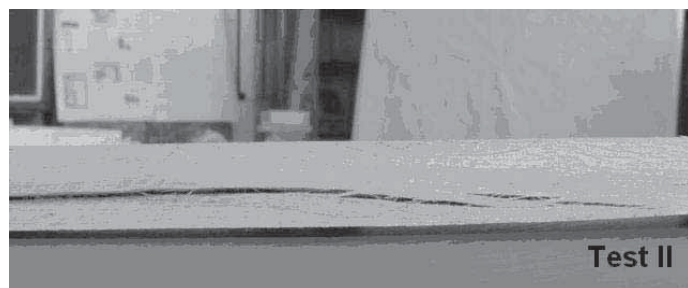


FIGURE 6. Drying defects in “mixed” test pieces.

By comparing the drying quality of white wood and red heart, it was noticed that some of the white wood parts bowed, while no such defect occurred with the red heart parts (Fig. 7). As far as the influence of temperature is concerned, both white wood and red heart parts dried without fissures within tests I and II;

only few fine checks occurred at the red heart parts dried within test III. But the most significant influence of the drying temperature concerns colour: the colour darkening with increasing temperature is clearly detected, even by the naked eye, both for white wood and red heart samples (Fig. 8).



a.



b.

FIGURE 7. Deformation tendency of white wood parts (a) compared to red heart parts (b) under the same drying conditions (test II).



a.



b.

FIGURE 8. Colour darkening under effect of increasing temperature within test II ($t=80^{\circ}\text{C}$) compared to test I ($t=70^{\circ}\text{C}$): a-white wood; b-red heart samples.

CONCLUSIONS

As a conclusion with a view to optimising drying schedules for beech wood, it can be stated that white wood can be dried with temperatures up to 90°C and pure red heart parts with temperatures up to 80°C with no other inconvenient than colour change. But in the case of “mixed” boards, the situation changes because of the high internal stresses generated by density and shrinkage differences. The experiments showed that quality drying in this case is not possible with a normal drying schedule ($t=70^{\circ}\text{C}$) without prior steaming.

Further research will pursue the possibility to improve the drying quality of this assortment through prior steaming.

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*** STAS 85/2-91: Wood – Determination of Shrinkage Coefficients.

SESSION 2

METHODS FOR MONITORING THE DRYING PROCESS

Nondestructive determination of moisture transfer in wood by means of neutron imaging

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ABSTRACT

The relationship between wood and water is of special interest within the field of wood research as all of the wood properties depend to some extent on the moisture content. With conventional methods it is practically impossible to determine moisture transport processes with high spatial and temporal resolution. Neutron imaging is a non-destructive and non-invasive testing method, which is comparable to X-ray but disposes of a considerably higher sensitivity for hydrogen and hence water. Within the scope of the presented work, diffusion processes in along the fibre (longitudinal direction) were determined for solid wood samples of European beech (*Fagus sylvatica* L.) and Norway spruce (*Picea abies* (L.) Karst.). Oven-dry samples were exposed to a differential climate and the water absorption process was ascertained over several hours. With neutron imaging it was possible to determine the distribution of water contents within the wood samples for every moment during the experiment. The obtained moisture profiles were then used to calculate the diffusion coefficients in longitudinal direction for unsteady state conditions along Fick's second law. This is particularly interesting as the only values, which can be found in literature concern the diffusion coefficient under steady state conditions.

The utilisation of neutron imaging can thus be used to close gaps in the knowledge on dynamic moisture transfer processes in wood. The direction of the water transport process is for the application of the method irrelevant. With neutron imaging the absorption of water as well as desorption / drying processes in wood can be examined. The method allows to quantify and localise even very small amounts of water within wood samples and to observe moisture transfer over an arbitrary time period.

INTRODUCTION

Since all wood properties (e.g. mechanical properties, heat conductivity, etc.) depend to a certain degree on the moisture content (MC), the interaction between wood and water is crucial for the utilisation of wood and wood based composites. Wood-water

relations thus have long since been in the scope of many investigations (e.g. Skaar 1988; Wadsö 1994; Siau 1995; Koc et al. 2003; Olek et al. 2005; Frandsen et al. 2007). Conventional destructive experimental methods applied in this context do not yield spatial information on water distribution within an object (e.g. standard

diffusion experiment with regular weighing) or are of limited precision and their evidence is restricted to layers close to the surface (e.g. measurements based on electrical conductivity).

Experimental assessment of moisture distribution and transport processes is particularly difficult by destructive methods (Plagge et al. 2006). Non-destructive testing methods are better suitable. Most frequently X-ray transmission measurements are applied. This approach includes evaluating computed tomographies (CT) (Wiberg and Morén 1999; Alkan et al. 2007; Scheepers et al. 2007) and X-ray densitometry (Baettig et al. 2006; Cai 2008; Watanabe et al. 2008). Nuclear magnetic resonance (NMR) is also a promising method in this context (Merela et al. 2009).

Neutron imaging (NI) using digital detection systems is a relatively new method, which has the same working principle as the X-ray methods. NI seems to be particularly suitable for moisture-related investigations as its sensitivity for hydrogen is considerably higher than that of X-ray photons (Lehmann et al. 2001a, Niemz et al. (2002) demonstrated the general suitability of NI for detecting moisture in wooden corner joints.

The goal of the present work is to show the possibilities of NI as a tool for time-dependent investigations on wood-water relations. The transport of moisture by diffusion in a differential climate was quantified and localised by means of NI on samples of European beech (*Fagus sylvatica* L.) and Norway spruce (*Picea abies* [L.] Karst.) over several hours. Diffusion coefficients in the longitudinal direction were calculated based on the results obtained.

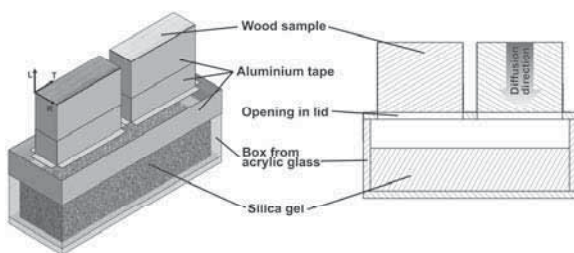


FIGURE 1: The samples were isolated on four sides with overlapping aluminium-tape and then fixed above openings on a box containing silica gel as dehydrating agent; moisture uptake occurred exclusively over the cross-section, diffusion was only possible in longitudinal direction; L, R, T = longitudinal, radial, tangential direction

PRINCIPLE OF NEUTRON IMAGING

NI is based on the intensity measurement of a neutron beam transmitted through an object, thus integrating the objects properties in the direction of the beam. The intensity of the transmitted beam I , can be

described in a first order approach with the linear attenuation law:

$$I = I_0 e^{-\Sigma \cdot z}, \quad (1)$$

where I_0 is the intensity of the incident neutron beam, Σ is the attenuation coefficient and z is the thickness of the object in the beam direction (Figure 2). Σ is the main parameter describing the degree to which a material interacts and attenuates the neutron beam. It is defined as the product of the microscopic cross section σ and the atomic density N :

$$\Sigma = \sigma \cdot N \quad (2)$$

The microscopic cross-section σ , represents the interaction probability of an element with the incident radiation, while the atomic density N is defined as:

$$N = \frac{\rho}{A} \cdot N_A, \quad (3)$$

where ρ is the material density, A the atomic weight and N_A is AVOGADRO'S constant. With the attenuation coefficient Σ , it is thus possible to determine the density ρ of a specimen if the thickness is known. A detailed overview on the interactions between neutrons and wood and the attenuation coefficients of wood for cold and thermal neutrons was given by Mannes et al. (2009).

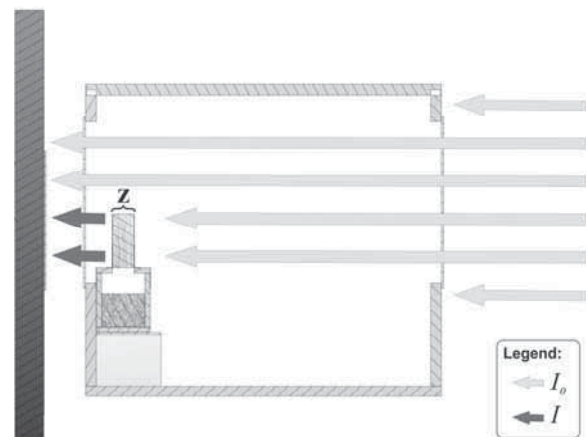


FIGURE 2: Neutron radiation with the intensity I_0 is sent onto the sample with the thickness z , which was placed in a climatic chamber. The transmitted beam with the intensity I is registered behind the sample by the neutron detector.

Eq. (1) applies for objects containing only one material. For compounds containing several materials the attenuation is given by:

$$I = I_0 e^{-\sum_i \Sigma_i \cdot z_i}, \quad (4)$$

where i sums all materials with their respective attenuation coefficient Σ_i and layer thickness z_i . For the presented experiments, considering the tested specimens as time-dependent mixture of wood structure and water, the transmitted beam can be described as

$$I(t) = I_0 \cdot e^{-\{\Sigma_w \cdot z_w(t) + \Sigma_h \cdot z_h(t)\}}, \quad (5)$$

where w designates the attenuation coefficient and thickness of the wood layer and h designates the attenuation coefficient and thickness of the water layer. In this context wood and water layer have to be considered as discrete layers. The time-dependence shows in the intensity of the transmitted signal I . It reflects the changes in the layer thicknesses of the present materials, i.e. of wood and water. To separate the signal of the absorbed water from the wood signal, the images were referenced to the initial state. The time-dependence is given by:

$$z_i(t) = z_i(t_{ref}) + \Delta z_i(t). \quad (6)$$

As a reference time, the start of the experiment was chosen, where the samples were assumed to be absolutely dry, so that $z_h(t_{ref}) = 0$.

The images were referenced by dividing the time-dependent images by the initial dry state, yielding the changes between the images over time.

The wood component in eq. (5) can be assumed to be constant, despite the swelling. While the thickness of the sample increases the atomic density of the wood (without water molecules) diminishes; the overall number of "wood atoms" along the path of the neutrons remains the same. With this and the presumption that no water is present in the reference state, the amount of water can then be calculated as the change in the water layer with:

$$\Delta z_i(t) \approx \Delta z_h(t) = -\ln\left(\frac{I(t)}{I(t_{ref})}\right) \cdot \frac{1}{\Sigma_h} \quad (7)$$

EXPERIMENTAL SETUP

The experiments were performed at the NI facility NEUTRA at the Paul Scherrer Institute (PSI) in Villigen, Switzerland. This imaging beam-line is fed by the spallation neutron source SINQ and operates with neutrons in a thermal spectrum (Lehmann et al. 2001b).

The climatic conditions around the samples had to be regulated during the experiments. For this purpose, a climatic chamber was built, in which the specimens were placed during the experiment (Figure 2). The chamber consisted of acrylic glass and had two neutron-transparent windows of plain glass. The climate was regulated with two basins filled with demineralised water or saturated salt solutions (depending on the desired humidity), two Peltier elements with cooling fins and two ventilators. Two sensors recorded the temperature and relative humidity (RH). The climate reached during the actual experiment was 27°C at 86% RH.

The chamber was positioned in front of the neutron detector, which consisted of a scintillator-CCD-camera-system with a field of view of 130 mm. The scintillator (zinc sulphide doped with Lithium-6 as neutron absorbing agent) converts the neutron signal into visible light, which is led via a mirror onto a cooled 16bit CCD camera (resolution: 1024 x 1024 pixels), which registers the signal. The exposure time was 240 s per image. The conditioning of the chamber was initiated while the samples were being prepared (i.e. isolation of the sides and fixing on the box containing the silica gel) so that an almost stable climate in the chamber was attained, when the samples were inserted. However, to position the samples within the chamber it had to be opened, thus the air conditioning was interrupted for that period. After this, it took about 30 to 40 minutes for climate stabilisation.

To obtain a reference image of the dry samples, the experiment was started right after the samples were placed into the climatic chamber. From then on, images were taken every 15 min over the period of 39 h. The conditions in the climatic chamber were only stable for the first 8 h. Hence, only this part of the experiment was taken into account to determine the water absorption.

MATERIALS AND THEIR PREPARATION

The wood specimens were exposed to a differentiating climate (wet condition on one side, dry condition on the other) and time-dependent experiments about the moisture movement were performed. NI yields not only information on the quantity of the absorbed water but also on its spatial distribution.

Two cuboid samples from European beech (*Fagus sylvatica* L.) and Norway spruce (*Picea abies* [L.] Karst.) with sizes of 5.0 x 6.4 x 2.0 cm³ and densities of 0.65 g cm⁻³ and 0.38 g cm⁻³, respectively, were tested. The oven-dry samples (dried at 103°C until weight constancy) were isolated with aluminium tape on four sides, leaving only the opposite sides unsealed (the radial-tangential planes), so that only the longitudinal diffusion direction was permitted. The samples were then fixed on a box of acrylic glass filled with silica gel as the desiccating agent. One unsealed surface of the

samples was connected with the inner dry climate of the box via rectangular openings in the lid, which were slightly smaller than the size of the adjacent specimens. Gaps between box and specimen, as well as between box and lid, were sealed with aluminium tape (Figure 1).

EVALUATION

To evaluate the experimental data, the raw images were corrected with standard procedures common to all transmission-based methods. One such procedure is the “dark current” correction compensating the offset caused by the background noise of the CCD camera. The other is the “flat field” correction, which equalises inhomogeneities in the beam and on the scintillator screen. Furthermore, a median filter was applied on the image data to eliminate “white spots” (the result of hits by γ -particles on the CCD camera chip).

Neutrons are very susceptible to scattering, which can occur as “sample scattering” on the atoms within the specimen or as “background scattering”, where neutrons are scattered by the experimental facility. The neutrons, which are scattered on the detector are registered as an additional signal and distort the recorded data. For a quantitative evaluation of the experimental data, these scattering events were corrected by the scattering correction tool QNI (Quantitative Neutron Imaging) developed by Hassanein (2006).

The corrected images were further evaluated. The images gathered in the course of the experiment were referenced on the initial dry state: they were divided by the first image of the experiment to separate the signals of wood and absorbed water along eq. (7). The resulting referenced images represent the changes that had occurred in every pixel since the start of the experiment (Figure 3). These changes comprise not only the absorbed water but also dimensional changes. The swelling induced by the water absorption caused a dislocation of the sample edges. This made a direct quantification from the referenced images difficult and for the area of the sample edges impossible. The data had thus to be first retrieved from the images before they could be referenced. For this purpose, a line profile with almost the whole sample width was laid over the entire sample height. This profile yielded transmission values for every position in the vertical direction, averaged over the whole profile width. By using these averaged data, the noise was reduced and the signal smoothed. The dislocation of the edges was compensated by synchronising the transmission data rows using the slope representing the upper edge of the sample as fixed point. However, the edges show a slight blurriness as consequence to the phenomenon of geometrical unsharpness making an exact synchronisation difficult (Lehmann et al. 2007). The

transmission values were subsequently converted to attenuation coefficients.

The reference curves, i.e. the profiles from the start of the experiment, where the samples were presumed to be absolutely dry, showed conspicuous peaks towards the upper end of the sample. It was clear that the samples had already absorbed a certain amount of water during the preparation and positioning of the sample. Thus the start of the experiment did not correspond exactly to the start of the diffusion process and a temporal offset of 0.25 h for spruce and 0.1 h for beech had to be added to the time line. For the calculation of the diffusion coefficient D , only data from an area in the middle of the samples were taken into account (sector between vertical lines in Figure 6). This area corresponds to the penetration depths of the moisture at the start (right boundary) and the end of the experiment (left boundary); data on the left of this region (toward the dry side) were assumed to be zero and discarded because of the relatively high noise level; the right boundary corresponds to the point in the sample, which was still dry in the reference image.

In addition, an attempt was made to calculate the total water content of the sample using data over the entire range. To compensate the signal from the absorbed water on the right hand side of the dry reference state the data from the adjacent dry area was extrapolated toward the right edge, thus creating the most likely course of the attenuation coefficient values towards the end of the sample.

EXPERIMENTAL RESULTS AND INTERPRETATION

Total water content

The data from the last image (39 h) was used to verify the accuracy of the NI method. After the last image was taken, the samples were removed from the box and weighed with a digital balance. The difference between this weight and that of the start of the experiment gave the total mass of the absorbed water



FIGURE 3: Dry-referenced images of samples of European beech (left) and Norway spruce (right). The water absorption from the wet climate (above the samples) is visible as broadening band of darker grey. The black and white regions at the sample edges show the dislocation of the edges due to swelling.

As the results ascertained by NI correspond very well to those determined gravimetrically, it was verified that the images made at different times during the measuring campaign contain accurate information on the actual amount and location of absorbed water within the wood sample.

The theoretically detectable minimum water content of the samples was calculated along eq. (1) with the known attenuation coefficient of water for the thermal spectrum of NEUTRA. The calculated minimum thickness of the water layer is 30 μm . This corresponds to moisture content changes of 0.2% for the beech sample and 0.4% for spruce, which can be determined with NI.

The total water content within the wood samples was calculated for the first 8 h and is depicted in Figure 5.

The experimentally determined mass of the absorbed water shows a clear linear correlation with \sqrt{t} . The linearity could be expected for the first hours of adsorption where the influence of the opposite, dry side of the specimen is negligible. The fact that the linear regression cuts the y-axis in Figure 5 below zero was already described by Crank (1956). This may be attributed to surface convection losses and compressive stresses on the surface (Siau 1995).

ATTENUATION COEFFICIENT PROFILES

The total attenuation coefficients include both the attenuation by wood and by water. The vertical profiles for the spruce sample are presented in Figure 6. The rapid increase over the measuring period is conspicuous already in the unreferenced data. The inhomogeneous profile with higher values in the centre of the sample, which already appear in the curve for the dry initial state, may have several reasons. One could be due to an inconsistent density distribution within the wood sample, which plays an important role. However, the slight peak in the middle is at least partially caused by the isolating aluminium tape. While the aluminium itself is transparent for neutrons, the adhesive, which contains hydrogen, can attenuate the neutron beam to a certain degree. The accumulation in the middle is due to the fact that several layers of tape had to be used as it was not as wide as the sample height.

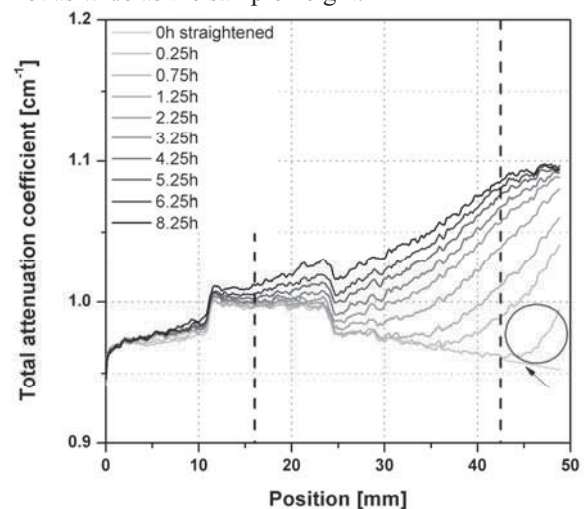


FIGURE 4: Vertical profiles of the attenuation coefficients over a spruce sample during the diffusion experiment; the left side represents the specimen's lower part (toward the silica gel), the right part is the upper part open to the wet climate (ca. 27°C at 86% RH); the samples had already absorbed water until the start of the experiment (circle); for the determination of the diffusion coefficient, only data between the vertical dashed lines were used; for the determination of the sample's total water content, the graphs were extended along the most likely course (arrow).

WATER CONCENTRATION AND DIFFUSION COEFFICIENT

The profiles of the volumetric water concentration were calculated on the basis of the dry-referenced data (Figure 6). As mentioned in the methods part, the differences between the experimental results and the regression curves were minimised by an optimisation algorithm. For the upper part towards the wet side, the fitted curves scarcely differ from the experimental

results. However, the experimental data towards the dry side lie clearly above the calculated values. This could be due to the assumption used for the calculation that the RH in this part of the samples is 0%, while the actual value was higher.

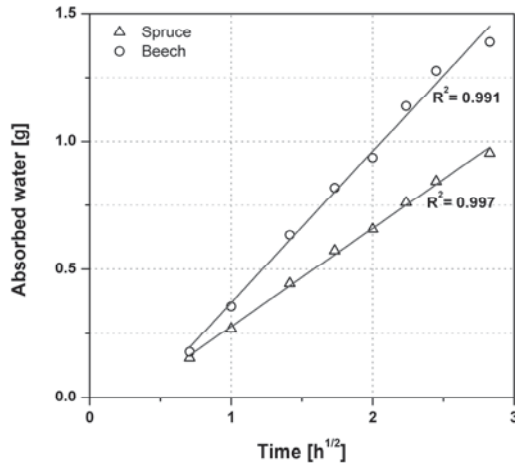


FIGURE 5: Mean total water content in the beech and spruce sample over the time.

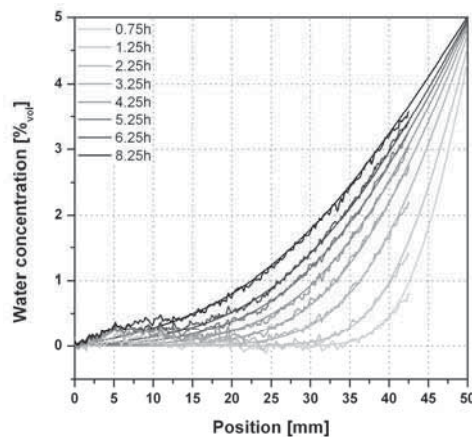


FIGURE 6: Vertical profiles (experimental results and the corresponding model curves) of volumetric concentration of water over the position in the spruce sample during the diffusion experiment; the left hand side represents the specimen's lower part (toward the silica gel), the right hand part is the upper part open to the wet climate (ca. 27°C at 86% RH).

Overall, the experimental results are still in good agreement with Fick's second law. The determined diffusion coefficients and the corresponding calculation parameters for diffusion in longitudinal direction determined under unsteady state conditions for beech and spruce are presented in Table 2. Here, the results are compared to values determined by Olek et al. (2005), who used a similar analysis approach for the

determination of the diffusion coefficient in beech wood. Differences between the literature values and the NI-results can be accounted to several reasons:

- experimental data – the NI-data comprise information on location and time while the data of Olek et al. depend only on time
- moisture boundary conditions – absolute values and influence of air flow (ventilators)
- sample thickness in diffusion direction – using only a single transport equation can yield different results for varying thicknesses (Wadsö 1994)

More publications than under unsteady state conditions are available for the diffusion coefficient determined under steady state conditions. These values are clearly lower than the ones determined with NI under unsteady state conditions. The differences can be attributed to the different experimental conditions and to the different theoretical approach chosen for the calculation. For instance, Pfriem (2007) shows a difference of factor 10 between the diffusion coefficients determined under steady and unsteady state conditions for spruce wood in tangential direction. The approach presented in this article represents just one possibility for the evaluation of the data ascertained by NI. Other approaches could for example be based on a multi-Fickian model (Frandsen et al. 2007).

CONCLUSIONS AND OUTLOOK

By means of NI, it was possible to quantify the water content within wood samples in a non-destructive way. In contrast to conventional methods, NI allows not only the time dependent resolution of diffusion processes but also to localise the moisture distribution within the specimen. Based on the NI data, it was possible to ascertain the moisture dependent diffusion coefficients for beech and spruce in the longitudinal direction. Due to the high sensitivity of NI for hydrogen, even small amounts of water (e.g. by absorption from air moisture) can be detected and quantified. The quantitative resolution for the wood MC is in the order of 0.2% for the beech sample and 0.4% for spruce.

However, the presented investigation featured some difficulties. Due to the complexity of the experiment and availability of measuring time at the NI-facility the number of samples was restricted. The experiment can only be regarded as first test series, which has to be followed by more extensive measuring campaigns with a higher number of samples. Further, during the evaluation of the data, it was not possible to use the data from the sample edges. The dry-referencing was difficult in the edge areas due to geometrical unsharpness, swelling and the fact that the diffusion process had already begun before the start of the experiment.

Nevertheless, NI is a method, which proved to be very suitable for investigations of wood-water related processes. It allows visualising moisture transport processes in wood and can contribute to a better understanding of diffusion processes.

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Infrared thermography for monitoring surface checking of wood during drying

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ABSTRACT

Infrared thermography technique was adopted for exploring the more convenient ways to investigate the occurrence of checking during drying that is indispensable for the development of improvement of drying schedule and kiln operation. A small constant temperature chamber was combined with infrared thermography system and the occurrence of checking on cross section was observed and the coefficient of variation of the surface temperature was measured by the system during drying.

This research aimed at monitoring of surface checking in a drying process of wood using the infrared thermography, and this method expected to develop drying schedule. The advantage of measurement using the thermography is nondestructive, prompt, and easy to detect over a wide area.

Japanese cedar (sugi) boxed heart specimens were prepared and dried under a constant temperature at 105°C. During drying, infrared thermography images were taken. Results indicate that the coefficient of variation of the surface temperature in the checked area of cross section increased. However, it decreased in the not-checked area. The change of the surface temperature during drying showed some potential for detecting surface checking. Infrared thermography system may be useful in the development of a kiln control system based on the surface temperature during drying.

Combined method for monitoring wood drying process

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ABSTRACT

The combined method is based on using electrical method for moisture gradient monitoring and acoustic emission method for detection of micro-cracking. In the method, electrodes are used to create electric field in drying wood and to measure the electric complex spectrum using the impedance spectroscopy method while at the same time measuring acoustic emissions from drying wood. The result can be used for calculating the parameters required for determining the stress state prevailing in the wood. The spectrum is affected by the properties of the wood, such as moisture content, moisture gradient, temperature, density, and structure. When the electric complex spectrum and acoustic emission response are determined at the same time, it is possible to estimate both the main reason for the stresses (moisture gradient) and the outcome (micro- and macro-cracking). Thus the results may be used to control drying in order to achieve wood products of superior quality. The method was studied and tested both in laboratory and industrial kilns.

Effect of Oscillating Drying Conditions on Variations of the Moisture Content Field inside Wood Boards

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ABSTRACT

Wood drying is an essential process in wood industry. During drying, the stress developed in the boards can produce several defaults such as deformations and cracks. The use of oscillating drying conditions should reduce the drying stresses in boards by activating the mecanosorptive creep. Actually, the advantages of this strategy remain an open question in the scientist community. In this paper, the effect of oscillating conditions on moisture content variations across the board thickness is studied by the way of an analytical model and a numerical code, *TransPore*. Also, mechanical consequences of moisture content variations produced by oscillations have been studied by the way of non-symmetrical drying (flying wood) and loaded drying (cantilever beam test). Beech wood, the second kiln dried hardwood after oak in France, has been chosen for this study due to its elevated shrinkage coefficient, hence an elevated risk of drying defaults.

This research is developed in partnership between a fundamental public research laboratory, LERFoB – Bois Biomatériaux Biomasse Team, and Institut Technologique FCBA.

Keywords : wood oscillating drying, mecanosorptive creep, flying wood, drying simulation.

Acoustic emissions and radial shrinkage behavior of fresh versus pre-dried Norway spruce sapwood

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ABSTRACT

Some authors suggest that internal checking can be induced by tension forces of free water because checking occurs long before most cells reach fiber saturation. Acoustic emission (AE) testing is a powerful tool for optimizing lumber drying conditions, where the analysis of the amplitude or energy distribution of AE signals has been successfully used to pinpoint checking. Combined shrinkage- and AE tests are scarce in AE literature on wood and lumber shrinkage assessment starts either at moisture contents around fiber saturation or at “green” moisture content, which might not correspond to the moisture content (MC) at 100 % saturation.

In the present study, we compare AE and shrinkage of fully saturated fresh and pre-dried Norway spruce sapwood specimens during dehydration at ambient temperature. We present a novel approach, where shrinkage is calculated from changes in the contact pressure between the AE transducer and the dehydrating specimen.

Both fresh and pre-dried specimens showed radial shrinkage due to drying surface layers right from the beginning of dehydration, which induced almost no AE. Whereas no dimensional changes occurred in pre-dried wood thereafter, fresh wood showed a rapid shrinkage increase starting at 130% MC. This shrinkage process ceased when further moisture got lost and was even partially reversed. The partial recovery reveals that a remarkable percent of shrinkage was induced by strong tensile forces of free water inside the capillaries, which are released when it comes to cavitation. AE of fresh wood showed much higher activity, amplitudes and energy. Extremely high single AE energy events might be attributed to mechanical failure at this critical stage of dehydration. After partial recovery from shrinkage, neither dimensional changes nor AE activity showed differences between fresh and pre-dried wood below 30% MC. Our results suggest that fresh sapwood is more prone to dehydration stresses than pre-dried sapwood.

KEYNOTE ADDRESS II

Problems and Solutions in Wood Drying Modelling – History and Future

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ABSTRACT

The aim of this paper is to give a historic overview of wood drying modelling during the last 30 years. Some of the problems encountered and their solutions are discussed. Finally some remaining problems that require solutions in the future are presented.

The modelling work increased strongly when personal computers became available to everyone. Numerical solutions of Fick's equations were now easy and the first promising simulations of the drying process were presented. The models required numerical values for material parameters such as the diffusion coefficient and models were used for adapting values in order to have a good fit with test results. The external heat and mass transfer was a subject for discussion for a long time. Unfortunately a lot of work was devoted to the surface emission concept, which has turned out to be useless from a practical point of view. Another problem in this field was the apparent deviation from the analogy between heat and mass transfer. Only recently these external transfer problems seem to have been solved, or at least understood.

As the moisture migration modelling had reached a reasonable level of accuracy, the focus was turned towards calculation of moisture induced stress. This required modelling of the mechanosorptive creep behaviour, which is a subject that is still not fully understood. Initially only low temperature, single board models were developed but gradually other areas were included such as; kiln-wide models, energy consumption, drying costs, deformations and temperatures above the boiling point.

Areas that still require research and development are; modelling free water behaviour in the capillary network, inclusion of sorption hysteresis, environmental impact, modelling discolouration, etc. Finally, the importance of technology transfer in the form of easy-to-use models for kiln operators and imbedded models in kiln control systems should be emphasized.

SESSION 3

PHYSICS OF WOOD DRYING: MODELLING

A Numerical Study on the Influence of the Bond Line Diffusivity on Moisture-Related Stresses and Deformations of Three-Layered Spruce Cross-Laminates

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ABSTRACT

In diffusion processes through glued wooden elements the glue lines play an important role. For the numerical calculation of the moisture distribution, the diffusion coefficient of the adhesive is needed. In previous studies it was evaluated from moisture profile measurements. The diffusivity of the bond line was found to be significantly lower than that of wood. The application of this knowledge is the intention of the present paper. Numerical studies on the influence of different diffusion coefficient on hygroscopic warping and stresses in three-layered spruce cross-laminates were performed. It is the objective to reduce moisture-induced stresses and deformations of cross-laminates in order to improve their performance. The results reveal a significant influence of the bond line diffusivity on the moisture content. Mainly the middle layer was affected. The influence on warping, which was induced by a moisture gradient, is also very significant. A 25% reduction of deformation was achieved by applying a diffusivity identical to that of the wood material. Significant differences in stresses occurring perpendicular to the grain were detected only in the middle layer. Stresses in the outer layers were not affected by changing the diffusivity of the glue. It was concluded to apply an adhesive with high moisture permeability in order to reduce the results of moisture impact on wooden cross-laminates.

INTRODUCTION

Wood adsorbs or desorbs moisture depending on whether the relative humidity (RH) of the surrounding air increases or decreases. The change of the wood moisture content yields a volume change of the material. The swelling and shrinkage vary between the transverse and longitudinal to the grain directions. When the humidity changes, hygroscopy, volume change and orthotropy of wood cause stresses in the layers of wooden cross-laminates. These moisture-induced stresses and deformations, thus, play an important role in the application of wood cross-laminates.

Adhesive joints are applied not only in cross-laminated wood panels but also in a plenty of modern solid wood based materials. Nowadays, the diffusion coefficient of adhesives is widely unknown. The newer literature only concerns with extreme values for the adhesive, i.e. $D_{adh}=D_{wood}$ and $D_{adh}=0$ (Sprcic et al. 2008). The results show that both assumptions do not fulfil the experimental results. However, correct knowledge about the moisture behaviour of adhesive

joints is fundamental in the simulation of moisture flux through wooden structural elements and, consequently, moisture-induced stresses and deformations. The evaluation of the glue line's diffusion coefficient by Gereke et al. (2009) revealed a dependency on moisture concentration c [kg m^{-3}] as

$$D_{adh}(c) = A_1 \cdot c^{-A_2} + A_3 \quad (1)$$

The shape factors were determined to $A_1=3.3 \cdot 10^{-3} \text{ mm}^2 \text{ h}^{-1}$, $A_2=0.51$ and $A_3=-8.6 \cdot 10^{-3} \text{ mm}^2 \text{ h}^{-1}$. Compared to solid wood, adhesive layers provide a high resistance to moisture diffusion.

In the present study, the numerical calculation of stresses is based on a strain rate formulation, which was established by Santaoja et al. (1991) and Ormarsson (1999). The approach was successfully validated to moisture-induced stresses and deformations in spruce cross-laminates by Gereke et al. (2009) and Gereke and Niemz (2009). The three-dimensional orthotropic formulation is given by

$$\dot{\epsilon} = \dot{\epsilon}_{el} + \dot{\epsilon}_{\omega} + \dot{\epsilon}_{\omega\sigma} \quad (2)$$

It takes into account elastic strain rate $\dot{\epsilon}_{el}$, moisture-induced strain rate $\dot{\epsilon}_{\omega}$ and mechano-sorptive strain rate $\dot{\epsilon}_{\omega\sigma}$, where the dot denotes derivative with respect to time. The formulations of the orthotropic material matrices and the moisture dependent material data are given in Gereke et al. (2009).

METHODS

The investigated panels wer built up with three layers, each 10mm thick. The annual rings were aligned vertically. Diffusion was modelled by means of Fick’s law. The edges of the panels were assumed to be insulated at the small edges. Thus, moisture impact at the large panel faces caused one dimensional diffusion tangentially to the growth rings and through the glue lines. The diffusion coefficient of the spruce layers under steady-state conditions ($t \geq t^*$) is according to Hanhijärvi (1995)

$$D_{wood}(c) = 0.288e^{1.8c} \tag{3}$$

It is formulated on a concentration basis with $\rho_{wood}=0.45 \text{ kg cm}^{-3}$. Under unsteady-state conditions ($t < t^*$) it is reduced, which refers to Non-Fickian diffusion:

$$D_{wood}^*(c,t) = D_{wood}(c) \left[(1-\kappa) \frac{t}{t^*} + \kappa \right] \tag{4}$$

The barrier between steady-state and unsteady-state diffusion was determined to $t^*=1000\text{h}$ and the reduction factor is $\kappa=0.45$ (Gereke et al. 2009).

Different moisture diffusivities of the bond lines were tested. The parameter A_l (Eq. 1) was both increased and decreased in two steps of 5%. Furthermore, waterproof glue lines ($D_{adh}=0$) and glue lines where $D_{adh}=D_{wood}$ were applied. Two moisture conditions were investigated: moisture gradient 65/100% RH and wetting from 35 to 85% RH on both

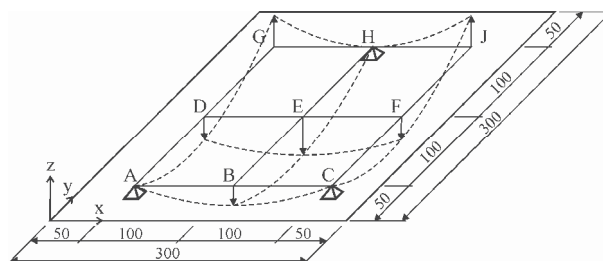


FIGURE 1 Coordinate system (x – grain direction outer layers) and point pattern at the upper surface for the determination of cup deformations, dimensions in mm

large panel faces. The moisture gradient led to hygroscopic warping, which was divided into two types of cup deformation (Fig. 1):

$$cup_{xz} = \frac{1}{2} (\bar{u}_z^{A,D,G} + \bar{u}_z^{C,F,J}) - \bar{u}_z^{B,E,H} \tag{5}$$

$$cup_{yz} = \frac{1}{2} (\bar{u}_z^{A,B,C} + \bar{u}_z^{G,H,J}) - \bar{u}_z^{D,E,F} \tag{6}$$

The notation $\bar{u}_z^{i,j,k}$ indicates the mean value of the displacements in thickness direction (z-direction) in the points i, j and k.

RESULTS AND DISCUSSION

Moisture gradient

The results are shown in Figs. 2 and 3. The variation of A_l yielded different moisture profiles. The middle layer was significantly influenced by a change in the water diffusivity of the bond lines. The influence on the moisture content of the top and the bottom layer was less significant. At the end of the investigated time span, the moisture content calculated by both extremal A_l varied by 0.69% in the bottom layer, 2.12% in the middle layer and 0.80% in the top layer. A larger A_l resulted in a larger D_{adh} and, thus, in a larger amount of water that was allowed to penetrate through the adhesive. Consequentially, the moisture content in the

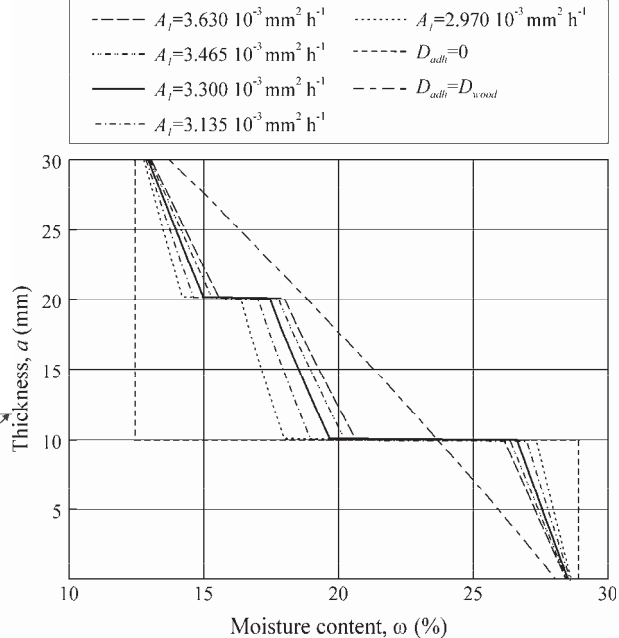


FIGURE 2 Moisture profiles in three-layered spruce laminates due to relative humidity difference of 100% (bottom face, $a=0\text{mm}$) and 65% (top face, $a=30.2\text{mm}$), influence of different D_{adh} (Eq. 1).

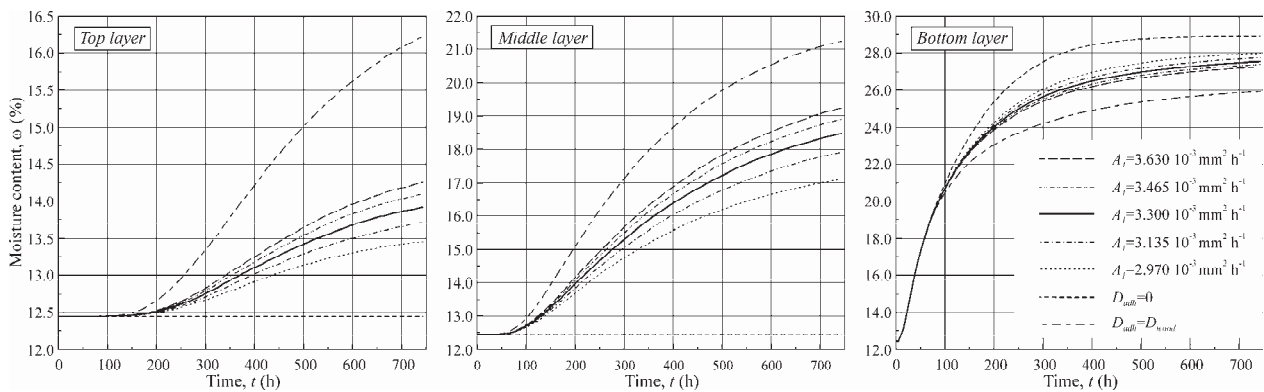


FIGURE 3 History plots of moisture content in different layers, initial climate: 65% RH, test climate: 65/100% RH

top and the middle layer increased when A_l increased. In contrast, the moisture content of the bottom layer decreased. When $D_{adh}=0$, only the bottom layer was affected by the changed humidity. Since the panels were assumed to be insulated at the ends and moisture flow was one-dimensional, the moisture content of the top and the middle layer was constant and the moisture content of the bottom layer increased rapidly. This increase was larger than the increase, when $D_{adh}>0$. Glue lines with the same diffusivity as wood yielded a linear moisture distribution in the panel (Fig. 2).

The influence of different D_{adh} on warping is summarised in Table 1. The tests on different moisture distributions indicate that both cup_{xz} and cup_{yz} were influenced. $D_{adh}=0$ yielded considerably larger cup deformations than the reference cupping, since the bottom layer expansion perpendicular to the grain was very large. A balanced (linear) moisture distribution ($D_{adh}=D_{wood}$) led to 17.8% smaller cup_{xz} and 24.7% smaller cup_{yz} . As expected, the cup deformations decreased with increased A_l . This was a result of the drier bottom layer and the moister middle and top layers (compared to the reference). The influence on cup_{yz} was more significant than the influence on cup_{xz} . The

increase and the decrease of A_l each of 10%, resulted in a 17.6% increased cup_{yz} and a 5.8% decreased cup_{yz} , respectively. On the other hand, cup_{xz} was influenced only with 8.1% and -3.4%

Single moistening step

Fig. 4 illustrates the resultant moisture profiles for a relative humidity step from 35% to 85%, which affected from both large panel faces. A distinctive moisture profile with a significant influence of the glue lines was present after seven days of moisture impact. The less water was allowed to penetrate through the glue lines, the moister were the outer layers. This effect resulted from moister accumulation at the glue lines.

Different diffusivities of the glue lines implied only small differences in stresses occurring in the outer layers perpendicular to the grain (Fig. 5). With increased moisture content of the middle layer, the expansion of this layer increased. This also affected the deformation of the outer layers. The in-plane deformation also increased since the opposite constraint between outer and middle layers was reduced. However, significant differences of the radial stresses in the

Table 1 Cup deformations for different moisture profiles (Fig. 2)

Moisture profile	cup_{xz} (mm)	$cup_{xz}/cup_{xz,ref}$ (%)	cup_{yz} (mm)	$cup_{yz}/cup_{yz,ref}$ (%)
$D_{adh}=0$	0.189	27.0	0.380	36.6
$A_l=2.970 \cdot 10^{-3}$ (-10.0) ¹	0.161	8.1	0.327	17.6
$A_l=3.135 \cdot 10^{-3}$ (-5.0) ¹	0.152	2.4	0.290	4.2
$A_l=3.300 \cdot 10^{-3}$ (reference)	0.149	-	0.279	-
$A_l=3.465 \cdot 10^{-3}$ (5.0) ¹	0.146	-1.9	0.270	-3.1
$A_l=3.630 \cdot 10^{-3}$ (10.0) ¹	0.144	-3.4	0.262	-5.8
$D_{adh}=D_{wood}$	0.122	-17.8	0.210	-24.7

¹ in $mm^2 h^{-1}$ (% to reference)

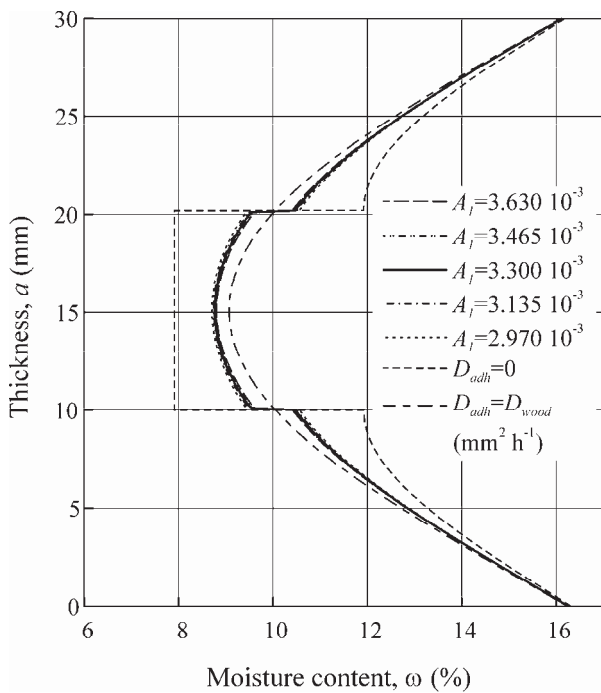


FIGURE 4 Moisture profiles of three-layered spruce laminates due to wetting from 35% to 85% RH on the large panel faces ($t=7d$).

middle layer are shown by Fig 6. When $D_{adh}=0$, tensile stresses occurred perpendicular to the grain in the middle layer. The moisture content of this layer was constant compared to the initial state and only the moisture content of the outer layers increased. The resulting expansion of the outer layers yielded tensile stresses. When the moisture content of the middle layer was also increased compared to the initial state, compressive stresses developed in the middle layer. The expansion of the middle layer occurring perpendicular to the grain was hindered by the cross-lamination. A moister middle layer yielded increased expansion and, thus, increased compressive stresses.

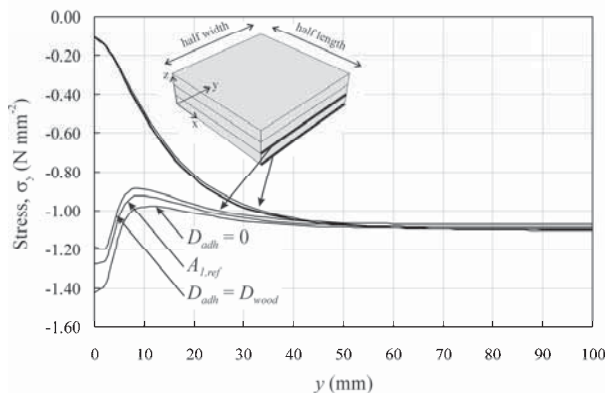


FIGURE 5 Stresses σ_y (radial stresses) in three-layered cross-laminates along the y-axis, wetting from 35% to 85% RH

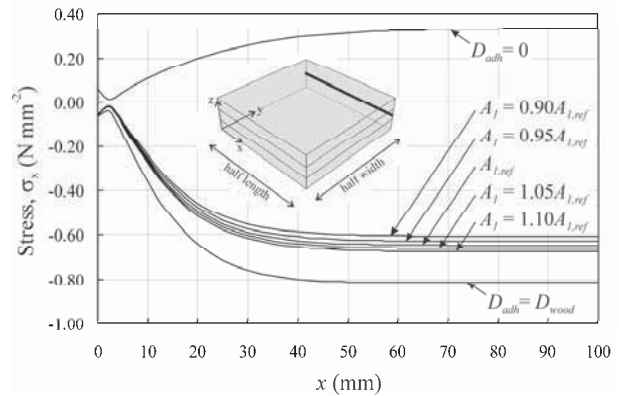


FIGURE 6 Stresses σ_x (radial stresses) in three-layered cross-laminates along the x-axis in the middle layer, wetting from 35% to 85% RH

CONCLUSIONS

The diffusivity of the bond line was found to strongly influence moisture distribution, stresses and deformations in cross-laminated solid wood panels. Different moisture diffusivities of the adhesive yielded significant differences in moisture content, mainly in the middle layer. Due to water accumulation at the glue lines differences existed also in the outer layers. The tests of the influence of different diffusion coefficients of the adhesive on hygroscopic warping indicated a decrease in cup deformations, both cup_{xz} and cup_{yz} , when the diffusivity was increased. In further numerical analysis, it was found that a moistening of cross-laminates and a rise in the diffusivity of the adhesive layers resulted in increased compressive stresses perpendicular to the grain in the middle layer. In contrast, tensile stresses would develop when the panel would be dried. The results showed that the outer layers were only slightly influenced by the diffusivity. Since the prevention of warping and of stresses in the outer layers is more important than the formation of stresses in the middle layer, it is recommended to apply an adhesive that has a high permeability for moisture. Alternatively, one could apply another connection system, which gives $D_{adh}=D_{wood}$, but ensures the effect of the crosswise orientation of the layers. In future investigations the implementation of models for ductile and brittle failure would improve the accuracy of the simulations. Ductile failure in terms of plastic deformations would have a strong influence on stresses in wooden cross-laminates under moistening. However, under drying cross-laminates would fail in terms of cracking. Appropriate models were introduced by Fleischmann et al. (2007), Mackenzie-Helnwein et al. (2003), Schmidt and Kalsike (2006, 2007, 2009), among others.

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Shrinkage response to tensile stresses during hemlock (*Tsuga heterophylla*) drying

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ABSTRACT

This paper reports on the results of the shrinkage, tensile set and moisture content interaction during drying in relation to air parameters. The experimental design was structured on two levels: study the effect of tensile stresses on artificially restrained small wood strips and correlate these experiments with drying tests made on short pieces of lumber.

The measurements were performed perpendicular to grain on clear wood specimens of green western hemlock (*Tsuga heterophylla*) while drying at 40, 60 and 80°C down to 17, 11 and 5% final moisture content. The resulting shrinkage was dynamically measured by pairs of resistive transducers located on the middle part of each specimen. The same type of transducers was positioned around short pieces of lumber dried to similar drying conditions.

The study of wood shrinkage process provided much information about wood-water relationship: the correlation between the amount or rate of moisture loss and partial vapor pressure of the surrounding environment, the elastic and visco-elastic components of the restrained shrinkage process. It has also shown how interconnected variables like temperature and moisture content can have a great impact over the desorption process. The model developed for small wood strips yielded high coefficients of determination ($R^2=0.83-0.85$, $p<0.05$) and could be used to calculate the tensile stresses in full boards. The findings are intended to be used in further studies of the shrinkage process as an indicator of the tensile stresses generated in the early stages of wood drying.

Modeling of moisture transport in wood below the fiber saturation point

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ABSTRACT

This paper describes a multiscale homogenization model for macroscopic diffusion properties of wood. After a short introduction the physical background of steady state diffusion processes in wood will be highlighted, resulting in a physically motivated macroscopic description of diffusion processes with only one diffusion equation and thus one diffusion tensor. This macroscopic diffusion tensor is derived by revisiting the morphological structure of wood in the framework of continuum micromechanics. Starting point is the cellular structure of wood; further homogenization steps include wood rays and the succession of annual rings. The quality of the model is assessed by a comparison of model predictions and measured values at different temperatures and moisture contents.

Experimental study of moisture-driven distortion and fracture in solid wood

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ABSTRACT

Moisture-induced fracture and lack of shape stability in solid wood products are well known problems to the saw-milling and building industries. Cracks that initiate during the drying process may cause severe material losses and the building industry may be forced to use alternative building materials. The cracking caused by kiln-drying of solid timber (and round wood) is extremely difficult to predict due to the strong orthotropic and non-homogeneous characteristics of the material in combination with considerable amounts of microscopic defects which may act as crack initiators.

An experimental study has been performed to reveal the cracking behaviour of Norway spruce during drying from green moisture content down to equilibrium moisture content (EMC) at a temperature of 22-24°C and a RH of 64%. The moisture related strains and crack widths were measured with a digital image correlation system (ARAMIS) on thin discs cut from a timber log. The history of the strain field over the entire cross section of the discs was measured throughout the drying period. The results showed that the thicker discs (30 mm) cracked very early during the drying process. They also cracked significantly more than the thinner ones (15 mm) and the crack patterns developed differently. For the thicker discs the early cracks which may partly be caused by the moisture gradient in the longitudinal direction of the log, closed and became invisible later during the drying process. This indicates that sealing of timber log ends in the green moisture state could significantly reduce the development of end-cracks. It was also recognized that the initial moisture content and the shrinkage properties vary significantly from pith to bark. Based on this experimental finding it can be concluded that modelling of crack propagation in solid wood must take the material inhomogeneities into account.

SESSION 4

APPLIED WOOD DRYING

Determination of Dynamics of Moisture Content, Temperature and Mechanical Stress of Pine Wood During Convective Drying

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ABSTRACT

The present research describes the methods and test equipment of experimental determining of essential variables (i.e. temperature, humidity and mechanical stress) in the process of convective drying. The gained results are compared to those of the one-dimensional wood drying simulation programme TORKSIM ver.3.1 (<http://www.tratek.se>). On the ground of experiments and computer simulation, the following conclusion was made: to characterise the drying process Fick's first and second law in one dimension can be applied on the assumption that the wood moisture effective diffusion coefficient ($m^2 s^{-1}$), that depends on the humidity and temperature, can be fixed by the experiment in the sufficient amount and with necessary exactness. In tests at +50 to +60 degrees C° up to 12 effective diffusion coefficients were determined. The appearance of the first drying crack on the surface of the material was predicted with an accuracy of 30 minutes by simulation program TOKSIM ver. 3.1. The development of compressive stress in the central part of the drying pine wood specimen was also identified. It was found that the laboratory test device is suitable for determining the exactness of the drying simulation program TORKSIM ver.3.1 as well as for using it for modelling of industrial wood dryers.

Keywords: heat transport, moisture transport, effective diffusion coefficient, tensile stress, compressive stress

1. INTRODUCTION

The quality of convective drying of wood, i.e. final moisture content, mechanical stresses, initiation of cracks in the wood etc is determined by the choice of the drying schedule, i.e. the choice of the drying control programme of the kiln.

Nowadays drying control programmes for kilns are developed by mathematical modelling, i.e. computer simulation (Salin, 1990; Rémond et al., 2007) of the drying process. Stimulated drying schedules are carefully tested both under laboratory conditions and in industrial environment (Tronstad et al., 2005). Also, it

can be done the other way round – i.e. to take a drying schedule which has proved to function efficiently in industrial kilns as the basis and test it under laboratory conditions. At the same time computer simulation for the drying process is performed. Certain difficulties can be encountered with the evaluation and interpretation of the results of using commercial simulation programmes as the exact mathematical model being the basis for the commercial programme is not known to the user. In most cases general information about the simulation programme is known – i.e. whether the model is one-, two- or three- dimensional (1D, 2D, 3D Model),

isotropic or orthotropic. Sometimes we have background information from other sources like a description of the mathematical model likely used in the simulation programme (Salin, 1990; Rémond et al., 2007). In this paper the performance data and relevant computer simulations of two industrial experiments and one laboratory experiment of convective drying of pinewood using the 1D programme TORKSIM ver. 3.1. are presented. Also, the inverse determination of efficient diffusion coefficients is presented using the parabola method well-known from simulated moisture profiles (Kretchetov, 1972). In the laboratory drying test the diffusion coefficients were determined experimentally by means of electrical conductivity method – ECM using Fick's First Law.

In addition, differences in the temperature of the material subjected to drying and initiation of the first drying crack as a result of drying stress were examined. For this purpose, a forced drying schedule three times shorter than the regular schedule used in industry was used.

2. METHOD

2.1. The coupled, uncoupled and diffusion-based simplified models.

The coupled model to calculate the combined heat and moisture transport through a porous medium was developed by Luikov (Luikov, 1966), and specific to wood by Siau (Siau, 1984).

The governing equation for heat transfer through wood board:

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(\lambda \frac{\partial T}{\partial x} \right) + \frac{\partial u}{\partial t} \rho_w G_m H_m, \quad (1)$$

where x is the distance along the direction flow (m), t is the time (s), ρ is the wood density (kg m^{-3}), function of the moisture content u , c_p is the specific heat capacity of wood ($\text{J kg}^{-1} \text{K}^{-1}$), function of temperature and moisture content u (kg kg^{-1}), T is the Kelvin temperature, λ is the wood thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$), expressed as a function of temperature and moisture content u , ρ_w is the water density (kg m^{-3}), G_m is the wood specific gravity (kg kg^{-1}) and H_m is the latent heat of moisture in wood (J kg^{-1}). The specific gravity of wood, G_m is by definition the ratio of the oven-dry mass of wood to the mass of water displaced by the bulk specimen at a given moisture content u . The local moisture content u in the wood material is expressed as the weight of water present in the wood divided by the weight of oven-dry wood substance.

The governing equation for unsteady-state isothermal moisture transfer through a wood board is given as the Fick's second law in one dimension:

$$\frac{\partial u}{\partial t} = \frac{\partial}{\partial x} \left(D_t(T, u) \frac{\partial u}{\partial x} \right), \quad (2)$$

where D_t is the transverse wood moisture diffusion coefficient ($\text{m}^2 \text{s}^{-1}$).

It is possible to simplify a coupled model and turn it into an uncoupled model on the assumption that there is no heat generation inside the wood. This assumption can approximately be implemented on certain conditions of an experiment – i.e. in case the velocity of heat transfer process throughout the wood sample is over ten times higher than the velocity of mass transfer i.e. diffusion process. Another simplifying assumption would be the use of empirical formula for thermo-physical properties of wood and other non-linear transfer coefficients (Younsi et al., 2006).

On exceptional cases the isothermal diffusion equation (i.e. Fick's Second Law) can be used to describe the process of drying wood in narrow temperature range 50...60°C with reasonable accuracy, ref.eq.2 The prerequisite for using the extremely simplified diffusion-based model is presence of as many reference points of comparison as possible all over the sample to observe the dynamics of moisture content and temperature.

The mathematical model being the basis for the wood drying simulation programme TORKSIM ver.3.1 has not been disclosed in detail, however, on the basis of (Salin, 1990) it can be assumed that it is the perfect isotropic Luikov-type coupled model.

2.2. Stress calculation model.

In order to ensure quality in the process of drying wood it is necessary to calculate the strain and stress evolved in wood on the basis of previously calculated moisture profile.

The mathematical model in the one-dimensional isotropic case can be presented on the basis of (Salin, 1990).

The governing equation for stress calculation:

$$\sigma = aE \left(\frac{\int_0^{l/2} E \rho_b dx}{\int_0^{l/2} E dx} - \rho_b \right), \quad (3)$$

where σ – tensile stress (Pa), ρ_b – bound water content (kg m^{-3}), E – modulus of elasticity (Pa), l – board thickness (m), x – coordinate (m).

The governing equation for creep calculation:

$$\frac{\partial \varepsilon}{\partial t} = \frac{1}{E} \frac{\partial \sigma}{\partial t} + \frac{\partial \varepsilon_v}{\partial t} + (a + m\sigma) \frac{\partial \rho_b}{\partial t}, \quad (4)$$

where ε – total strain, σ – tensile stress (Pa), E – modulus of elasticity (Pa), ε_v – viscoelastic strain, a – unrestrained shrinkage coefficient ($\text{m}^3 \text{kg}^{-1}$), m – mechano-sorptive creep coefficient ($\text{m}^3 \text{kg}^{-1} \text{Pa}$), ρ_b – bound water content (kg m^3), t – time (s).

Modulus of elasticity E is non constant, but depends on both moisture content and temperature.

3. MATERIAL

In an industrial kiln two samples of pinewood of cross-section area of $150 \times 22 \text{mm}^2$ and $150 \times 50 \text{mm}^2$ and of the length of 6m were dried. The laboratory drying experiment involved pinewood of the area of $600 \times 200 \text{mm}^2$ and of board thickness of 56 mm. In all three experiments the content of heartwood was 40%. In the laboratory experiment the ends and sides of the wood sample were covered with neutral silicone (a product by Bostik) to ensure the validity of the assumptions of the one-dimensional mathematical model in the experiment.

4. EXPERIMENT

In the industrial chamber type convective dryer a reliable soft drying schedule having successfully been tested in practice was used ensuring the high final quality of wood. The drying times of the 22mm and 50mm pinewood samples were 90 and 336 hours and the initial moisture contents were 55% and 36% respectively. The drying chamber was controlled by means of indications of the relative air humidity and temperature sensor (ROTRONIC Hygro Clip; www.rotronic-humidity.com) The moisture content was measured by means of screw electrodes in six different points in the location of 1/3 of the thickness of the sample from the surface. The moisture content indicators were averaged and registered in the logfile. Information about the average moisture content of wood was not used in the control of the drying chamber, however, it was saved as additional information. The average velocity of air in the drying chamber was 2 m s^{-1} . Hysteresis in the ,on-off' control of the drying chamber was adjusted to $\pm 1.5^\circ\text{C}$ in the temperature channel and to $\pm 2\%$ RH in the relative moisture channel of drying air. During the drying time mostly a schedule of linearly rising temperature of the speed of 0.01°C and 0.1°C per hour was used for the samples of the thickness of 22mm and 50mm, respectively. In both cases the temperature rising speed was smaller than the fluctuation of temperature per hour caused by the automatic control system of the chamber (i.e. $\pm 1.5^\circ\text{C}$).

The laboratory experiment with pinewood was carried out in the climate chamber FEUTRON; (www.feutron.com). The climate chamber was operated according to the indications of relative air humidity and temperature of the same type of sensor (ROTRONIC Hygro Clip) as in the industrial experiment. The climate chamber was controlled by the on-off' system whereas the hysteresis was adjusted to $\pm 1.5^\circ\text{C}$ in the temperature channel and to $\pm 2\%$ RH in the relative moisture channel – the same as in case of the industrial experiment. The temperature schedule in the laboratory experiment rose linearly by 0.08°C per hour. In the laboratory experiment the temperature range was $50^\circ\text{C} \dots 60^\circ\text{C}$, i.e. the same as in the industrial experiment.

Difference between the laboratory experiment and an analogous industrial experiment (50mm pinewood) was related to the fact that the laboratory experiment was carried out in a time period of three times shorter than the industrial experiment (120 hours and 336 hours respectively). The first objective of the laboratory experiment was to create bigger stress in the material subjected to drying and register the time of the initiation of the first crack. The other objective was to compare the results of the computer simulation with the results of the experiment. Thus, a forced drying schedule was consciously selected for the laboratory experiment expecting the drying result not to be of good quality. Location of sensors in the sample, on the surface and near the surface of the sample in the laboratory experiment is shown in Figure 1.

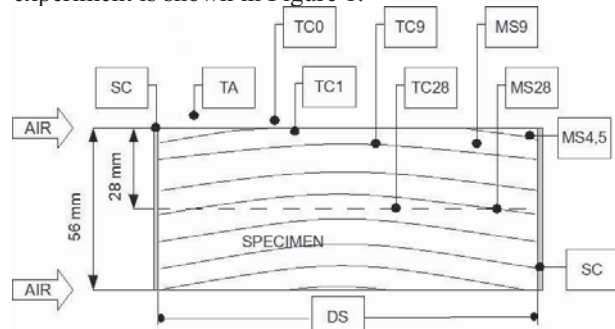


FIGURE 1. Location of sensors in the sample

Differences in temperature in the sample, on the surface and in the ambient air of the surface of the sample were registered by a thermocouple of AHLBORN; (www.ahlborn.com) of the type FTA 3901 of the resolution of 0.1K and the data were saved by means of a nine-channel datalogger AHLBORN ALMEMO 2890-9. The location of the thermocouple was 10 mm from the surface of the sample in the air, on the surface of the sample and in the depth of 4.5mm, 9mm and 28mm from the surface of the sample. The moisture content of wood was measured in the depth of 4.5mm, 9mm and 28mm from the surface by means of

AHLBORN timber moisture sensor of the type FHA 636M and the data were saved by the datalogger. Also, the moisture content of wood was measured manually at least twice in 24 hours by means of moisture measuring device GANN HYDROMETTE HT 85T; (www.gann.com) The velocity of drying air was registered by AHLBORN thermo-anemometer of type FVA645 TH2 at 10mm from the surface of the sample. Strain in the surface layer of the sample and the time of initiation of the first drying crack were registered by datalogger and displacement sensor of type FWA 025T with the resolution of 0.001mm.

5. RESULTS

The graphs of logfails of the results of industrial drying experiments and relevant simulations with the programme TORKSIM ver. 3.1. are shown in Figures 2 and 3.

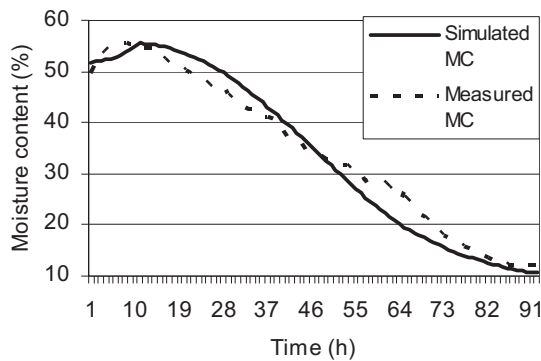


FIGURE 2. The graphs of logfails of the results of industrial drying experiments

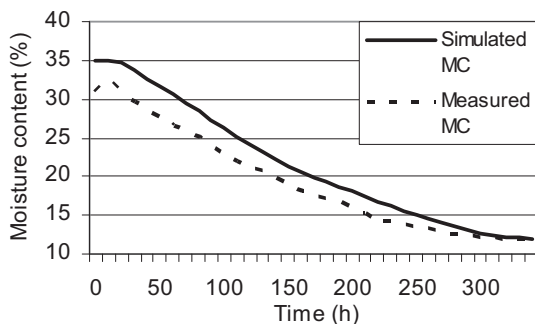


FIGURE 3. Results of simulations with the programme TORKSIM ver. 3.1.

The result of simulation by hours indicates the distribution of moisture content and relative stresses (i.e. in relation to maximum tensile stress allowed for wood) in the cross-section of the material perpendicularly to the surface, from the surface inwards

up to half of the thickness of the material. The user manual of the programme provides that simulated relative allowable tensile stresses cannot exceed the value of 0.33 throughout the drying process. According to the results of computer simulation of industrial experiments with pinewood samples of the thickness of 22 mm and 50 mm the values of relative tensile stresses did not exceed the value of 0.21 – i.e. the drying schedule was safe in terms of initiation of drying cracks. Simulation of industrial and laboratory experiments using the programme TORKSIM ver. 3.1. indicated that simulated distribution of moisture content can very easily be approximated with the second level polynom or parabola equation (example in Figure 4).

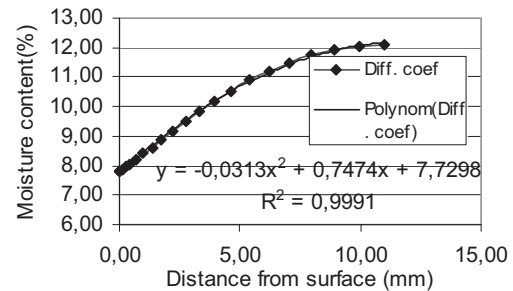


FIGURE 4. Example of approximation of the simulation of distribution of moisture content with the second level polynom or parabola equation

The value of average R^2 was 0.9991 which can be considered as the existence of functional relation. According to the simulation results the moisture content can also be determined by the first time-derivate. These data enabled the inverse determination of diffusion coefficient by means of the parabola method (Kretchetov, 1972) well-known from the Fick's Second Law. Also, it was possible to define the dependence of inversely determined diffusion coefficients on moisture content of wood shown on Figures 5 and 6.

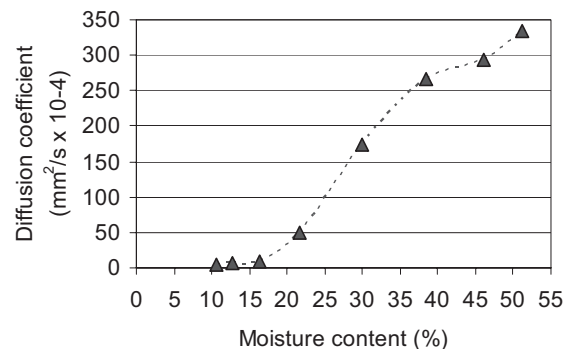


FIGURE 5. Dependence of inversely determined diffusion coefficients on moisture content of 22mm wood shown

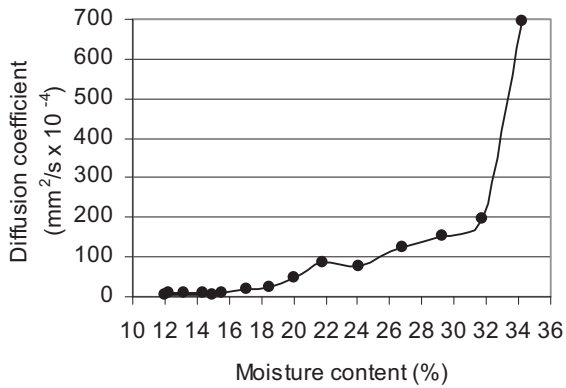


FIGURE 6. Dependence of inversely determined diffusion coefficients on moisture content of 50mm wood shown

Such drying schedule resulting in parabolic moisture content distribution in the cross-section of the material perpendicularly to the surface was named quasi steady-state by Luikov (Luikov, 1966). In such case Fick's Second Law eq. (2) can be presented in the form of:

$$D_t \frac{\partial^2 x}{\partial x^2} = const, \quad (2a)$$

and the solution of its differential equation is square root function. The diffusion coefficient D_t in this context is defined as the effective diffusion coefficient of the total diffusion flux of the liquid phase and vapour phase and water and bounded water.

The diffusion coefficient can also be determined by an experiment using Fick's First Law from which it can be directly concluded that the diffusion coefficient equals to the moisture flux through the surface ($\text{kg m}^{-2} \text{s}^{-1}$) divided with moisture gradient, kg m^{-4} . Figure 7 shows the dependence of the diffusion coefficient of inverse determination of TORKSIM simulation and the diffusion coefficient determined directly by the laboratory experiment from the drying time.

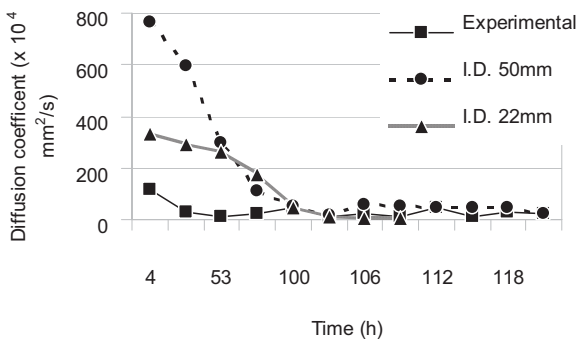


FIGURE 7. Dependence of the diffusion coefficient of inverse determination of TORKSIM simulation and the

diffusion coefficient determined directly by the laboratory experiment

Upon determination the diffusion coefficient it is very important to fulfil the assumptions of isothermal diffusion. Isothermal properties were checked by constant observation of differences in temperature on the surface of the sample and at different distances from the surface of the sample both inside the sample and in the drying air. Differences in the temperature on the surface of the sample and inside the sample did not exceed $\pm 0.7^\circ\text{C}$. Also, the simulation programme TORKSIM ver.3. 1 shows differences in the temperature on the surface of the sample and in the drying air near the surface of the sample. There is a good match with the differences in temperature measured in the course of the experiment. Results of the measurements of temperatures and the simulation are shown in Figure 8.

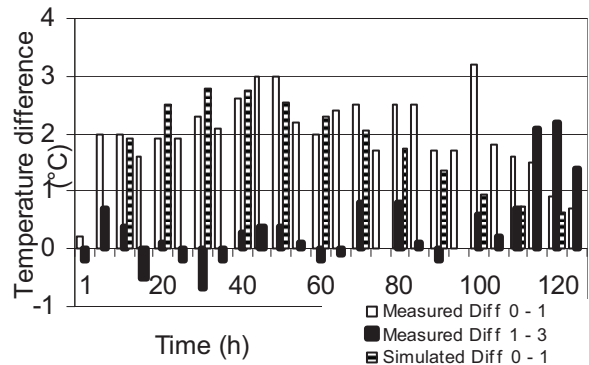


FIGURE 8. Results of the simulation and the measurements of temperatures

The first crack in the 56 mm thick pinewood sample emerged in the 82 hour after the initiation of drying. The computer simulation of the laboratory experiment indicated maximum relative tensile stresses of the value of 0.33 in 80...90 hours referring to the risk of initiation of drying cracks.

6. ACCURACY IN MEASUREMENTS

The accuracy of AHLBORN (type FHA 636MF) timber moisture sensors used in the experiment is $\pm 2\%$. There are no data on accuracy in the technical specification of the manual of the measuring instrument GANN HYDROMETTE HT85T used for measuring the moisture content of the wood, however, the instrument is operating on the principle of electric conductivity of wood and thus, the accuracy could be considered approximately the same, i.e. $\pm 2\%$. In the experiment the moisture flux and gradient were measured with the same sensor and as the diffusion coefficient is

calculated as the quotient of these two indications the accuracy of the determination of the diffusion coefficient is +/- 4%.

7. DISCUSSION

Direct experimental determination of the diffusion coefficient according to Fick's First Law is a widely used method. As this method enables the diffusion coefficient to be determined in different locations of the wood sample subjected to drying, dependence of the diffusion coefficient on moisture, temperature and coordinate, i.e. the function $D(u, T, x)$ can be examined by means of experiments. The diffusion coefficient can be determined by oven-dry method (Hukka, 1999), computed tomography, x-ray CT scanning) (Danvind, 2005; Cai, 2008) and electrical conductivity method described in this paper. However, only the oven-dry method can be considered as an absolute method, i.e. a method which does not require any comparison or calibration with other methods.

The accuracy of experimental determination of the diffusion coefficient in a given coordinate point is largely dependent on the resolution capacity and time stability of the measuring device. The accuracy is also dependent on the fact that the gradient itself is a coordinate function, consequently, the size of the measuring volume is also important. When comparing the accuracy of experimental determination of the diffusion coefficient with the method of computed tomography (+/- 3.6%) and conductivity method (+/- 4%) it can be seen that the difference in accuracy is not significant. However, such accuracy is not sufficient for the generation of empirical approximation formulas for the function $D(u, T, x)$ but the achieved accuracy can be satisfactory for diffusion-based control of wood drying.

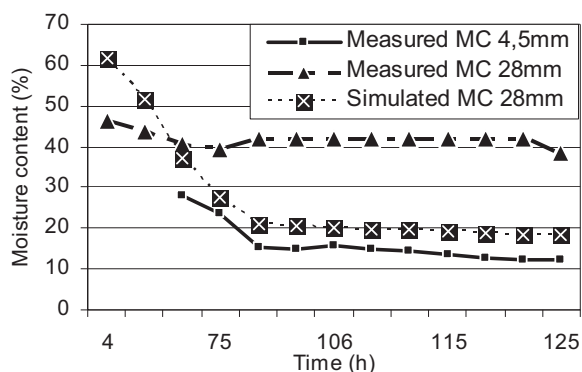


FIGURE 9. Comparison of the measuring data of the laboratory experiment with computer simulation

When comparing the measuring data of the laboratory drying experiment with computer simulation it can be seen (Figure 9) that there is relatively good match between the measured and simulated moisture

content in the layer near the surface of the sample, however, moisture content in the middle part of the sample measured at the end of the experiment was considerably higher (39%) than in case of simulation (18%). The 20% difference in moisture content cannot be explained by an error (+/- 2%) of the measuring device. On the basis of the aforementioned statements it can be concluded that problems can be encountered when using the simulation programme TORKSIM ver.3.1 for simulating forced drying schedules.

8. CONCLUSIONS

In this paper inverse determination of effective diffusion coefficient is presented using the well-known parabola method. Also, experimental determination of the diffusion coefficient according to Fick's First Law using electric devices for measuring moisture content in timber is presented.

It can be concluded that experimental determination of diffusion coefficients using electric conductivity method is possible at least with the same accuracy as using the method of computed tomography.

It has been found that increasing the accuracy of experimental determination of diffusion coefficients would enable to generate more accurate empirical formula for the development of mathematical models of the drying process of timber.

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Optimising Softwood Drying Schedules

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ABSTRACT

In an era of increased energy costs and concern about profitability, using the best drying schedule is important for softwood drying. The first part of this study looked at the feasibility of finding the combination of dry bulb, wet bulb and air velocity that either minimises overall drying cost (electricity cost + heat cost + fixed cost) or maximises profit in a simple softwood drying schedule with fixed conditions. A full stack drying model simulation was used to predict drying time and energy costs. Drying parameter constraints were included but drying degrade was ignored. Typical structural and appearance grade setups were examined for given energy and fixed cost combinations. It was concluded that significant cost reductions or profit gains are possible by selecting the best schedule. The schedule that gives lowest cost is not necessarily the same that gives best profit. The second part of the study then allowed the parameters to vary during the schedule and used a Simplex optimising algorithm to select the best parameters as the schedule proceeded. The resulting time varying schedule should be optimal for the given combination of energy and fixed costs. While it was found that such an approach could result in further cost reduction (~10%), it was concluded that a more responsive full stack drying model simulation is required.

The Impact of Various Measures to Optimize the Air Velocity in an Industrial Wood Drying Process

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ABSTRACT

Both the relationship between fan speed and energy consumption and the prices of energy justify studies on the possibilities for reducing air velocity during the drying process. In this study, effects of air velocity have been examined in order to find when and how much it can be reduced, without affecting the drying rate of the boards. The first experiments were performed in a laboratory kiln, and 36 samples of 50 mm by 100 mm boards (2xlog) of Norway spruce (*Picea abies* L. Karst) were dried at 70 °C with varying air velocity.

Results show that a too early or too strong reduction in air velocity gives a reduced drying rate and a large variation in moisture content. The results are based on limited samples dried in a small-scale laboratory kiln with very good control of the airflow.

The next step in the project has been to examine whether it is possible to transfer these results into full-scale kilns in the industry. Air velocity has been measured in kilns at a Norwegian sawmill to compare and verify the results from the laboratory kiln. To optimize air velocity conditions, batten spaces were sealed. This had no significant effect on air velocity in the kiln. A high reduction of air velocity in the kiln to 60 % frequency at 40 % moisture content and to 40 % frequency at 20 % moisture content, without considerable changes in the drying schedule, resulted in an increase in final moisture content.

KEYNOTE ADDRESS III

FUTURE DIRECTIONS IN DRYING RESEARCH

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ABSTRACT

Drying is an important step in the manufacturing of many products, especially wood. Over the next 50 or 100 years energy will become more expensive, carbon emissions will become a commodity, a cleaner environment will be mandated, and the need for quality-dried wood will increase. How these factors are changing and what drying might look like in the future as a result are discussed.

INTRODUCTION

It would be great to have a business in which you made a material that is useful for a variety of purposes, has always been an integral part of society, and will be in demand as far into the future as we can clearly see. If I could design a machine to make this material, the machine would be solar powered. It would utilize a raw material that comes from a resource that is plentiful and people are willing to pay you to use. The machine would repair itself throughout its useful life and the parts that are not used for construction, furniture, paper, or energy could be recycled to make more machines.

We are in such a business and, of course, trees are the machines producing wood from carbon dioxide. If I could tweak the machine a little, the trunks would be square instead of round so we could saw it more efficiently and the growth "rings" would be growth "lines" parallel to one face to eliminate cup. I'm sure you could think of a few more modifications that would make drying easier, maybe a lower green moisture content to reduce energy consumption.

Our part in producing wood involves the oldest unit operation, drying. As attendance at each IUFRO conference demonstrates, drying probably involves more disciplines than any other operation. Indeed, Mechanical Engineering, Chemical Engineering, Industrial Engineering, Electrical Engineering, Material Science, Biology, Mathematics, Physics, and Chemistry

all have a role in drying research. The range of age and experience at these meetings is always broad.

While our basic product, wood, is arguably the most environmentally friendly material on the planet, drying can easily change the shade of green. Water has a high latent heat and wood contains a lot of water. A number of studies, including Milota (2005), have indicated that as much as 70% or more of the energy to process wood is due to drying. It is estimated that drying consumes 15-20% of industrial energy (Kudra, 2004) across all sectors. It is a process that is inherently not efficient and limited by thermodynamics. We are also hampered when drying wood by product limitations. Long drying times are needed for some impermeable species which develop high capillary forces while the free water is present that result in collapse. For other species cracks and checks result from low diffusion rates and high shrinkage values. The desire for a bright, stain-free product forces us to dry other species for long periods at low temperature and humidity, exhausting unsaturated air that has not been used to its potential for water removal.

The problems with wood drying do not begin at the sawmill. Wood, being a biological material, comes to us with lots of variability. Not only do we have literally hundreds of commercial species, many of these vary regionally. Some species grow over 30-40 degrees of

latitude and elevation ranges of 3000 m. Even in one region, there is tremendous variability between trees and within a single tree. The variability going into the drying process makes it difficult to have uniformity coming out. The problems do not stop after the wood is dry at the mill. Many of wood's problems in use are related to moisture changes that occur seasonally or with transportation from region to region. Proper construction techniques in housing, furniture, and other wood products are used to accommodate the shrinking and swelling that will occur throughout the life of a product.

FACTORS THAN INFLUENCE DRYING

There are always things changing in the world that impact how we do business. Most of these tend to be beyond our control and we can only react to them, but we can react earlier if we are aware of them. I have tried to group these into broad categories – social, environmental, and technical.

Social Changes

Recent economic events have certainly affected everyone. First, the availability of funds for research has decreased, both from industry because of lower cash flow and small or negative profit margins and from government sources because of reduced tax revenue. When governments must choose between funding research and immediate social and human needs, even the best lobbyist would find it hard to argue for research. We will probably lose some drying research capability as a result of the temporary financial crisis. From industry we also see less cooperators involvement. This is unfortunate because if our ideas are to be implemented, we need more cooperators than just other researchers.

The current world financial crisis is hopefully a short-term problem and then things can get back to normal. Normal? Normal after the monetary crisis may be far different than it was a few years ago. Government programs are likely to become more directed to specific areas as lawmakers try to have more control over the outcomes. This is unfortunate for fundamental work in wood drying because at present many proposals are not viable unless they have "biomass" or "biofuel" in the title. The government granting agencies are also increasingly measuring the success of research based on impacts. Sometimes these are difficult to show in drying where technology is used for tens of years or centuries compared to other disciplines which can appear and disappear within one's career. For many funding opportunities this leads to research focused on short-term problems. On the other hand, energy is a very important topic now and drying

should have great potential in this area due to its high energy consumption. Capital for industry to implement technology that is not thoroughly proven may be less available forcing researchers working at a pilot-scale to demonstrate technology after proving a concept in the lab. Instead of handing off a project to industry after the R part of R&D, researchers will need to work well into the D part so industry can get financing on a proven concept. Researchers will need to involve industry earlier in projects and be excellent spokes persons for their ideas because the D part of R&D is more likely to be funded by industry than government funding agencies.

The standard of living will increase in developing countries such as Brazil, India, China, and hopefully many others. This is highly desirable from both a human standpoint and a political standpoint. A greater demand for energy will accompany the standard of living increase placing further demands on a limited energy supply. China is a good example of this – while world energy use was up 19%, China's increased 98% from 2000 to 2006 (U.S. Department of Energy, 2009). Use of fossil fuel will increase in developing countries causing its price to increase and possibly restricting its availability. In turn, biomass currently used as an energy source for many dryers will be in demand in other industries and other sectors of the wood industry, both for fuels and as raw materials. The increase in the value of biomass will increase the cost of drying. At the same time an increase in the standard of living will increase the demand for wood products, many of which are dried. This will further drive our need for energy efficiency and good drying methods.

We have continued to see mergers of companies. International Paper, Georgia Pacific, Weyerhaeuser, Stora-Enso, and Smurfit Stone Container are examples of multinationals. Along with the company consolidation, we tend to see larger and fewer sawmills. This means logs come to a mill from a larger region and there is likely to be more variability in the resource to challenge the kiln operator. One mill I work with gets logs from as far away as Canada, 700 km to the north, and California, 400 km to the south. We also see more movement of wood overseas. I worked with another company that was getting dried wood from the eastern U.S., shipping it to China where they take advantage of low labor costs to manufacture cabinets, then ship the cabinets back to the U.S. The moisture content of the wood was changing somewhere in this process resulting in defective cabinets in drier markets. Two points from this. First companies need to have someone knowledgeable about wood on staff. While solving the moisture issue might be hard, determining where in the process the problem is occurring should be easy for

anyone who has studied wood. The second point is that one has to question how green a product really is after accounting for the fossil fuels used for shipping wood and products this far.

In contrast to the mergers and globalization, at least in the U.S., there is a push to do things locally on a small scale. We hear this in advertisements for buying our food locally because it supports the local economy and is more green because the fuels and pollution associated with shipping are less. Local food growers also claim, in many cases, to have healthier food due to organic methods and reduced storage time. We also see this in wood products with owners of small tracts of land and small sawmills trying to develop local markets for their products. They will never compete with large mills on framing lumber, but in furniture, cabinets and high value items consumers can find a certain pride in saying that their dining room table was grown and manufactured locally.

Environmental Changes

There is a lot of discussion by nearly every organization from the UN on down about climate change, greenhouse gas emissions, and carbon neutrality. The discussions are much more far reaching than just the wood industry. These are clearly global issues and affect every industry and individual. The discussions are in their infancy and there is often disagreement over who takes the first step and over what we would expect to be simple definitions. The definition of biomass is an example. Clearly residue from a forest or mill is biomass, but there are people who want legislation in the U.S. to exclude forest biomass or only call it biomass if it comes from certain forest regimes or types of land. These discussions progress into complex rules based partly on science and, unfortunately, mostly on politics.

The definitions of biomass and how it is credited in renewable energy standards is important for future projects at forest products facilities. The availability of fossil fuels is not going to increase, their cost is not going down (in the long term), and the carbon footprint of fossil fuels will not get any better without major technology changes. This will obviously impact operations that utilize a fossil fuel for drying by making it very expensive. However, it will also impact dryers heated by biofuels because the biofuels will have more value as other industries try to use them.

The high energy demand in drying will make the issue of carbon trading important to mill operations. Allowable carbon emission will be reduced through cap and trade systems. How our products and residues are defined in these systems and how non-fossil CO₂ is

regulated will be critical for mills. Cap and trade systems for reducing emissions by regulation originated in the late 1960s through studies commissioned by the predecessor of the US EPA (Burton and Sanjour, 1968) and were first implemented in the US 1990 Clean Air Act Amendments under what is now known as the "Acid Rain Program." This program reached its reduction target by 2007, three years ahead of schedule, and resulted in a 40% reduction in SO₂ emissions (US EPA). This highly cost-effective method is now being applied to greenhouse gas emissions.

The Kyoto Agreement in 1997 was an international attempt to reduce CO₂ emissions which allows for some emissions trading. It has had mixed results to date with Germany and the UK having 18.5 and 15.9% reductions while Canada, the U.S. (not a signer), and Spain having increases of 21.3, 15.9, and 49.5%, respectively (Cassata, 2008) compared to 1990 baselines. In 2003, the Chicago Climate Exchange (CCX) began with 13 companies as members. It is worth noting that 4 of the 13 were Forest Products companies. There are now 300 members and it is the only emissions reduction and trading system for all six greenhouse gases and the only operational cap and trade system in North America. There is a branch exchange in Europe, although the European Union (EU) Emission Trading Scheme (ETS) has overshadowed it.

The voluntary CCX exchange aside, North America is behind the EU in environmental policy to limit carbon emissions. The EU ETS cap and trade system has been in place since 2005 whereas the American Clean Energy and Security Act of 2009 (Waxman-Markey bill) is currently (July, 2009) being debated. While some politicians are drooling over how to spend the USD\$150 billion 1st year permit revenue, more sensible ones are considering the effects of permit distribution. Grandfathering companies into permits rewards those who already pollute the most. Selling permits disproportionately penalizes consumers in regions where it is more difficult to create renewable energy and electricity is produced from coal. The role of forestry is also a hot topic in the discussion. Forests as carbon sinks are being considered in the US whereas currently, the EU does not allow CO₂ credits under the ETS to be obtained by planting trees, partly due to scientific uncertainties.

The role of forests and the forest industry in reducing our carbon footprint is complex science which depends on where the boundaries are drawn and what benefits are included. For example, a strong case can be made for storing carbon in the forests (Mitchell et al, 2009). Clean water, wildlife habitat, and aesthetics supplement the argument. It is also possible to make a

strong argument for extracting biofuels and forest products from a forest. Reduced danger of catastrophic fire, improved forest health, and less fossil fuel use supplement this argument (OFRI, 2006). Meanwhile, it is possible to also make an argument against some of the carbon storage in trees and wood products and the resulting environmental benefits (Ingerson, 2009). Afforestation, for example, may contribute to reduced stream flow, salinization of soils, and increased nutrient demands (compared to grasslands, shrublands, or croplands). Eucalyptus is worse than pine in this respect, but exceptions exist in SW Australia and the farm belt of North America (Jackson et al. 2005). The science is not simple or clear. Another, perhaps very legitimate, argument against allowing forests to be used as sinks is that it would permit allow more industrial fossil CO₂ emissions.

While many approaches to reducing carbon emissions have merit, in the end, the validity of the arguments and the benefits of an approach depend on the system boundaries. When using biomass for drying, for example, we can directly combust and feed a dryer, heat a boiler, run a turbine, gasify, or do pyrolysis, each with different coproducts, efficiency, and emissions. Should the carbon footprint be compared based on petroleum not burned and what role does the carbon storage play in forests and products and how is this verified? The best pathway is far from clear and what is optimal for one region may not work in another. If forest biomass is considered to be a biofuel under renewable energy standards, we are likely to see much more cogeneration at mills. This will define our heat source for drying. If forests are allowed as sinks for carbon trading, woody biomass is likely to become harder to obtain making our future fuels more difficult to envision. It is likely that in the long-term we will develop the ability to permanently sequester CO₂ at coal-fired power plants. Soon after this happens, the same technology could be applied to the combustion of woody biomass. At that point, many years from now, we can then use trees to remove CO₂ from the atmosphere and sequester it in a measurable and permanent way, all while providing energy for drying.

Technological Changes

I am almost afraid to touch the technical changes that are occurring because there are so many people in this organization are far more qualified than I to address them individually. We have seen the ability to look inside of objects using tomography, both on a macro level and on a cellular level. Computing power continues to increase and is to the point where is no longer limits modeling efforts. The computer simulation allows many things to be tested without actual experiments.

Three points on technical changes, however. To apply modeling and to test on a computer, we still need to know the fundamental properties of the material. There is still a lot to learn about the behavior of wood, especially at the temperatures and moisture contents encountered in drying. A second point is that wood is highly variable. In the drying process we will be limited by the pieces that are slowest to dry or most likely to degrade. Modeling needs to account for this variability. Lastly, we are drying a very low-value product and much new technology is very expensive. This prevents some ideas that could help drying from reaching a practical level. I'm not trying to throw cold water on hot technology with the last two points. As researchers we cannot always be working in the realm of what is possible today if we expect change tomorrow.

NEEDS IN DRYING TO MEET CHANGES

We can't solve all of the world's problems with better drying, however, we can contribute in many ways. When one considers the magnitude of drying across all industries and the amount of energy consumed to dry forest products, drying for low energy consumption and reduced environmental impact is very important. Drying for good quality will also continue to be important as wood is used in more complicated assemblies.

Move From Fossil Fuels

Many or most wood drying operations already use a biomass fuel. Those that do not will need to convert. Economic constraints may force this to happen as the cost of fossil fuels escalate. Biomass fuels are, in many cases, available on site so there are minimal transportation costs and carbon emissions compared to shipping the fuel. Notice that I have said fuel. The term wood waste or mill waste does not belong in our vocabularies.

We will see more cogeneration at wood producing companies and this will operate in close association with the dryers. Smaller cogeneration units in the 1-5 MW range will avoid some of the transmission problems often associated with sending power back to the grid from larger-scale power generation. Project plans to add electrical capacity, be it from biomass, wind, waves, or solar, are sometimes thwarted because of the cost and legal issues associated with building power lines. This issue was brought to light last July when T. Boone Pickens, a former oilman and now promoter of renewable energy, cancelled a USD\$2 billion project involving 687 wind turbines in Texas because it was too difficult to get the power to the grid. To make this more ironic, the US became the world leader in wind power in 2008.

There will be a need for more research on drying biomass. If biomass is to be shipped, drying and compressing may reduce shipping costs. Some reduction in moisture content is needed for gasification. Even for direct combustion and cogeneration, predrying the fuel can increase the boiler efficiency by allowing a lower stack gas temperature. The research needs include efficient, cost-effective dryers on both the small- and large scales, reduced emissions, and the fundamental data needed for dryer design.

As carbon emissions become a traded commodity, there will be a need for cradle to grave life cycle analysis for wood products. Drying greatly impacts the results of this analysis. If the cost of carbon emissions become high enough, it may become easier to justify additional drying equipment utilizing of different techniques that are not practical at this time.

Need for energy efficiency

Wood is a low-value product with a high production rate. This makes energy efficiency essential compared to a high-value low volume product such as some foods or pharmaceuticals. To purchase and install a boiler and two new lumber kilns (120 mbf, 250 m³ ea.) costs about USD\$2,700,000. The wood will lose about 100,000 kg of water per charge (400 kg/m³, 100% to 12%) or approximately 25,000,000 kg per year if 2.5 charges are dried per week in each kiln. This would require 50,000,000 kg/year (115,000,000 MJ) of steam (2 kg_{steam}/kg_{water removed}) at a cost of \$650,000 (USD\$12 per 1000 kg). The electricity is likely to cost USD\$180,000 for 2,225,000 kWhr if these kilns have 150 kW each (200 hp) of electrical consumption and operate 7500 hrs per year (86% of the time). It is probably safe to say that at \$800,000/yr for energy, a company will spend much more money on energy than purchasing the kilns. Companies need to factor in these costs at the time of purchase.

The first step in making kiln drying more efficient is to remove less water. Most facilities could take advantage of air drying. As soon as this is mentioned there are moans about material handling and degrade, but there are facilities doing it, some only seasonally. The other way to remove less water is not to dry to as low of a moisture content. This might cause the lumber to not meet grade and may have some obvious quality problems for the consumer. Reducing final moisture content variability is also a way to reduce energy consumption if the drying time is not extended. Modern dryers are fairly well controlled. Better in-kiln measurement of moisture content might allow even better adaptive control. Additional research into why boards have final moisture variability might lead to

better sorting which could lead to reduced final moisture content variability.

Another way to make a dryer more efficient is by passing the exhaust air from the dryer through a heat exchanger and raising the temperature of the incoming air. To evaporate a kg of water with a conventional kiln requires approximately 4600 kJ of steam. To remove a kg of water at 82°C and 0.19 kg/kg absolute humidity requires 5.26 kg of bone dry air to enter the kiln. The energy to heat 5.26 kg of ambient air at 0.01 kg/kg from 15°C to 67°C (allowing a 15°C difference in the exchanger) is approximately 280kJ. Thus, one would expect only about 6% (280/4600) energy recovery due to heating the incoming air at these conditions. This will be less when a kiln is operated at a higher wet-bulb temperature. For a low temperature schedule (a wet-bulb of 30°C) this might go up to 900-1000kJ making the recovery approach 20%. Some electricity is required in each case to operate the exchanger and not included in the efficiency. Krokida and Bisharat (2004) use a case where the absolute humidity is 0.025 kg/kg to demonstrate that a heat exchanger on a dryer might recover up to 25%. Although Kemp (2005) states that with the fuel prices of the 1990s heat recovery from dryers is rarely economic, as fuel becomes more expensive we may see more of these simple devices.

The next step might be to assist the heat exchanger by adding a heat pump. Krokida and Bisharat (2004) claim that 100% of the energy can be recovered for a presented case. While there is a sufficient temperature difference they propose using a heat exchanger to avoid energy needed for the compressor, then extract additional energy with a heat pump. Heat pumps are widely used in the chemical industry, for example in distillation columns, and lumber kilns that utilize heat pumps are widely available, if not widely used. If a heat pump has a coefficient of performance of 3.5, one might expect that 1300 kJ of electrical energy would be needed to remove a kg of water. The cost of this energy (0.36 kW-hr) would be about \$0.026/kg_{water removed} compared to \$0.030/kg_{water removed} for steam. While there are some cost savings, the lack of widespread acceptance of heat pumps in kilns is probably due to the availability of wood fuel at mills, the initial equipment cost, and the ongoing maintenance costs. In the future one will also need to consider the carbon footprint of each. A steam kiln attached to a biomass boiler will have very low fossil CO₂ emissions. The fossil CO₂ associated with electricity will depend on how it is generated and the efficiency of generation.

Drying in superheated steam is technology that has the potential to eliminate the energy required to make up heat air. We have seen this in practice in some

dryers that operate under vacuum, but we also see it in high temperature dryers when the wet-bulb approaches 100C. Drying in an all water vapor atmosphere leads to the potential for energy recovery through mechanical vapor recompression. The kiln would need to be a pressure vessel at wet-bulb temperatures below the boiling point or the species must be capable of withstanding high temperature drying. Given the contamination of the kiln gas with acids and other compounds, the compressor needs to be made of very expensive materials. To avoid these issues, the heat pump kiln might be a better alternative. Either design will reduce or eliminate organic emissions to the air, something likely to be a great concern in the future. However, both designs create a liquid effluent, something mills are ill-equipped to deal with and, at least in the U.S., might have difficulty getting a permit to discharge.

So far I have omitted some technologies that are already practiced that may seem like they should be included. Solar drying would, of course, be very energy efficient and green. However, most large facilities would find it difficult to meet production schedules while depending on the weather. I suspect that solar drying slows considerably in Sweden this time of year. In other regions, where it could be effective, the use of solar, especially an integrated dryer with thermal and photovoltaic capture, should be encouraged. I have not included microwave or radiofrequency because the ratio of the electrical energy input to the energy to evaporate water is about 0.5, not much better than a wood- or gas-fired kiln and this drops to less than 0.2 if the conversion of fuel to electricity is included.

Staged dryers can increase thermal efficiency. We have seen a type of staged dryer with the continuous kilns that have started to appear at a few mills in which some of the energy from the center section is recovered at either end of the dryer and heat from the outgoing product is used to warm the incoming product. I think this is the beginning of an important trend in our industry that will lead to a fundamental change in dryer design. The outcome may not look like today's continuous kiln, but the industry makes evolutionary changes, not radical changes. Heat recovery from each stage might be enhanced by adsorption, for example on zeolite (Djaeni et al. 2007) or by chemical heat recovery (Ogura et al. 2003). None of these things are easy with solid wood because of the long drying time and the many products which are typically handled at a single facility. Also, the chemicals released by wood during drying make anything contacting the dryer exhaust, even a heat exchanger, subject to fouling.

Mills need to have a way to measure the important variables if they are to understand their energy efficiency. These include the air temperatures, humidities, and flow rates in and out, the wood moisture contents, temperatures, and mass in and out, the steam or fuel (direct-fired systems) used, and the electricity used. This list could be reduced to the mass of water removed and the thermal and electrical energy used. Steam flow and electrical use are not typically measured at each kiln and rarely does an operator think or talk in terms of energy used per mass of water removed. Most often a monthly report is produced with the steam consumption and the volume dried. While steam flow meters do not fall under the realm of drying research, there are certainly research opportunities for developing economical ways for mills to better estimate the water removed. To date, we still cannot accurately estimate green moisture content and basic density for green wood at line speed or in large batches.

The energy efficiency of a new dryer or other equipment, such as a heat exchanger, should be clearly specified by the manufacturer. There is a need for an industry standard for how this is calculated. In my mind, two measures are needed, electricity and thermal energy used per pound of water removed. With these two values a mill could not only consider energy efficiency, but could also estimate their carbon footprint by knowing their fuel sources and how electricity is generated in their region. Having an industry standard method for doing this is not as easy as one might think because of the different schedules used at different mills. Monitoring equipment at each kiln would allow mills to verify that new dryers perform as promised. Along the same lines, could there someday be a "drying certification?" This would be some sort of independent agency verifying in a standardized way that drying was done in a sustainable fashion, much like the FSC for forests and products.

Reduce dryer emissions

The increased value we place on clean air and clean water will continue. We will first progress to kilns having a single point of discharge. Some kilns with heat exchangers already have this. A single discharge point will allow better control of the conditions in the kiln and will allow air emissions to be measured. At present, the measurement of emissions from commercial-sized kilns with multiple vents or a continuous kiln to the accuracy level required by regulatory agencies is difficult. Once there is a single point of discharge, it becomes possible to use a stack to raise the elevation of the discharge for better dispersion. In a few locations this has already been required.

Emissions control devices on kilns are the next logical step. However, I would encourage regulatory agencies to do a life cycle analysis on the controls to see if they are beneficial. One common form of control on veneer dryers and composite presses is the regenerative thermal oxidizer. In some cases the use of control devices may be questionable. For example, Sauer et al (2002) indicate that while reducing organic pollutants from the dryer, NO_x, SO_x, and greenhouse gases were all increased when regenerative thermal oxidizers were used on presses and dryers for composite wood products. Given the lower temperature, high volume, and dilute organic content of kiln exhaust, I suspect the control devices would be even less favorable. Fortunately, at least in the U.S., the cost per pound of pollutant removed is considered when developing regulations. The cost per pound would be high on existing lumber kilns.

Beyond controls, completely eliminating air emissions is another possible future step. Some may scoff at such a statement, but if governments require controls on lumber kilns, it might be easier and less expensive for mills to switch to a technology such as heat pumps or MVR, eliminate air emissions, and improve energy efficiency. As the world becomes more industrialized, we cannot simply use the air and oceans as huge dumping ground. The elimination of air emissions means that we will have a liquid effluent to deal with. Mills will need more space for ponds and water treatment. Overall it might be easier to treat a liquid effluent than a gaseous one.

Drying in the community

Economical small-scale drying systems are needed to support the small producers. For lumber, this means relatively inexpensive kilns for local industries both in developing countries and developed countries. Drying is almost always an impediment to the success of the small business owner. They usually do not have a good grasp of the large amount of energy it takes to evaporate water, let alone the time. They also lack the skills necessary to operate a kiln and respond correctly to defects in the wood when they occur. Simple educational programs for the small business would go a long ways toward solving this. Drying is simple, right?

As a society, we need to think about how we place industries. Energy as heat is not something that is easily moved or stored. Siting processes with high thermal demand such as kilns proximate to boilers with turbines is one obvious example that has been exploited. If we cannot figure a way to capture the energy in our dryer exhaust and use it again in the dryer, we need to think about what other processes could take advantage of this low grade heat, greenhouses and district heating might

be examples. Many things that are not economic or do not appear possible now, may become reality as energy becomes more expensive and we as a society work together to reduce our environmental impact.

Better understanding of wood as a material

So far I have not touched on wood quality, a subject on which many in the audience work. Everything I have said becomes unimportant if the wood does not meet the needs of the customer. There is still a need to better understand the mechanical and rheological properties of wood at the elevated temperatures used in drying and while the moisture content and temperature of the wood are changing with time. Researchers in other drying fields, especially agricultural products, have this same need. Some day we will have a unified drying theory that covers all materials. Given the complexity of wood, I expect that researchers in wood will continue to be at the forefront of this effort.

We need to understand what makes boards dry at different rates. Sorting undried boards by moisture content or density (green mass/volume) helps make the final product more uniform, but not to the extent we would like. We need to better identify what wood characteristics affect the rate at which water leaves a board so that we can use both initial moisture content and an expected drying rate to group boards for drying. This will result in less moisture variability in the final product and also lead to shorter drying schedules, better energy efficiency, lower emissions, and a higher quality product. More sorting can also complicate handling at the mill, result in more sorting bins in the sawmill, and a need for more and smaller kilns.

Lastly, we need to continue to produce well-trained graduates who not only have a grasp of the many facets of mill operation, but can enter the workforce and apply the principals of wood science to processes and problems. These will be valuable employees. As wood science program shrink and get rolled into forestry and natural resource program, we need to work to keep drying as vital in the curriculum as it is in the process.

CONCLUSION

The kiln, heat exchangers, fans, vents – they are all just engineering and are pretty well understood. Wood as a material remains a difficult component to understand. It will be a sad day when we completely understand wood because we will no longer be able to call wood drying an art.

Many factors will influence drying over the next 50 or 100 years. A need to reduce energy use and reducing (or sequestering) carbon will be two of these

factors. Maintaining a clean environment will be another. Some day we may harness a great energy source making fossil fuels seem prehistoric. We might have technology that allows us to manufacture any material from sand, rock, or all the CO₂ we will be collecting. Until then, our factory should stay busy processing wood.

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Adrift in the “See” of Green Kerfing

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ABSTRACT

A series of drying tests have been conducted in which the results for green kerfed lumber are compared to those of closely matched controls. Green kerfing increased the drying rate in a variety of conditions used for the drying. It greatly reduced the time required to reach a highly desired level of final average moisture content and with small variation among boards. Due to the increased flux of moisture in kerfed boards it is of paramount importance to serve it with an adequate supply of properly conditioned air. If the flux to board surfaces exceeds the transfer capability of the transient air, the full benefit of green kerfing to accelerated drying is not realized.

The series of tests provided confirmation to results obtained in previous research. The modulus of elasticity for kerfed lumber again came out higher than that for controls. This is tentatively concluded to be a result of the lower final average moisture contents for kerfed boards coupled with an improved surface to core distribution. The modulus of rupture was again in keeping with past research as the decrease in edgewise bending strength was commensurate with the modest decrease in moment of inertia attributable to the insertion of kerfs. The testing also confirmed that green kerfing is able to reduce the amount of warp existing in the dry, surfaced lumber.

INTRODUCTORY OVERVIEW

U. S. Production of Softwood Lumber

In the year 2005 the production of softwood lumber in the USA was 40.7 billion board fee (MMG 2008). The present Authors estimate that 75% of that total was of nominal 2" thickness and of various widths and lengths. In the USA, nearly all such softwood lumber is utilized for structural framing in new housing units plus improvements of existing housing.

Essentially all of this framing lumber is kiln dried, almost exclusively in steam heated and direct fired kilns. There is modest recovery of latent heat of evaporation but generally it is vented to the atmosphere along with volatile organic compounds (VOC's). The southern yellow pine (SYP) industry most commonly uses high temperature (HT) drying, i.e. dry bulb temperatures (dbt's) in excess of 212° F. One-half, or possibly even more, of the softwood framing lumber produced in the USA is provided by SYP species.

Estimating the Total Weight of Evaporable Water in Green Lumber

Comstock (Comstock 1975) reports that 70% of the total energy required in the production of softwood lumber, from tree harvesting through final machining, is in the drying. In light of this it seems fitting to estimate, using an industry perspective, the amount of wood moisture involved and the energy implications there from.

A starting point is arriving at an approximate initial green moisture content (MC) for a mix of species being dried. In this regard we chose three SYP species included in Tables 1-5 and 1-8 of the Dry Kiln Operators Manual (DKOM 1997). These tables provide respectively average green MC and green volume basis specific gravity Sg for the 3 species, namely Loblolly, Longleaf and Shortleaf pine.

In Table 1-5 the average heartwood MC for the 3 species is 32% while for sapwood 113%. Comstock (ibid) states, "...since smaller trees tend to have a

much larger percentage of sapwood, moisture content will be much higher from small trees than from larger old growth trees.” In the contemporary utilization of small trees, plus insights gained from drying experiments conducted with softwood species, the Authors adopt 110% as the average initial green MC of the lumber sawn from the 3 SYP species.

Table 1-8 provides an average Sg of 0.493 for the 3 species. This is considerably higher than that for most of the commercially important ‘white wood’ species such as ponderosa and red pine, spruce and the true firs. Commensurate with a higher specific gravity comes an increase in the amount of adsorbed water.

Table 1-9 (DKOM 1997) gives the weight per actual Mbdft of lumber by species at various levels of MC. The average for the 3 SYP species at an average MC of 80% is 4623 lbs. Earlier herein the authors adopted an initial average green MC for the SYP mix of 110%, which exceeds the maximum 80% MC column utilized in Table 1-9. However, a weight correction factor is provided by species for “each 1.0 % MC change above 30% moisture content.” The average correction factor for the 3 species is 25.6 lbs. Thereby, at an average initial MC of 110%, the total weight per actual Mbdft equates to 5391 lbs. Using an average Sg of 0.49, the weight of oven-dry wood per actual FT³ is 30.58 lbs. This multiplied by 83.3 FT³ yields 2547 lbs. of oven-dry wood per actual Mbdft. Subtracting this from the total wt. of 5391 lbs. yields a weight of water per actual Mbdft of 2844 lbs.

In the year 2005, nearly 2×10^6 housing units were built in the USA, using on average at least 10,000 nominal bd ft of softwood lumber per unit. The total comes to an estimated 20×10^9 bd ft. Using the SYP mix for this illustration, the 20×10^9 bd ft would have contained about 48×10^9 lbs. of evaporable water. (An adjustment factor of 0.85 was used to convert the nominal 20×10^9 bd ft to an initial actual bdft of 17×10^9).

Water, Water Everywhere but Not a Drop to Drink

What volume of water is contained in the 48×10^9 lbs? What size of lake could this make? A FT³ of water weighs 62.4 lbs. so in 48×10^9 lbs. there are 769×10^6 FT³. In a square mile there are about 28×10^6 ft². At a uniform lake depth of 1.0 ft there would be 28×10^6 FT³ of water per square mile. Dividing the 769×10^6 FT³ of water by 28×10^6 FT³ of water per square mile, we get a lake area of 28.5 square

miles. If we name it “Long Lake”, it is over 9.0 miles in length by 3.0 miles wide at a uniform depth of 1.0 ft. Using the water contained in the entire 40.7×10^9 bd. ft. of softwood lumber produced in the USA in 2005, the lake has a uniform depth of 2.0 ft. Capturing the huge amounts of water available in the commercial drying of softwood lumber for subsequent productive applications(s) seems worthy of consideration, especially in the context of societal emphasis upon recycling.

An Alfred J. Stamm “Expose” of Water in Wood

Dr. Stamm (Stamm 1964) describes in detail the types of water contained in green wood, doing so in terms of 4 types. The first type is capillary condensed, essentially all of which resides in the cell lumens. The next two, defined as polymolecular adsorbed and mono-molecular adsorbed, make up the “Type 2 adsorption isotherm” that is characteristic of wood and cellulose. Stamm’s second type of water is the polymolecular adsorbed. It is said to reside in the form of 6 to 7 indiscreet layers of water. The lesser in number of these indiscreet layers, the greater the intensity by which water molecules are bonded to associated wood substance. His third type of water is the mono-molecular layer, stubbornly adsorbed and housed in the approximate moisture content range of zero to 5% MC.

In the lumber drying scenario, about 1000 BTU’s are required to vaporize 1.0 lb of capillary condensed water. For the mono-molecular adsorbed water the approximate average is higher, perhaps about 1300 BTU. The 4th type of water identified by Stamm is that of chemical composition. It comes into play in the context of using wood for fuel but presumably little is driven off in kiln drying, even in HT drying.

Hitching a Ride on a Moisture Content Gradient

In the HT drying of SYP dimension lumber, there are reports of water cascading down the leaving air side of the charge early in drying. As the lumber increases in temperature the embodied air expands, which in turn could explain the cascading water via enhanced capillary flow. However, another possibility is that a condensation phenomenon is accounting for the presence of liquid water. By either cause, or a combination of the two, this clearly illustrates the initial cooperation of the lumber in the production of rapid drying. In this stage of drying the MC gradient within boards may exist solely in the form of a free water gradient, sort of analogous to water flowing downhill. If the cell pitting is cooperating, and the

total amount of polymolecular water is remaining intact, the rate of water egress seems well enhanced.

However, at some stage of drying, the MC gradient will pass through two distinctly different portions of the board; one is the interior portion in which all parts of it are above the fiber saturation point (FSP) and the exterior second portion for which all parts have a MC below the FSP. The dividing line between the two portions is often named the "wet line." Diffusion through the exterior portion will now determine drying rate, and the drier it becomes, the greater the resistance to diffusion. This seems especially significant in the context of HT drying. For example, at a DBT of 220° F with a 50° F WBD, the published EMC is 3.4% (DKOM 1997). A water molecule diffusing through this region of monomolecular adsorption must overcome the intense attraction afforded by the "hungry" bonding sites. Also, wood at an EMC of 3.4% is well insulated against heat transfer from kiln air into the board. In HT drying, dbt's reach 240° or even higher. A seemingly plausible argument can be made that such severe drying conditions are self-defeating toward attaining desirable end results as to both drying rates and energy efficiency.

An Energy Overview

Brubacker (Brubacker 1991) gives the average dry kiln an efficiency of about 45%. Comstock (ibid) writes that the heat of vaporization for water varies from 1037 BTU/lb at 100° F to 970 BTU/lb at 212° F, for an average in this temperature range of about 1000 BTU/lb. However, adding in the heat of desorption, it is reasonable to assume an average of about 1100 BTU/lb of water vaporized.

There is little doubt that the efficiency of 45% given by Brubacker varies considerably in the overall arena of lumber dry kilns. Shottafer and Shuler (Shottafer and Shuler 1975), in a detailed analysis of drying eastern white pine, give an estimate of 4.24×10^6 BTU/Mbdft.

Earlier in this paper the Authors estimated 48×10^9 lbs of evaporable water in 20×10^9 nominal bd. ft of SYP lumber. Though not often attained in the industry, a highly desirable final average MC would be 10%. With an initial average green MC of 110%, drying to an average final MC of 10% results in a water loss of nearly 43.9×10^9 lbs. Comstock (ibid) provides a range of 1500-3000 BTU per lb. of water evaporated in lumber drying. We elect to use the average of this range, 2250 BTU, for obtaining the total BTU for vaporizing the 48.9×10^9 lbs of water

in the drying of the SYP. In so doing, the total is near 99×10^{12} BTU, i.e. 99 trillion BTU.

Wilson (Wilson 1988) gives combustion efficiencies for wood, natural gas and heavy oil of respectively 61.2%, 77.8% and 82.5%. The heat recovery per pound of wood waste, at 61.2% efficiency, is about 5300 BTU. The usable heat content per short ton of wood waste = 10.6×10^6 BTU. Dividing 99×10^{12} BTU by 10.6×10^6 BTU/short ton = 9.3×10^6 short tons. The current price/short ton of semi-dry wood waste fuel is about \$30 U.S. and thus the total value of the 9.3×10^6 short tons is about U.S. \$280,000,000. At the present time natural gas is cheap, around \$3.00 U.S. per MM BTU. At an assumed efficiency of 78.8%, the total cost via natural gas is approximately U.S. \$440,000,000. Oil, at the current approximate U.S. \$70/barrel, equates to well over one billion U.S. dollars. Green Kerfing, where applicable such as for softwood framing lumber, has the potential to achieve large savings of energy.

Green Kerfing as an Assist to Drying

In the US, about 75% of the softwood lumber produced falls into a category of use definable as "structural framing." As such, grading is based primarily upon mechanical properties and less upon appearance. For example, the grading rules for the standard 2 x 4 stud allow on the normal 4" wide face, a 1½" diameter hole or equivalent smaller holes per 1 linear foot. This allowance of holes is not restricted to studs. Case in point, a No.2 structural joist of nominal 2" thickness and 12" width is allowed on the 12" face a 3" hole, or equivalent smaller, per 2 linear feet. It appears the grading rules allow the holes in recognition that they would not seriously inhibit performance in the expected structural applications, such as for a floor joist in which the loads are applied perpendicular to the joist thickness.

It is well known that moisture can move parallel to the grain of wood at a rate approximately 15 times that of perpendicular to the grain. Since the grading rules for structural framing lumber allow a generous number of holes in the wide face of the piece, it seems reasonable to conclude that saw kerfs can be made on both wide faces without seriously compromising subsequent structural performance and thus ostensibly should not take the piece out of grade. The kerfs would be of a length and depth such that the cross section of the board becomes a simulated I-joist. As an illustration, consider a green nominal 2 x 10 with actual nominal 1.75 inch thickness and approximately 10 inch width. It's

moment of inertia (I) is 145.8 in^4 . With kerfs on each wide face placed 3" apart, 5.75" long and at a uniform depth of 1/2", the calculated I value is 0.89. However, the loss of I value can be easily reduced by modified kerfing. For example, instead of a continuous kerf length of 5.75" use two kerfs each of 3" length, while leaving a 1.0" wide band of unkerfed wood along the board's neutral axis and a band along

each edge that is 1.5" deep. With kerfing of this type on both wide faces the estimated I value becomes 141.3 in^4 , which is 97% of that for the unkerfed board. Kerfing designs can be modified to best serve a given width of the structural member. Kerfing should be of value not only in drying but also for improved treatment with preservatives.

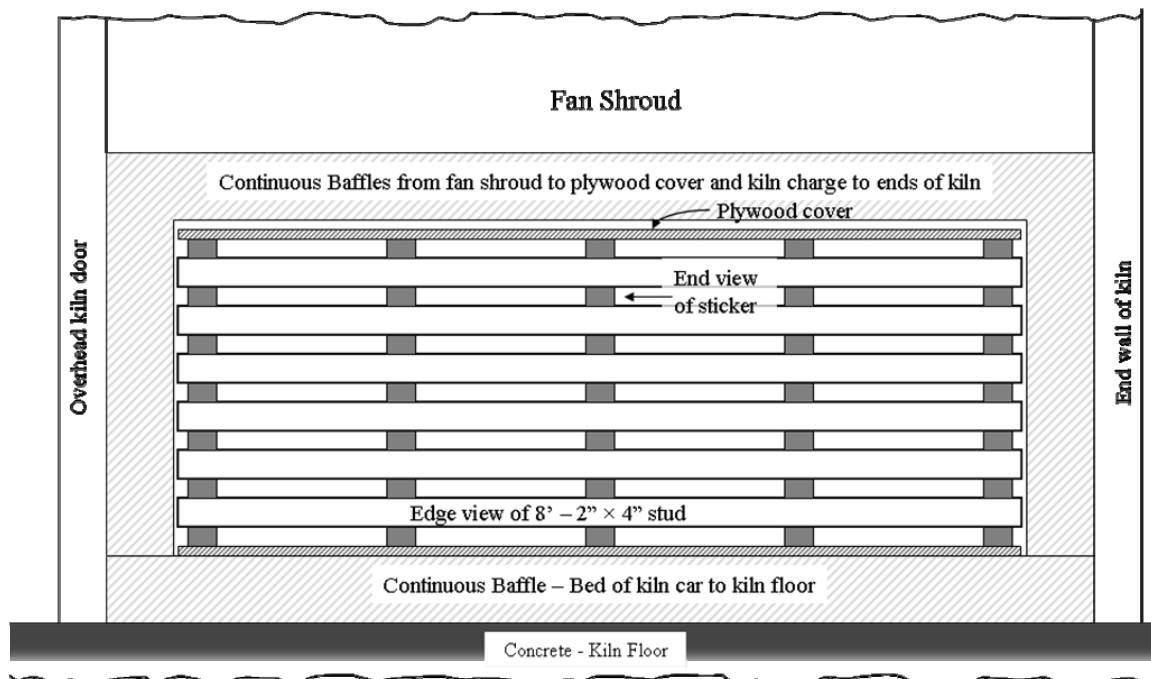


Figure 1 Schematic of a kiln charge in place with emphasis upon the integrity of the baffling. Items are not drawn to scale.

PARTIAL DESCRIPTION OF TEST METHODS

Figure 1 is a schematic representation of 8-foot nominal 2" x 4" lumber stickered for drying as in either our steam heated or dehumidification (DH) experimental kiln. In the four tests subsequently presented, only one utilized nominal 8-foot length lumber. However, the illustrated integrity of tight baffling prevailed throughout. Stickers 3/4" thick and 1.5" wide were used with but one exception, that was in the drying of short-length samples in a Blue M environmental unit. Sticker placement was consistent at approximately 2-foot intervals. (Again, the only exceptions being that required for the Blue M). Top weighting of kiln charges was minimal, restricted to that needed to keep cover sheet(s) in place.

The ability for air delivery differed among tests. Usually the air velocity employed was in keeping with the maximum available. Specific velocities, plus other particulars, will be documented in the coverage provided per individual test.

THE SERIES OF FOUR DRYING TESTS

Test 1

The parent material was 20 pieces of northern white pine lumber, each of 100 inch length or slightly more and with nominal cross section of 2 x 4 inches. Each piece was crosscut into three end-matched lengths of 33 inches apiece. One length was assigned to the control group and the other two for kerfing.

Kerfing was done via an improvised arrangement that allowed guided horizontal movement of a hand-held router. The router bit was 1/4" diameter and set for 1/2" depth of cut. Kerfs were at 3" intervals on both nominal 4" wide faces. One design had kerfs perpendicular to the length of the board and the other at an angle of 45°. Each kerfing design left a continuous uncut 3/4" deep shoulder along each narrow edge of the board. Kerfs on one face were located at mid-length to those of the opposite face.

The perpendicular and angular kerfs had respective lengths of about 2-3/8" and 3-1/8".

The DH kiln charge consisted of the sixty 33" long pieces. They were stickered as two end-butted stacks of thirty pieces each with the stacks being 10 courses high and each 3 pieces wide. A given course for each stack contained the 3 end-matched pieces provided by the parent piece of lumber.

The DH kiln is equipped with a 1.0 Hp dehumidification unit mounted internally as are the 3 1.0 Hp variable speed fans. The air velocity measured to an average 1200 FPM and evidenced the fluctuations that are normally encountered. There were no fan reversals. This is also the case for the 3 tests that follow.

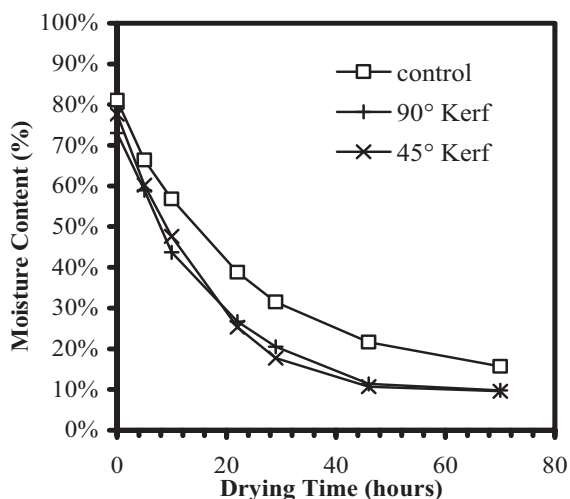


Figure 2 Moisture Content vs. Drying Time for dehumidification drying of end-matched samples; respectively controls, kerfing perpendicular to board length and kerfing at a 45° angle to board length.

Figure 2 presents average MC vs. drying times in hours. The data were obtained from periodic weighings of 20 pieces, i.e. 1/3rd of the kiln charge. The 20 included 7 controls, 7 angular kerfed and 6 perpendicular kerfed. Each of the 20 was held in a snug fit available from the aligned columns of stickers on the leaving air side of the charge. After each weighing the pieces were returned to their original locations, thereby keeping intact the integrity of course content from start to end of drying.

Figure 2 exhibits a divergence of the rate curves for controls and kerfed. It is minor during the initial 5 hours but quite apparent in the time frame of 5 to 29 hours. This divergence confirms a more rapid transfer of moisture from interior to surface for the kerfed boards. For this to be made apparent, desiccation of the air stream had to exceed the rate of moisture arrival at the surfaces of the kerfed boards. If the desiccation had not been adequate, the rate of evaporation into the air stream would have taken control of the drying rate and thereby the controls and kerfed would have exhibited equal rates. Thus, to obtain the full benefit offered from green kerfing, an adequate volume of properly conditioned air is an obvious requirement. It is possible that this requirement could be most efficiently realized via a dehumidification approach.

Test 2

Four 19" long samples were obtained from each of four full-length boards left over from Test 1. These parent "green" boards had been wrapped in plastic and stored in the cold room while awaiting use in Test 2.

One of each four became a control while the remaining 3 were kerfed at respective spacings of 2", 4" and 6". Kerfing was done as described in Test 1 but for Test 2 it was solely at the 45° angle. Each of the 16 pieces got a heavy end-grain coating of plastic roofing cement plus a tacked-on strip of properly sized thin plywood.

The 16 pieces were stickered into the Blue M drying chamber using wood strips of 1.0" cross section. Baffling was self imposed as the 4-course charge was adequately matched to both chamber height and depth. Measurement of air velocity was dismissed due to the obvious difficulty of so doing. From past research involving use of the Blue M unit the velocity was estimated at 500-600 FPM.

Readings of dry and wet bulb temperatures were made periodically off a psychrometer at rest in the chamber. This was possible because the inner door to the chamber is heat resistant glass. The readings are summed up as follows: Initial dbt and wbt were respectively 26 and 22° C; at 1.0 hour 74 and 47° C; at 2.0 hours 89 and 53° C; and at 15 hours 95 and 58° C. The following 12 hours of equalizing was at steady state 85° C dbt and 73° C wbt.

Table 1 Summary of the moisture content data collected in the elevated temperature drying in the Blue M unit.

Sample Type	Drying Time (hours)					
	0	3	6	15	22	27
Kerfed:	Moisture Content (%)					
2-inch	78.6	57.2	42.5	14.4	11.3	9.8
4-inch	74.8	58.2	44.4	15.8	12.4	10.6
6-inch	76.0	59.9	47.0	17.8	13.9	12.7
Controls	62.5	46.0	39.5	23.2	17.0	15.2

Table 1 has MC data obtained via periodic individual weighings of the 16 samples. The decreasing order of drying rates is 2, 4, and 6" kerfing then controls. It is of interest to compare Table 1 to Figure 2. In Figure 2 the initial MC for controls is 80% and at 22 hours 40% MC. In Table 1 the initial MC for controls is 63% while at 22 hours of drying 17%. The total decrease in %MC is almost the same for the low temperature DH drying of Figure 2 and the 200° F Dbt drying of Table 1. The elevated temperature per se did not translate into noticeably faster drying.

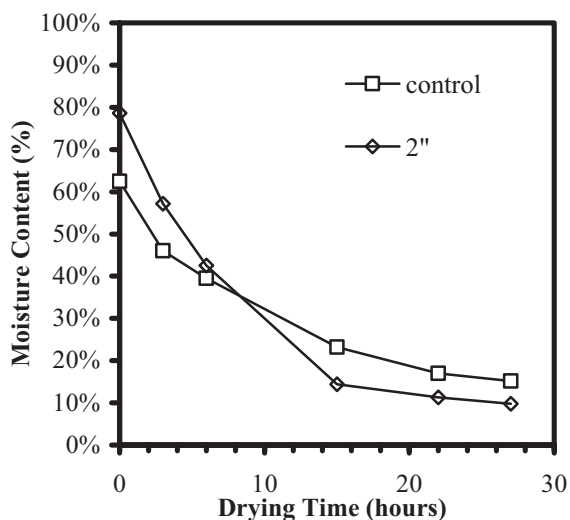


Figure 3 Drying rate comparison for end-matched controls and those spaced at 2" intervals at an angle

of 45° to board length. Drying done at an elevated dry bulb temperature of about 200° F.

The Table 1 data for controls and 2" kerfed were used for making the curves shown in Figure 3. For the % MC range of 80% down to 30%, i.e. during the release of all free water, the rate curve for the 2" kerfed is quasi linear. The curve for controls, in the range of 63% down to 30%, is representative of the usual inverse relationship between drying rate and time. Green kerfing greatly expedited the removal of free water.

Test 3

Mill run nominal 8-foot 2" x 4" unseasoned stud grade lumber was donated by the Potlach lumber mill in northern Minnesota from which 31 studs were crosscut to obtain end-matched pieces of 45" length. One was chosen as the control and the other for kerfing. The kerfing was done by router as described earlier with the kerfs being perpendicular to board length and at 3" intervals.

A fresh approach was adopted as to the type of samples to employ for collection of drying rate data. This entailed using 6" long pieces that were crosscut out of the green end-matched 45" lengths provided by 4 parent studs. Usually three 6" lengths were obtained from each of the control and the end-matched kerfed. The 6" long pieces were double end-coated as described for Test 2.

Periodically during the DH kiln run samples were selected for removal and immediate processing. This consisted of taking a cross section from mid-length of the 6" piece which was then quickly band sawed into 7 thin slices, in which the sawing progressed perpendicular to parent board thickness. The MC of each slice was thereafter obtained and available for illustrating MC gradients for both controls and kerfed. By summing green and oven dry weights of the 7 slices, average MC values were also obtained.

The 62 boards of 45" length made up a kiln charge of 2 homogeneous units, one for the 31 control boards and the other for the 31 kerfed. The 2 units were end-butted to a barrier made of a plywood sheet dimensioned to the height and width of the two units.

Table 2 Moisture content data as a function of drying time and board depth. These data were obtained via bandsawing the MC cross section into 7 thin slices, each about 3/16” thick.

DRYING TIME HOURS	CONTROLS				KERFED			
	BOARD DEPTH IN INCHES							
	1/8	3/8	5/8	7/8	1/8	3/8	5/8	7/8
0	61.9	108.1	121.0	126.9	60.3	113.5	125.9	141.4
5	52.7	93.4	107.7	114.2	65.8	105.3	132.7	133.1
10	84.1	96.1	95.0	97.5	72.2	115.5	129.0	138.1
24	21.3	45.8	66.6	72.4	23.1	50.6	74.5	81.8
48	15.7	29.5	40.1	41.6	7.3	10.5	15.0	17.2

The adopted method for tracking MC change fell short of expectations as shown in Table 2. In the time frame of 0 to 10 hours the MC values for both controls and kerfed appear discordant. For example, in comparing the MC values of board depths of 1/8” and 3/8” for the controls at 5 and 10 hours of drying, the MC’s at 10 hours are higher than those at 5 hours. This is the case as well for the analogous comparison for kerfed, plus other comparisons within the kerfed regime. This is no doubt the consequence of considerable variation in the green MC of the original 6” long tracking samples and their random selection in the passage of kiln drying.

However, in the time frame of 10 through 48 hours of drying there is no discordance of values. In light of this, the values for 24 and 48 hours of drying for controls and kerfed were used to generate their comparative MC gradients as shown in Figure 4. It is noteworthy how the green kerfing accelerated this latter stage of drying and intuitively, this seems reasonable. A water molecule, utilizing an improvised parallel-to-grain ‘freeway,’ undergoes a greatly diminished number of adsorption/desorption events in making its way out of the board.

Table 3 confirms Figure 4. The tabular data are from resistance meter readings on all 62 of the 45” length boards, 31 controls plus the 31 end-matched kerfed. Insulated pins were driven to 1/4 of board thickness to obtain the average board MC. They were further driven to mid-thickness to obtain the core MC. For all categories of MC in Table 2, the improvements via green kerfing appear excellent.

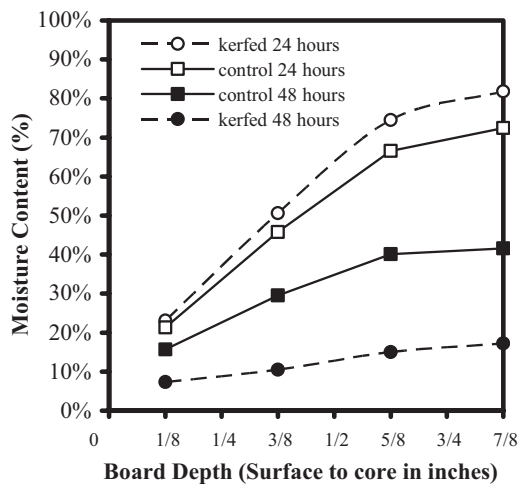


Figure 4 Comparison of moisture content gradients at 24 and 48 hours of dehumidification kiln drying for controls and kerfed. (See Text for procedure.)

Table 3 Moisture content data obtained with the resistance type moisture meter after 48 hours of dehumidification kiln drying.

Sample Type	Board MC's		Core MC's		Std. Dev. of Avg. MC's	N
	Average	Range	Average	Range		
Controls	19.3	9.50-29.0	22.1	9.50-033	5.81	31
Kerfed	8.0	6.00- 11.5	9.2	7.0 - 14	1.77	31

Test 4

The data were collected in the content of an undergraduate course conducted in the Department of Bioproducts and Biosystems Engineering. Stud grade lumber of nominal 2” by 4” cross section and approximate 100” lengths was utilized. The red pine lumber, of dead green MC, was again donated by the Potlatch mill in northern Minnesota.

The lumber was allocated, piece by piece into two batches, one for HT drying in the steam kiln and the other for drying in the DH kiln. The HT drying achieved a dry bulb temperature of just under 230° F, which was in place for the majority of the kiln run. The wbt was near an average 170° during the kiln run.

For the DH drying, 2 dehumidification units were rented to complement the 1.0 Hp in place unit. Each rental unit was rated at 15 gallons/day. At the start of the DH run a 3-hour shutdown occurred due to an electrical outage and failure of baffling. Once corrected, drying took place for a total of 42 hours. During that time the dbt never exceeded 106° and the wbt averaged about

80° F. Air velocity throughout the run was an average 1000 FPM.

For both kiln runs kerfing was at a 45° angle to board lengths. A 5” diameter blade, mounted in a portable circular saw, made the kerfs. The saw was secured to a work bench such that it could be angularly moved up and down around a pivot point.

There were 2 kerfing treatments; one of 2” spacing and the other of 6”.

At 15 hours of HT drying the 2” and 6” spacings were respectively at 26 and 31% MC while the controls were just over 33%. This depicts only a modest contribution of green kerfing in the context of simulated HT temperature. An “Information paper.doc” received from Dr. Shumlsky of Mississippi State university reports as follows: “The moisture content of the kerfed lumber averaged 3% lower than that of the non-kerfed lumber. Even more importantly, the moisture content standard deviation, a measure of the variability in dryness, was reduced by more than 50%, from 3.81 to 1.43.” This was for 10 hours of drying at a maximum dbt of 240° F, consistent with the drying practice of the sponsoring mill.

What our DH run demonstrated was a huge deficiency in dehumidification capability. At 20 hours of drying time the MC of controls was 65% while for kerfed near 60%. The initial MC's for the HT and DH kiln runs were near equal, right at 160%. One can but speculate as to the outcome for the kerfed lumber in the DH run if a modest level of dbt had been combined with an ample volume of sufficiently dry air.

The 2 kiln runs did provide valuable peripheral data. The modulus of elasticity (MOE) and modulus of rupture (MOR) were determined on 30 studs, 10 each of controls, 2” kerfed and 6” kerfed. They were machined to 1.5” thickness and 3.5” width for strength testing at an equilibrated MC near 12%.

Table 4 Strength, specific gravity and moisture content data for controls and kerf spacings of 2 and 6 inches.

Sample Type	MOE X10 ⁻³ Lb in ⁴	MOR Lb/in ²	Specific Gravity	Moisture Content - %			
				Shell	Core	Avg.	N
Controls	1,183	6638	.373	11.4	12.5	12.0	10
2” Kerfed	1,261	6152	.381	10.7	11.9	11.3	10
6” Kerfed	1,134	5289	.376	12.0	13.0	12.5	10

Table 5 Warp data for controls and kerfed studs dried in the HT and DH runs of Test 4. The average values are in increments of 1/32 inch.

	Crook	Bow	Twist	N
Controls	5.9	9.9	9.7	30
Kerfed	3.0	10.1	5.9	44

Table 4 contains the strength data. The MOE of the 2" kerf spacing is nearly 7% greater than that for the controls. The MOR for 2" kerfed is about 93% of that for the controls, which is in keeping with the estimated reduction in moment of inertia due to the kerfing. These MOE and MOR results are in keeping with those previously reported (Erickson and Moya 2005).

The results for 6" kerfed appear out of order and are not explainable via a significant difference in specific gravity. Where they do differ from controls and 2" kerfed are in the modestly higher MC values. The higher values stem from their extended solo storage in the "controlled" environment room during which the EMC condition drifted upward. The authors suspect that in the upward drift of EMC, the 6" kerfed studs experienced a considerable increase in their near-surface MC's which had a large effect upon both their MOE and MOR. The strength testing in each instance was done immediately out of the environment room.

With regard to finding higher MOE values for kerfed by comparison to controls, we offer this

quotation: (USDA Wood Handbook 1987 p. 4-15). "MOE measured from a simple supported, center loaded beam, on a span ratio of 14/1. The MOE can be corrected for the effect of shear deflection by increasing it 10%." The values in Table 3 were gotten with a span ratio of 23/1 for the nominal 2" by 4" studs. There is an obvious need for measurement of the MOE for kerfed lumber in the context of 4-point loading for which shear is absent.

Finally, warp measurements were made on 30 control studs and 44 of the kerfed. The data are presented in Table 4. The measurements were made after several months of stickered storage in the 12% EMC environment room. The warp values are comparatively low compared to what has been normally found for red pine studs. This might be due to the high initial average MC of the studs, about 160%. The high MC means they came primarily from the sapwood portion of the tree and thereby devoid of warp-prone juvenile wood. In spite of the low average warp values, the results are consistent with previous research in which green kerfing also reduced the amount of warp.

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Kiln Climate and Internal Wood Climate during Drying and Heat Treatment of Logs, Planks and Clearwood Samples

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ABSTRACT

Effects of elevated temperatures on wood properties have been reported in numerous studies. Altered properties on microscopic level as well as plank level have been reported. The altered properties are related to physical as well as chemical phenomena.

Changes in chemical properties can be expected to be greatly influenced by the internal wood climate. The internal climate will influence speed of chemical reactions and possibly also lead to different processes for a dry specimen as compared to a moist, and for specimens at high temperature as compared to lower temperature.

The internal wood climate during drying and heat treatment will be determined by factors like drying climate, moisture content of the wood, material properties, and size of the specimen studied. Evaporation of moisture and moisture flux will influence kiln climate as well as internal wood temperature level and temperature distribution. A small specimen will adapt faster to the surrounding climate than a large specimen. A specific kiln climate will lead to different moisture gradient and internal stresses in a small sample as compared to a full size plank. When results from small samples are to be compared to results from planks or logs, the correlation between internal climate in small and large samples needs to be considered.

The present paper reports results from temperature measurements during drying and heat treatment of logs, planks and small clearwood specimens. The results illustrate the great difference in internal climate between small and large specimens treated in the same external climate. The paper includes principal suggestions on strategies for how to adapt laboratory tests on small samples to industrial treatment of sawn lumber.

INTRODUCTION

Research as well as industrial development of wood drying related issues are commonly performed in small laboratory cabinets or semi scale pilot kilns. Often the test samples are small clearwood samples. By obvious reasons this both reduces costs and enhances the possibilities to maintain a controlled environment during the tests. However, as the present paper will illustrate, the reduction in kiln dimensions as well as sample size can lead to major differences in effective kiln climate as well as internal wood climate, and consequently also in the chemical and physical response of the wood material.

A different response of the wood to the drying or treatment schedule can be related to physical as well as chemical effects. As will be illustrated in this paper, a few small size samples in a laboratory cabinet will not have the same influence on the kiln climate as a batch of possibly 200 m³ of green lumber in an industrial kiln. A small clearwood sample will not react to a specific climate in the same way as a log or a full size sawn plank.

Both the influence of the wood load on kiln climate and the different response to the actual climate surrounding the test material need to be taken into consideration when a study is planned as well as when the final results are evaluated. A laboratory test needs to be designed in such a way that the actual effects on the wood material reflects influence on full size material treated under industrial conditions.

DEGRADE MECHANISMS IN WOOD

Drying and heat treatment processes can lead to degrade of the wood material through chemical processes as well as physical effects. Chemical degrade and physical damage can be linked, Fengel and Wegener quotes several studies where presumably thermal decomposition precedes failures between cell wall layers (Fengel and Wegener, 2003).

Three main processes lead to chemical degrade of wood at elevated temperatures: hydrolysis, dehydration, and oxidation (Fengel and Vegener, 2003). The principal characteristics of the three degrade processes are summarized in Table 1.

Table 1. Summary of principal mechanisms for chemical degrade of wood during heat treatment.

Degrade process	Principle	Requires	Accelerated by	Initial impact on dry weight
Hydrolysis	Molecule is broken as water is added	Water	Temperature Acidic environment	Increase
Dehydration	Molecule is broken as water is released	Heat	Unknown to author	Decrease
Oxidation	Molecule is broken as oxygen is added	Oxygen	Temperature Acidic environment	Increase

It is obvious that hydrolysis only will occur if moisture is present. Degrade of a dry specimen can be expected to be primarily caused by dehydration or oxidation.

Hydrolysis of polysaccharides will by definition lead to an increase of the total weight as water molecules are added to the structure. At the same time several researchers report weight loss after heat treatment. Weight loss of the polysaccharides during heat treatment in a gaseous environment (air or other) will require that the polysaccharides are reduced to volatile compounds. Fengel, in a study of heat treatment of sawdust, expects that that the conversion of the polysaccharides into volatile substances is performed in three stages; the first stage is a partial decomposition of the long chains into shorter ones, the second stage either is a direct or indirect disintegration of short chains into monosaccharides, after which an immediate further disintegration into volatile substances takes place (Fengel, 1966).

The temperature level of the wood will not only influence the speed of the reaction, but also which chemical reaction that will occur (Fengel and Wegener, 2003). An industrial example is heat treatment wood, where treatment at 185-190 °C is used to reduce swelling and shrinking of the material, whilst treatment at 200-212 °C is required in order to also improve resistance to decay (Thermowood handbook, 2004).

It is obvious that internal stresses during drying and heat treatment of wood is influenced by sample size and growth characteristics. A small clear wood sample will not face the same internal stresses as a full size plank, when exposed to the same climate. Size will also influence the moisture content and temperature distribution, which in turn will have a direct influence on physical damage since both influences strength properties (Siimes, 1967).

The combined physical and chemical effects on strength of sawn planks are far greater than the reduction of strength of small clear wood samples. Figure 1 shows the logarithmic time to reach different degrees of degradation of small clear wood samples at

various temperatures and atmospheres (Stamm, 1964). The treatment times to reach 10 % loss of strength for clear wood samples are roughly 100 times longer than the periods used for treatment of planks to reach strength loss of the same magnitude in (Källander et al, 2001).

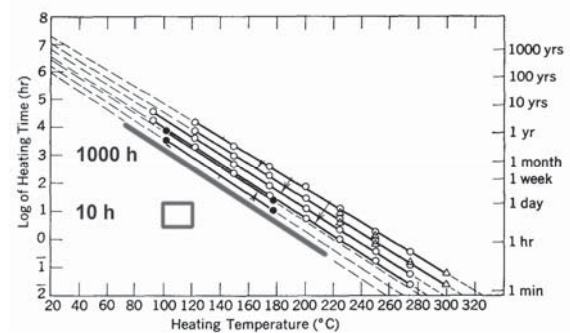


Figure 1. Loss of tensile strength roughly 100 times faster in planks as compared to clearwood samples. Figure from (Stamm, 1964) with treatment leading to 10% reduction in strength highlighted, and treatment periods and climates of Norway spruce planks leading to 12 % reduction of tensile strength shown. From (Källander and Bengtsson, 2004).

MATERIAL AND METHODS

Studies quoted in this paper were conducted at SP Swedish Testing and Research Institute in the period 1998-2006. The studies have been conducted on Scots pine (*Pinus silvestris*), Norway spruce (*Picea abies*), and Douglas fir (*Pseudotsuga menziesii*). Tests have been conducted on 40x40x40mm clearwood samples, 50x150 mm planks and 500+ mm diameter logs. Drying and heat treatment have been conducted in industrial and pilot High Temperature (HT) kilns as well as in laboratory drying cabinets and climatic cabinets. All tests were made with constant set dry temperatures.

Kiln climate was recorded by wet and dry bulb measurements in different positions in the kilns. Internal wood temperature was recorded by Pt100 gauges and Thermocouples inserted into holes drilled into the wood. The holes in planks and logs were filled with one component Polyurethane adhesive to reduce local drying

at the measurement position. Holes in small clear wood samples were not plugged.



Figure 2. Small clear wood samples in laboratory cabinet. Saturated conditions were guaranteed by means of constant supply of vapour from an external boiling pot. Power rate exceeding 2 MW/m³. From (Landel, 2004).

RESULTS

All industrial and pilot kiln drying tests show temperature curves where the dry temperature, after the heating phase, gradually increases up to the set value. Figure 3 shows a typical temperature development during HT drying. The drying process was made with constant heating power, nominally 100 kW for a batch of 4,5 m³ 50 x 150 mm spruce planks. Set temperature value 125 °C is reached after approximately 12 hours heating with closed vents.

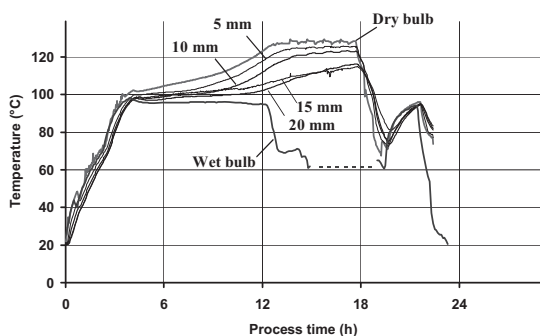


Figure 2.3. Internal wood temperature in Norway spruce plank during HT drying, from Bengtsson et al, 2001.

Figure 3. Temperature development in kiln and wood during drying test at Moelven Soknabruket AS. Set dry bulb temperature 125 °C is reached after approximately 12h. Nominal power rate 20 kW / m³. From (Källander et al, 2001).

The temperature in a small laboratory cabinet increases much faster. Figure 4 shows the temperature development in kiln and wood in a laboratory cabinet

with nominal power rate in excess of 2 MW/m³. Saturated conditions during treatment achieved by means of an external boiler.

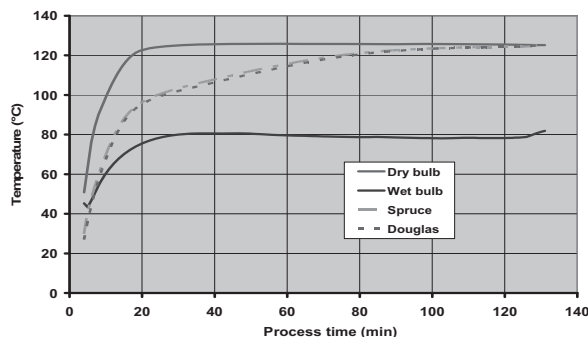


Figure 4. Temperature development in kiln and wood samples during treatment in laboratory cabinet. Kiln reaches set dry bulb temperature within 40 minutes. Centre of test samples reaches surrounding temperature approximately 126 min after insertion in kiln. From (Landel, 2004).

An extreme opposite case is represented by a 500+ mm diameter log dried in a HT drying kiln. The large cross section in relation to the surface area lead to a very slow increase of internal wood temperature as shown in Figure 5.

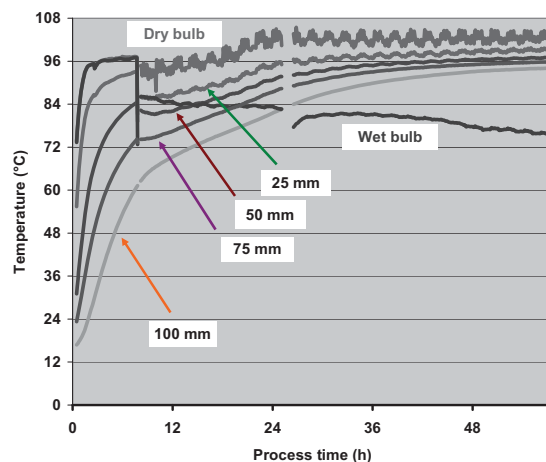


Figure 5. Temperature measurements during drying of a 500 mm log at 105 °C set dry bulb temperature. Dry bulb and wet bulb temperatures drop as vents are opened after approximately 8 h heating, after which the HT kiln requires an additional 16 h to reach the set dry temperature. Part of figure from (Landel 2004).

The three drying tests clearly illustrates the influence of sample size on the internal wood climate. The temperature of the small clear wood samples in Figure 4 rapidly adapts to the surrounding temperature. Internal temperature reaches surrounding temperature

after approximately 2h, indicating that the samples are completely dry.

Figure 3 shows how the internal wood temperature in planks during industrial drying closely follows the saturation temperature of the surrounding atmosphere during the early stages of drying. As the evaporation zone reaches each temperature gauges at different depths of the wood, temperature starts to increase.

The temperature development in a log during HT drying shows a slightly different behaviour. The temperature development close to the surface has a similar behaviour as the temperature development in the planks. After an initial period where the temperature closely follows the saturation temperature, temperature starts to increase as the free water has evaporated. However, the internal parts of the log will show a different behaviour due to the very large cross section of the log in relation to the surface area. As the surface layers of the log dry out, heat conductivity as well as moisture flux will be reduced, which in turn will reduce cooling of the log. The internal temperature of the log will thus increase above the saturation temperature and reach levels close to the surrounding dry bulb temperature.

As is shown in Figure 6, small clear wood samples show reduced Equilibrium Moisture Content (EMC) after treatment 24h treatment in humid air of 105 °C temperature, a clear indication of chemical change (Källander and Landel, 2007).

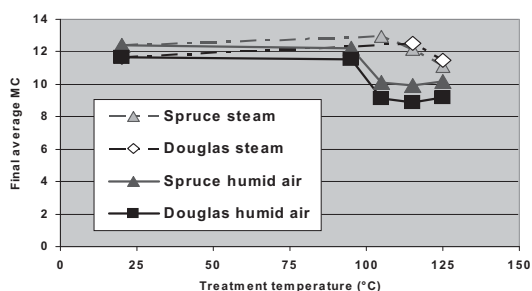


Figure 6. Effect of 24 h treatment of small samples in humid air and in saturated steam at various temperatures. The drop in EMC shows that chemical changes in the wood material have occurred. From (Källander and Landel, 2007).

The drop in EMC seems to happen early in the treatment process. Figure 6 shows EMC after treatment in humid air at 105 °C for different periods.

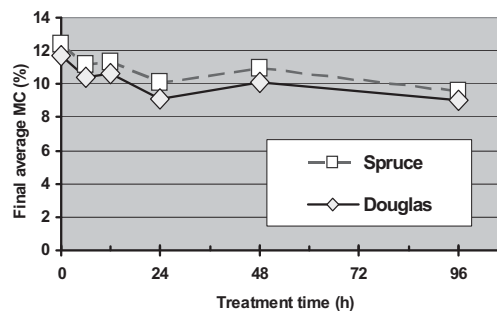


Figure 7. Influence on EMC of treatment of small samples in humid air. The test results indicate that changes occur occur early in treatment. From (Källander and Landel, 2007).

DISCUSSION

The results illustrate how evaporation of moisture from the wood influences the kiln climate. In the early phases of HT drying or heat treatment, kiln temperature will remain low also if the heating power is high. As the surface wood dries, evaporation rates will decrease and the kiln temperature can rise.

Small samples treated in temperatures above 100 °C will dry out in a relatively short period of time. In the studies by Landel, 40 mm x 40 mm x 40 mm softwood cubes were completely dry after periods ranging from 1h to 3h, depending on treatment temperature. After this period moisture is no longer available for hydrolysis, and chemical degrade of the wood material will primarily be attributed to dehydration or oxidation. As is shown in Figure 7, chemical change shown by reduced EMC occurs primarily during the early phases of treatment, which can be seen as an indication that the changes are attributed to hydrolyzation linked to moisture present in the wood. As the samples are dried out, no further changes in EMC can be detected.

A plank or log of full size cross section will show a principally different behaviour as compared to small samples. Moisture will be present throughout a drying process, either as liquid or bound water in the interior inside the evaporation zone, or as vapour or steam passing out from the interior to the surface outside. In the case of a log, the slow drying process will keep the interior at a high temperature also at high moisture content levels. Thus, during drying of planks or logs, hydrolysis should be possible throughout the process.

It is clear that different parts of a plank will face different internal climates during a drying process, as the surface wood faster than the interior parts will dry out and allow for increased temperature. However, it can also be expected that the different volumes of a plank will influence each others. Although the surface

wood quickly will dry out, water vapour or steam flowing out from the evaporation zone will still be present. Mass flow will vary between different parts of the plank depending on the permeability of the material. How this flow of probably superheated vapour affects the wood material is unknown.

Under the assumption that the internal wood climate during drying or heat treatment will pass through different principal stages during, leading to different degrade processes in each stage, a laboratory treatment of a small sample should be made to simulate these internal climates.

At the same time it can be expected that the sequence of the internal climates also will influence the process. Acids and other reaction substances formed by hydrolysis during the convective phase can influence later degrade, polyoses already shortended by hydrolysis can be affected differently as if they had not been previously damaged.

The combined effects will make it rather complicated to recreate the drying and degrade process within a plank in a small test sample. Treatment of a small sample will primarily lead to effects corresponding to one internal wood climate, and to simulate the drying process of a full size plank would not only require treatment in a series of climates, but possibly also supplement vapour flux through the hot and relatively dry specimen in the later treatment stages.

Due to the difficulties to reproduce an actual drying or treatment process of a plank in a small sample, a high temperature drying tests or heat treatment tests should preferably be made on larger specimens, where at least the cross section corresponds to actual plank sizes.

CONCLUSIONS

The evaporation of moisture from the wood load in an industrial kiln will have a strong influence on the kiln climate, also when very high heating power is used. Kiln temperature will correspond to the evaporation of moisture and heat transfer into the wood, and not increase until the surface layers of the wood has dried and evaporation rate is reduced.

The climate or drying schedule in a laboratory test with aim to study influence of a drying or heat treatment process on wood properties needs to be designed to follow the actual climate surrounding the wood, rather than a fixed constant climate.

The moisture distribution in the wood during treatment will limit the internal wood temperatures also when the wood is surrounded by high temperatures. In

volumes with liquid water present, temperature will not increase significantly above 100 °C. In volumes showing temperatures well above 100 °C, no liquid water is present.

Different degrade mechanisms will occur in presence of water and without presence of water. Hydrolysis can only occur in presence of water. A dry specimen is primarily degraded by oxidation and dehydration.

Due to the difficulties to reproduce the effects of the sequence of internal climates occurring in a plank during HT drying or heat treatment in a small clear wood sample, use of such small samples should be avoided. Laboratory tests with aim to study influence of a drying or heat treatment process on wood properties should if possible be made on samples with dimensions or at least cross section corresponding to actual industrial products.

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Kiln Drying Properties of Rowan (*Sorbus aucuparia* L.) Lumber

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ABSTRACT

The objective of this study was to determine the kiln-drying behavior of naturally-grown Rowan (*Sorbus aucuparia* L.) lumber. This study focused on two conventional drying approaches applying protective (mild drying) and non-protective (harsh drying) schedules. The drying time (from 75% initial to 8% final moisture contents) and lumber quality for two schedules that determined according to the classification of European Drying Group (EDG 1992) compared. Drying time of protective and non-protective schedules found 875 and 605 hours, respectively. In terms of non-protective drying quality; S (Standard) quality level was obtained based on the slope and target final moisture contents and drying tensions, E quality level was achieved based on collapse which was determined for 5% of the samples. Deformations (warp) such as cupping, bowing and crooking observed in all samples, and cross-section and surface splits were also observed for all samples, which was indicated S quality level. On the other hand protective schedule resulted in a better drying quality. E (Exclusive) quality level was obtained according to target final moisture content and slope moisture content. E quality level was achieved according to drying tensions in first measurement and Q quality class was achieved in second measurement. Collapse, discolorations, splits and warps such as bowing, crooking and twisting were not occurred. Consequently, acceptable results obtained with non-protective schedule. But, to obtain better quality protective drying schedules should be applied for kiln drying of rowan lumber. From an energy efficiency point of view, the harsh schedule, by saving 270 h of drying time, reduced electricity by 4320 KWh and was therefore found to be \$648 more profitable in this trial.

Keywords: *Rowan, kiln-drying, drying quality, Sorbus aucuparia* L.

INTRODUCTION

There has been an ever increasing demand for wood products in Turkey as in many other countries of the world. As a result, the gap between wood supply and demand is rapidly widening. To solve this problem, the general approach is to establish large wood plantations with fast growing trees. Additionally this approach, some researcher indicated that wood quality attributes should be regarded for special end-use. In general, plantations program and researches have been focused on native fast-growing and wide distributed species in Turkey [Korkut et al. 2007].

However, one area in which research has been neglected is that of understanding the importance of

some native species having excellent wood quality attributes, because of their limited growing stock. European Rowan (*Sorbus aucuparia*) is a good example for such kind of species.

Rowan timber is extremely hard and dense and has a dark, purplish brown heartwood surrounded by a pale, yellowish brown sapwood. Rowan has a strong, flexible, close-grained, yellow-grey wood, which was once widely used for making tool handles, small carved objects, plough-pins, small parts in tools, spinning wheels and wagons, mallet heads, platters, bowls, pegs for tethering animals, cartwheels, poles, hoops for barrels, household utensils, general woodcraft, churn staves, tackle for watermills, rough basketwork, etc. If

large enough it provided excellent planks and beams. It was used by the hill people to make long bows, instead of the yew and ash so often used by lowland people for this purpose. Rowan was also used for different purposes: wands, magical spears, talisman inscribed with runes and other meaningful patterns [Sachsse et al. 1988, Rameau et al., 1989].

The genus *Sorbus* is a genus of about 100-200 species of trees and shrubs in the subfamily Maloideae of the Rose family Rosaceae. *Sorbus aucuparia* is known as rowan or mountain ash or European Rowan [Price, 2007].

European Rowan (*Sorbus aucuparia*), the best-known species of the genus *Sorbus*, is native to most of Europe except for the far south, and northern Asia. In the south of its range in the Mediterranean region it is confined to high altitudes in mountains. Rowan is very tolerant of cold and is often found at high altitude on mountains; it occurs at up to 1.000 m altitude in the UK, and up to 2.000 m in France. It is native Britain and Ireland, south and east part of Europe from Iceland to Spain, Macedonia and the Caucasus, it is also found North Africa and Asia Minor [Raspe et al., 2000; Yaltrık and Efe, 2000].

In Turkey, Rowan is found primarily in the north and northwest Anatolia as small groups in angiosperm mixed forests [Yaltrık and Efe 2000]. It is a small to medium-sized deciduous tree typically growing 8–20 m height (rarely 20 m and exceptionally 28 m) and can live over 100 years. It is very tolerant of a wide range of soil conditions. The bark is a smooth, silvery grey in young trees, becoming scaly pale grey-brown and occasionally fissured on old trees [Anonymous, 1996; Yaltrık and Efe, 2000].

Rowan wood's air dry (801 kgm^{-3}) and oven dry (737 kgm^{-3}) were determined [Korkut et al. 2009].

To understand employability of European Rowan in construction of indoor goods (parquet, floorboard, timbering and other solid products) which have higher economical value in addition to the above-mentioned products required determining kiln drying properties of the species. It is well known that there is an inverse relationship between wood density and drying quality (with increasing density, drying quality decrease) even in the same drying conditions. Although there is not any previous study on drying properties of European Rowan in Turkey, some other researches on Eucalyptus [Kantay et al. 2002], European Hophornbeam [Korkut and Guller 2007] and Walnut [Unsal 1994] showed that wood species with high density can be kiln dried in a quality way when protective drying schedules applied but, drying period can be too long and not to be economically acceptable; therefore fresh lumbers of high-density wood should be pre-dried up to 30% humidity levels under shelters.

To efficiently utilize natural resources, it is essential to assess the wood quality attributes of native species. Besides wood properties, kiln drying capability plays an important role to understand usage potential in forest product industry. With this study, kiln drying properties of European Rowan wood which has been neglected for a long time in our country, determined. Thus, besides filling the gap in the existing literature on this subject and forming a base for further studies, but also intended to arouse the Forestry Department's interest on this species.

MATERIAL AND METHODS

Study material logs of 3 m^3 in volume and minimum 25 cm in diameter obtained from a mixed oak-hornbeam-rowan stand in Kastamonu region, north western part of Turkey. Logs without any sign of decay were used to obtain drying samples. Sample lumbers were cut in tangential direction as a 50 mm in thickness and 200 cm in length at a private sawmill (Oney Kaplama San. A.S.).

1 m^3 capacities automatic drying kiln heated with electricity used for trials (Figure 1). The kiln has three lumber humidity sensors, an environmental temperature sensor and an environmental equilibrium moisture sensor. In addition sensors the kiln also has an automated flap valve and automated humidifying valve as measurement tools and accessories. These are all connected to the command panel. To determine appropriate drying schedules, pre-trials carried based on the existing literature knowledge. Drying trend considered for the base of preparing trial drying schedules and the principle of decreasing the relative humidity via fixing the temperature below fiber saturation point has been adopted. In all the drying processes composed of heating, main drying, equalizing and cooling periods.

In automatic management, temperature and relative humidity is controlled automatically in the kiln.

Conventional drying method (drying via air and steam mixture at temperatures below $100 \text{ }^\circ\text{C}$) being the most common method in Turkey as many other countries preferred.

Humidity sensors and cables placed during piling and final quality control sample lumbers distributed among piles. Defects such as checks, knot, wounded, rottenness, were avoided in selection of the sample lumbers. Humidifying applied via normal pressurized water. Air movement speed was 3 m/sec. in side fanned and air horizontally circulated in the kiln.

Two different drying schedules (protective and non-protective) used for trials. The detailed information on schedules can be seen in Table 1 and Table 2.

Table1. Non-protective drying schedule for rowan lumbers

Wood Type: Rowan (<i>Sorbus aucuparia</i> L.) Lumber thickness: 50 mm Density: 0.737 gr/cm ³ Initial Humidity: 75% Final Humidity: 8%							Temperature T1:48.9, T2:82.2 Drying gradient:4	
1	2	3	4	5	6	7	8	9
Drying Periods	Moisture content of lumber (%)	Drying gradient	Equilibrium moisture content (%)	Dry-bulb Temperature (°C)	Wet-bulb Temperature (°C)	Wet-Bulb depression (°C)	Relative Humidity (%)	Approximate Durations (hours)
Heating	Pre heating	-	-	-	-	-	100	9
	Superficial heating	-	-	-	-	-	.	
	Deep heating	-	-	48.9	-	-	90	
Main Drying	75-40	-	17.7	48.9	46.7	2.2	88	548
	40-35	2.4	16.4	48.9	46.1	2.8	85	
	35-30	2.6	13.6	48.9	44.4	4.4	77	
	30-25	2.9	10.3	48.9	41.1	7.8	63	
	25-20	4.2	6.0	54.4	37.8	16.7	36	
	20-15	6.2	3.2	65.6	37.8	27.8	19	
15-8	4.2	3.6	82.2	54.4	27.8	26		
Equalizing	8	-	8	82.2	72.2	10	66	48
Kiln Type: Metal Air movement speed: 3 m/sec. Daily Operating Duration: 24 hours								

Table 2. Protective drying schedule for rowan lumbers

Wood Type: Rowan (<i>Sorbus aucuparia</i> L.) Lumber thickness: 50 mm Density: 0.737 gr/cm ³ Initial Humidity: 75% Final Humidity: 8%							Temperature T1:43.3, T2:71 Drying gradient:4	
1	2	3	4	5	6	7	8	9
Drying Periods	Moisture content of lumber (%)	Drying gradient	Equilibrium moisture content (%)	Dry-bulb Temperature (°C)	Wet-bulb Temperature (°C)	Wet-Bulb depression (°C)	Relative Humidity (%)	Approximate Durations (hours)
Heating	Pre heating	-	-	-	-	-	100	13
	Superficial heating	-	-	-	-	-	.	
	Deep heating	-	-	43.3	-	-	91	
Main Drying	75-50	-	19.3	43.3	41.7	1.7	91	795
	50-40	2.6	19.3	43	41	2	90	
	40-35	2.2	17.7	43	41	2	87	
	35-30	2.3	15.3	43	40	3	81	
	30-25	2.4	12.2	48	43	5	72	
	25-20	3.5	7.1	54	41	13	44	
	20-15	7.1	2.8	60	34	26	15	
	15-6	4.4	3.4	71	45	26	22	
Equalizing	8	-	8	71	60	11	58	67
Kiln Type: Metal Air Movement Speed: 2 m/sec over FSP, 3 m/sec below FSP Daily Operating Duration: 24 hours								

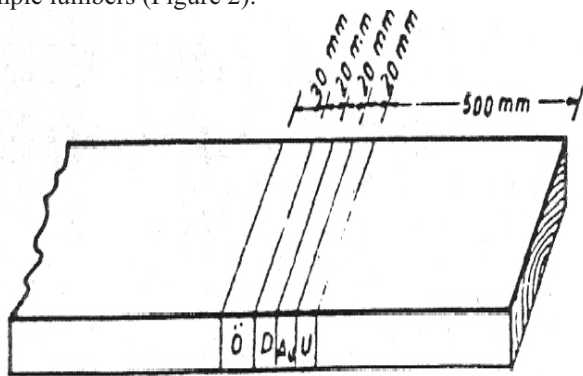


Figure 1: Drying kiln used for the trials

The reason of target final humidity considered as 8% was that the final humidity in indoor places heated by central heating is $7 \pm 2\%$.

Initial experiments were done according to the literature in the mentioned drying kiln. The appropriate drying schedules were based on the related literal information. The schedules were applied at the same drying kiln and the drying results were evaluated with quality control tests [Boone et al. 1998, Simpson 1991].

In accordance with E.D.G. (1992) [EDG 1992], testing samples were taken from at least 500 mm inside from transverse section of the final quality control sample lumbers (Figure 2).



- (U) Final humidity testing sample
- (ΔU) Humidity difference testing sample
- (D) Case hardening testing sample (prong sample)
- (Ö) Density testing sample

Figure 2. Sampling for final quality control

Samples taken the same sizes with the final humidity testing samples were divided into 5 slices, humidity of each slice was found by drying method and the humidity difference between inner and outer layers determined via the following formula using outer layer

samples no 1 and 5 and inner layer no 3 shown in figure 3 [TGL 21504].

$$\Delta U = U_3 - \frac{U_1 + U_5}{2} (\%)$$

ΔU = Humidity difference between inner and outer layers in percent.

U_3 = Amount of humidity in inner layer in percent.

U_1 and U_5 = Amount of humidity in outer layers in percent.

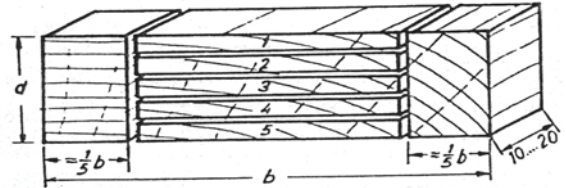


Figure 3. Samples used in determination of humidity distribution within transverse section [Lempelius 1969, Kantay 1978].

Prong samples prepared (Figure 4) and TRADA pattern (Figure 5) used for determination of drying tensions. Drying tensions determined in two stages as right after and 24 hours after the drying.

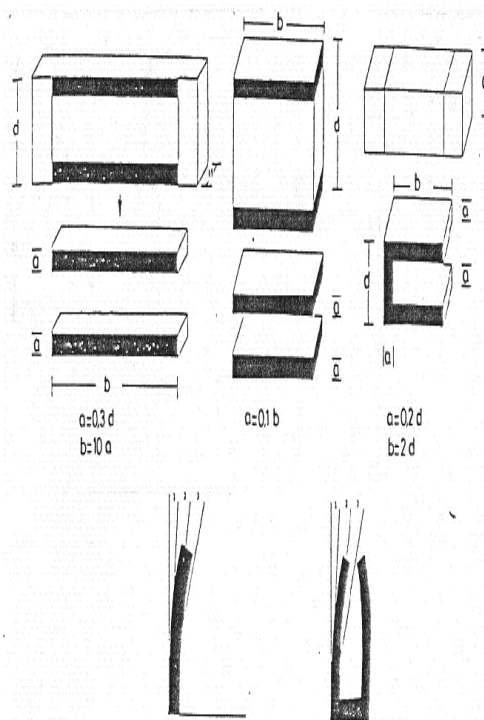


Figure 4. Preparation and usage of prong samples [EDG 1992].

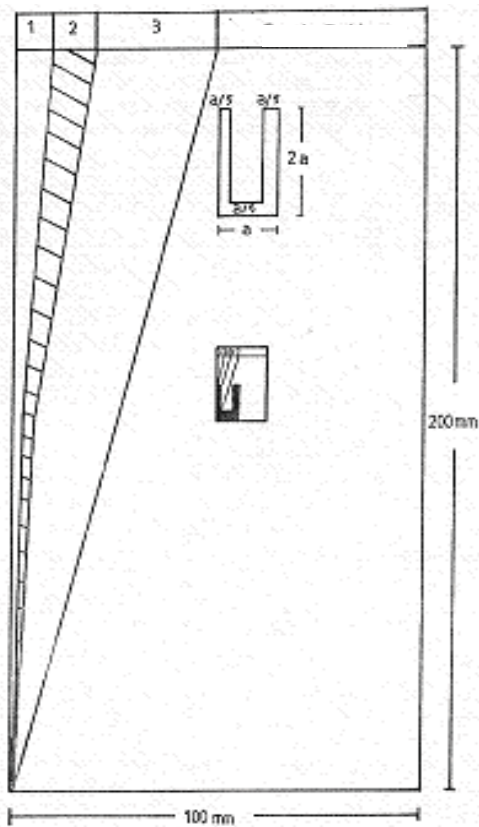


Figure 5. TRADA Pattern [EDG 1992].

Before drying, defects of the final quality control sample lumbers were determined and checks were marked on the lumbers.

At the end of drying process, final quality control samples which were marked and numbered previously, examined step by step according to following criteria [EDG 1992].

- Amount of humidity,
 - Average amount of humidity,
 - Distribution of humidity,
 - In each lumber,
 - Generally in the kiln,
 - Acceptable distribution width,
- Drying checks,
 - Surface checks,
 - Inner checks,
 - End checks,
- Drying tensions / Case-hardening,
- Collapse,
- Deformations

Quality classes determined by comparing obtained data with the tolerance values of E.D.G. (Table 3).

Electrical energy consumption was already known for the kiln. Comparison of two schedules in terms of electricity consumption and cost were calculated using the following formulas:

$$ECon = KEC * DT$$

$$ECon = Econ * EUP$$

where ECon = electricity consumption, ECost = electricity cost, KEC = kiln electrical energy consumption (16kWh), DT = drying time, and EUP = electricity unit price (0.15 \$=kWh).

Table 3. Tolerance values used for evaluation of the drying quality [EDG 1992]

Criteria		S (Standard)	Q (Quality dried)	E (Exclusive)	
Maximum Deviation between Target Final Humidity (%) and Average Humidity	d≤40 mm	+ 2.0 / - 3.0	+ 2.0 / - 2.0	+ 1.5 / - 1.5	
	d>40 mm	+ 3.0 / - 3.0	+ 2.5 / - 2.5	+ 2.0 / - 2.0	
Maximum Deviation between Target Final Humidity (%) and Separate humidity Measurements	d≤40 mm	+ 4.0 / - Unlimited	+ 3.0 / - 3.0	+ 2.0 / - 2.0	
	d>40 mm	+ 6.0 / - Unlimited	+ 4.0 / - 4.0	+ 3.0 / - 3.0	
Case hardening	Prong Sample Testing	First Measurement	Moderate (2)	Light (1)	
		Measurement after 24 hours	Severe (3)	Moderate (2)	
Collapse (reduction of thickness) (in 10% of the samples)		Max. 6 mm	Max. 3 mm	Max. 2 mm	
Checks	Surface Checks (On each surface)		Max. Depth 5 mm	Max. Depth 3 mm	Max. Depth 2 mm
	Internal Checks		in 10% of the samples	in 5% of the samples	in 2% of the samples
	End Checks (in 90% of the samples)	d≤40 mm	Max. Length 200 mm	Max. Length 100 mm	Max. Length 50 mm
		d>40 mm	300 mm	200 mm	100 mm
Deformations		Deformation caused by shrinkage and anisotropy of shrinkage, as well as those caused by inherent wood properties are allowed.			

FINDINGS

Results for Drying of Rowan Lumber via Non-Protective Drying Schedule

Drying of lumbers from 75% initial moisture content to 8% target final moisture content took 605 hours totally, as 9 hours for heating, 548 hours for main drying and 48 hours for equalizing stage.

At the final moisture content measurements, the maximum moisture was 14.4% and minimum moisture content was 4.6%. With the average moisture contents, S (Standard) quality level was missed by 0.5%. Maximum moisture content was 16.7% and minimum moisture content was 5.6% in the slope moisture content measurements. S quality level was about to be reached but the maximum value was exceeded by 2.5%.

Moderate case hardening was determined in the first (immediate) and severe case hardening was determined in the second (24 hours later) measurements. According to these results, S quality level was achieved.

Collapse was observed in the 5% of the samples. Maximum collapse width was 2mm. E quality level was obtained but the 10% limit was exceeded with the ratio of collapse.

In all the samples some deformations (warp) such as cupping, bowing and crooking were observed. It is thought that tree's shrinking anisotropy is most probable reason of this defect rather than stacking faults.

Cross-section and surface splits occurred all of samples. S quality level was achieved regarding to the maximum length of the splits (Figure 6). To prevent splits some chemicals (i.e. paraffin) should be applied on the cross-sections before drying.

Results for Drying of Rowan Lumber via Protective Drying Schedule

Total drying time took 875 hours for protective schedule, as 13 hours for heating, 710 hours for main drying and 67 hours for equalizing stage.

At the final moisture content measurements, the maximum moisture was 9.8% and minimum moisture content was 6.3%. With the average moisture contents,

E (Exclusive) quality level was found. Based on the slope moisture content measurements with 10.3% maximum and 5.9% minimum moisture content, E quality level was obtained.

The measurements with the finger samples; mild case hardening was determined in the first (immediate) and moderate case hardening was determined in the second (24 hours later) measurements. According to these results, E quality level obtained in the first and Q quality level obtained in the second measurement.

Collapse, discolorations and splits were not found in the samples. There were no warps such as bowing, crooking and twisting (Figure 7).



Figure 6. Outlook of dried lumbers with non-protective drying schedule.



Figure 7. Outlook of dried lumbers with protective drying schedule.

CONCLUSION

Although acceptable results and 270 hours shorter drying time obtained with harsh drying schedule, mild trial drying schedule gave better results for drying of rowan lumber comparing to non-protective one in

various aspects such as final moisture content, moisture trend and especially drying tensions.

This result shows that when a better quality is necessary the mild drying schedule should be applied. On the other hand, as the contribution of energy to the total drying cost is increasing and as the changing production and market strategies put more pressure to reduce drying times while asking for acceptable drying quality, the harsh schedule can become an alternative solution for kiln owners for improving the profitability of their operation.

This result shows that softening of the drying circumstances and extending the equalizing period positively effect of drying quality. A higher quality level obtained in kiln drying of rowan lumber compared to the quality level (S) obtained in kiln drying of Eucalyptus (*Eucalyptus camaldulensis* Dehn.). This result shows that even wood species with high density can be dried in a quality way, when protective drying schedules applied [Kantay et al. 2002].

Although Rowan has a denser wood than eucalyptus, applying a mild schedule resulted in a higher quality level for kiln drying of Rowan lumber as compared to the quality level (S) for kiln drying of eucalyptus (*Eucalyptus camaldulensis* Dehn.) and red bud maple (*Acer trautvetteri* Medw.) [Kantay et al. 2002, Korkut et al. 2007].

It should be taken into consideration that application of natural pre-drying up to FSP and then technically drying increases the drying quality of high density lumbers. In addition application of paraffin emulsion on cross-section in pre-drying phase as an additional precaution prevents checks. The density values obtained in this study show the difficulty of drying clearly.

It is the recommendation of the authors that further research be conducted to understand the drying behavior of other wood, including Rowan (*Sorbus aucuparia* L.), for different drying conditions and methods.

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New Methodology to Optimize Sorting in Wood Drying

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ABSTRACT

Drying lumber can be quite challenging when uniformity and consistency are required. Over-drying and under-drying are common causes for lower grade recovery and dimensional stability problems. It is known that both over-drying and under-drying can be reduced by sorting green lumber into different moisture content groups and sorting also offers the opportunity to redesign drying schedules. In this study, a new methodology was designed and tested to optimize kiln drying of lumber by implementing green sorting coupled with modified drying schedules. The methodology was applied to optimize the drying of 114mm by 114mm hem-fir lumber sorted with an NMI capacitance type meter at a local sawmill. It was found that in comparison to unsorted lumber, sorting into three groups can reduce the drying time in approximately 7% and recover around 3/4 of the under-dried lumber. The present paper also reports the experimental data on lumber degrade and moisture gradients measured after drying.

SESSION 5

ALTERNATIVE DRYING METHODS

Evaluation of super-heated steam vacuum drying viability for four commercially important Australian hardwood species.

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ABSTRACT

This work was instigated by the Australian hardwood industry to investigate the potential of vacuum drying technology to improve the drying time, cost and economy over conventional methods, for potential future investment. At the time of writing, very little research has been conducted on vacuum drying Australian hardwood species with no published records of convection vacuum drying of the species presented. This work presents the results of drying quality, time and economic viability of vacuum drying four commercially important Australian hardwood species compared with current conventional drying methods. The species investigated were *Corymbia citriodora* (spotted gum), *Eucalyptus pilularis* (blackbutt), *Eucalyptus marginata* (jarrah) and *Eucalyptus obliqua* (messmate). For each species two trials were performed and progressively optimised. For each trial, 350 boards of dimension 4500 x 100 x 25 mm were cut in half lengthwise and labelled to end-match. One half of the end matched boards were dried using current industry conventional methods and the other using a 2 m³ vacuum drying kiln. After drying the dried quality was assessed and compared between drying methods, by measuring average moisture content (MC), MC gradient, drying stress, distortion, collapse, surface and internal checking, and end split. The time to complete the vacuum drying trials ranged between 32% and 82% of conventional kiln drying from green, depending on the species. For each species the vacuum dried quality was as good, or better than, conventional drying. Analysis suggests that a vacuum drying time of at least 70% of conventional kiln drying is required for economic viability, due to the larger capital costs of vacuum dryers compared with their conventional counterparts. A simple and efficient method was designed to quantify the effect of reconditioning on collapse recovery using the image analysis software *MeshPore*.

Electrokinetic Drying of Wood

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ABSTRACT

Preliminary tests were performed to experiment electrokinetic drying of wood in the Department of Ecological and Environmental Sciences of the University of Helsinki, situated in Lahti. The tests were done with equipment normally used for soil testing.

Based on the preliminary tests, wood was dried electrokinetically in the woodworking laboratory of the Faculty of Technology of Lahti University of Applied Sciences, in order to determine various limit values. The objective was to investigate the possibilities to dry large solid-wood beams. The initiative came from companies.

The test series was conducted to study the drying of different wood species, the use of low pressure, different temperatures, and the effect of the initial moisture content on drying. Additional objectives were to study the effect of electrical current and voltage on the drying of wood, as well as possibilities to change the resistance of wood. The species that were tested were birch, spruce, pine and eucalyptus.

The test pieces were solid-wood beams measuring 100 mm x 100 mm x 1800 – 3600 mm.

The results were promising:

- Power used for drying was approximately 5 – 50 W.
- Drying times were 24 – 96 hours.
- Initial moisture content was 18 – 104 %.
- Average changes in moisture were 3 – 62 %.

Based on the tests, possible topics for further research would be to study the evenness of moisture distribution and to develop practical applications.

INTRODUCTION

HFV (High Frequency Vacuum) drying has been studied in the woodworking laboratory of Lahti University of Applied Sciences. With this method, wooden components can be dried fairly quickly. It takes about four hours to dry green timber to a moisture content of under 10 %. HFV drying also makes it possible to dry components that have large thicknesses and hardwood components containing the pith. When using high power densities, the length of the pieces to

be dried must be less than 1200 mm in order to achieve even final moisture.

There is a need to dry long pieces with large dimensions, so a decision was made to investigate whether it is possible to remove moisture from wood electrokinetically, making use of vacuum in the same way as in HFV drying. In HFV drying, radio waves are used to transfer the energy required for evaporation to the water inside the wood. In vacuum the water inside the wood evaporates very fast when the evaporation temperature is below 40°C. As the resulting vapour

expands, it pushes free water out of the wood, thus reducing the amount of energy needed for drying.

An idea emerged to conduct research on how water can be removed out of wood electrokinetically by means of electric current, making use of vacuum. An existing application of using electric current is in cleaning contaminated soils so that electric current is directed between two electrodes buried in the ground. Water transports the contaminating compounds to one of the electrodes, from where they can be removed.

Professor Martin Romantschuk from the University of Helsinki performed preliminary tests, and based on them it was possible to state that electrokinetic drying of wood is possible.

Preliminary tests were continued in the laboratory of the Faculty of Technology of Lahti University of Applied Sciences. What follows is an introduction to the drying method used in the preliminary tests, the results of the preliminary tests, and conclusions about the feasibility of the method, as well as about the need for further research.

OBJECTIVE

The objective was to examine whether the following hypothesis works:

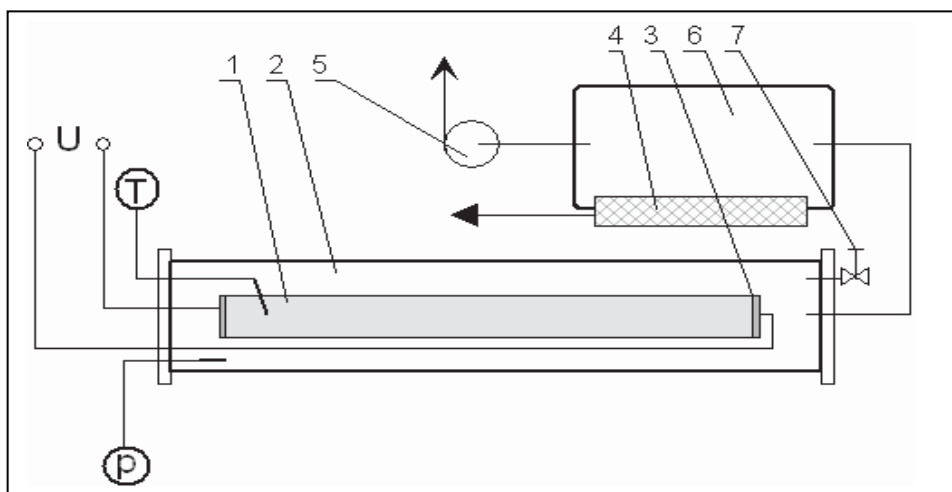
Electrokinetic drying of wood in vacuum is best when the temperature of the wood to be dried is above the temperature where water evaporates.

For example, if pressure is 0.05 bars, water evaporates approximately in 33 °C.

MATERIAL AND METHODS

Method of drying

Picture 1 illustrates how drying was done in a vacuum tube so that the tube was connected to the vacuum chamber and the drain system of the HFV dryer.



Picture 1. Diagram of the test arrangement

U = High voltage generator

T = Measurement of temperatures in the chamber and inside the wood

p = Measurement of vacuum

1. Wood to be dried 1800 mm x 100 mm x 100 mm

2. Drying chamber \varnothing 300 mm x 4000 mm

3. Electrodes at the ends of wood

4. Drainage of water

5. Vacuum pump

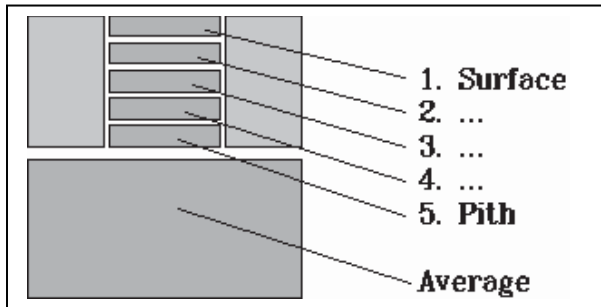
6. Vacuum tank, connected to the drying chamber (2) with a tube

7. Flow valve

Determination of moisture

The average initial moisture was calculated by measuring the initial and final weight of the wood and

mathematically calculating the average final moisture of the dried wood. The moisture of the dried wood was determined with the help of samples taken from ten different places, as shown in Picture 2.



Picture 2. Moisture samples from the dried wood were taken from ten (10) different places at equal intervals. Average moisture was determined from samples with approximate thickness of 10 mm. The moisture of the surface and the pith was determined from five samples of 60 mm approximate length, taken from relevant spots. Moistures were determined using the weighing-drying method.

Voltage and current

To generate voltage and current, the high voltage tester manufactured by Finero Oy was used.

The tester was programmed so that values for maximum voltage and maximum current were set. Current settled at the maximum value at the beginning of the drying test, and voltage started to increase as drying proceeded. When voltage reached the set maximum value, current started to decrease and approach zero (0 mA) as the resistance of the wood grew.

In test drying, two set values for voltage, 2 V/cm and 10 V/cm, were used, calculated from the length of the piece to be dried. The set value for electric current was 5 mA. Direct current was used in the preliminary tests.

Temperature

In the preliminary tests the drying chamber was located in a cold warehouse, so the test temperatures were low when additional heating was not used. Additional heating was provided by circulating warm water in a coil of flexible hose around the wood to be dried. Warm water circulated at the rate of 12.5 l/min. The temperature of incoming water was 52 °C and of outgoing water 48 °C.

Pressure in the test chamber

Vacuum was created in the test chamber, the strength of which varied between 0.10 – 0.05 bars in different

tests. Drying was also tested without vacuum in normal air pressure 1.00 bars.

Wood species

The species dried in the preliminary tests were birch, spruce, pine and eucalyptus.

Additives

When testing the effect of additives, the ends of the wood pieces were treated with various saline solutions, in order to improve electroconductivity.

The additives used were:

Aluminum sulphate $Al_2(SO_4)_3$

Sodium carbonate Na_2CO_3

Sodium hydrogen sulphate $NaHSO_4$

RESULTS

The hypothesis was that in wood water is transferred from the plus (+) electrode towards the minus (-) electrode. Based on the results of the preliminary tests, however, it can be concluded that water can be transferred in either direction, due to properties caused by impurities in the water inside the wood, and the effects of vacuum.

Removal of water without vacuum

The initial moisture of the wood to be dried was 104 % and the final moisture was 92 %. The temperature in the drying chamber ranged between 12 and 18 °C. In the test the voltage between the electrodes was established at 143 V from the initial value 111 V. The current was approximately 6 mA, so the voltage between the electrodes was about 0.8 W. The power remained low, because due to the electroconductivity and slow drying of green timber the voltage did not rise to the set value of 1800 V.

The drying time was 291 h, which is about 12 days.

Removal of water without electrical current

When drying with the equipment in Picture 1 without electrical current, using only vacuum, the tests gave the following drying results for birch.

The initial moisture of the wood to be dried was 68 % and average final moisture was 56 %. The temperature in the drying chamber ranged between 8 and 12 °C and the vacuum was -0.90 bars. The drying time was 48, which means 2 days. The moisture of the wood to be dried decreased 12 %.

In the second test the initial moisture of the wood to be dried was 80 % and average final moisture was 17 %.

The temperature that was measured inside the wood during the drying was 41 °C and the vacuum was -0.93 bars. The drying time was 96 h, which means 4 days. The moisture content of the wood to be dried decreased 63 %.

Effects of current and voltage on drying

When comparing the drying results with each other, using starting values of 5 mA/360V and 5 mA/1800 V, which correspond to nominal outputs of 1.8 W and 9 W between the electrodes, it can be concluded from the results that drying is a little faster at increased power.

Effect of temperature on drying

In low 10 – 15 °C temperatures free water escaped from the cells, but drying became slower as the moisture got below the saturation point.

When the temperature of the wood to be dried was 35 – 36 °C, drying was fast and the average moisture of the wood pieces to be dried decreased to 12 – 16 % moisture. The drying test was stopped when there was no more electric current between the electrodes or the drying time was up.

Effect of wood species on drying

Several drying tests were made with birch, because the HFV method had been used fairly extensively for drying it. Based on the preliminary tests it can be stated that pine, and to some extent also spruce, are easier to dry than birch. The differences are not great.

When drying eucalyptus, the average amount of water removed from the wood in one hour was 4.0 g/W, at approximately 13 °C temperatures. Correspondingly, when the temperature of the wood to be dried was about 37 °C, the average amount of water removed in one hour was 15 g/W. In both tests the drying time was about one day and the pressure in the drying chamber was 0.06 bars. In the test conditions the evaporation temperature for water was about 36 °C.

Length of wood to be dried

In preliminary tests a 3200 mm long test piece made of spruce was also dried from the initial moisture of 29 % to the average final moisture of 13.5 %, the drying time being 101 hours. During the drying process, the average amount of water removed in an hour was 54 g/W.

Respectively, 57 g/W of water on average was removed in an hour from an 1800 mm long test piece made of spruce. The test piece was dried from the initial moisture of 27 % to the average final moisture of 16.7 %, the drying time being 24 hours.

Effect of additives

When the ends of the wood pieces to be dried were treated with substances improving electroconductivity, it did not significantly improve the drying result. The reason is that as the ends of the pieces dried, the point where the electrodes were attached became non-conducting, i.e. similar to the ends that had not been treated.

DISCUSSION

Drying was relatively slow without the effect of vacuum. On the other hand, the power used in the tests was only 0.8 W and the drying temperature was low. The average amount of water removed in an hour was 0.004 g/W.

When drying with vacuum and without electrical current, if the interior temperature of the wood to be dried was 10 °C, the moisture content decreased 12 % in two days. Only free water was removed from the lumens.

Respectively, when drying in a higher temperature with the help of -0.93 bar vacuum and without electrical current, if the interior temperature of the wood was 41 °C, the moisture content decreased 63 % in four days. In this case the moisture content got below the saturation point of the wood grain. In this test drying was done using traditional vacuum drying. The test is not totally comparable with the parallel electrokinetic tests, because the temperature of the wood to be dried was approximately 5 °C higher and the drying time was 36 h longer.

When examining the effects of great or small electric power, it can be concluded that water is removed faster from the ends of pieces being dried with greater power, which results in slower electrokinetic drying as resistance increases.

Picture 3 shows the distribution of final moisture after drying according to the hypothesis. Similar distributions have been done for the results of all drying tests.

CONCLUSIONS

Electrokinetic drying is feasible, but the preliminary tests revealed a lot of open questions. More detailed research is required to answer those questions.

Vacuum drying first reduces moisture from the surface of the wood, which increases the risk of splitting. Electrokinetic drying removes water more

evenly also from inside the wood, which reduces splitting. It is possible to gain benefits by combining these two methods.

If one wanted to develop electrokinetic drying to suit industrial use, the attachment of electrodes should be improved so that the ends of the wood pieces remain electroconductive. In this way wood can be made to dry evenly along the whole length of the piece, as shown in Picture 4.

The method works on fairly low power, so relatively inexpensive high-voltage equipment can be shared by several drying units simultaneously. Also, several drying units can be connected to one vacuum pump.

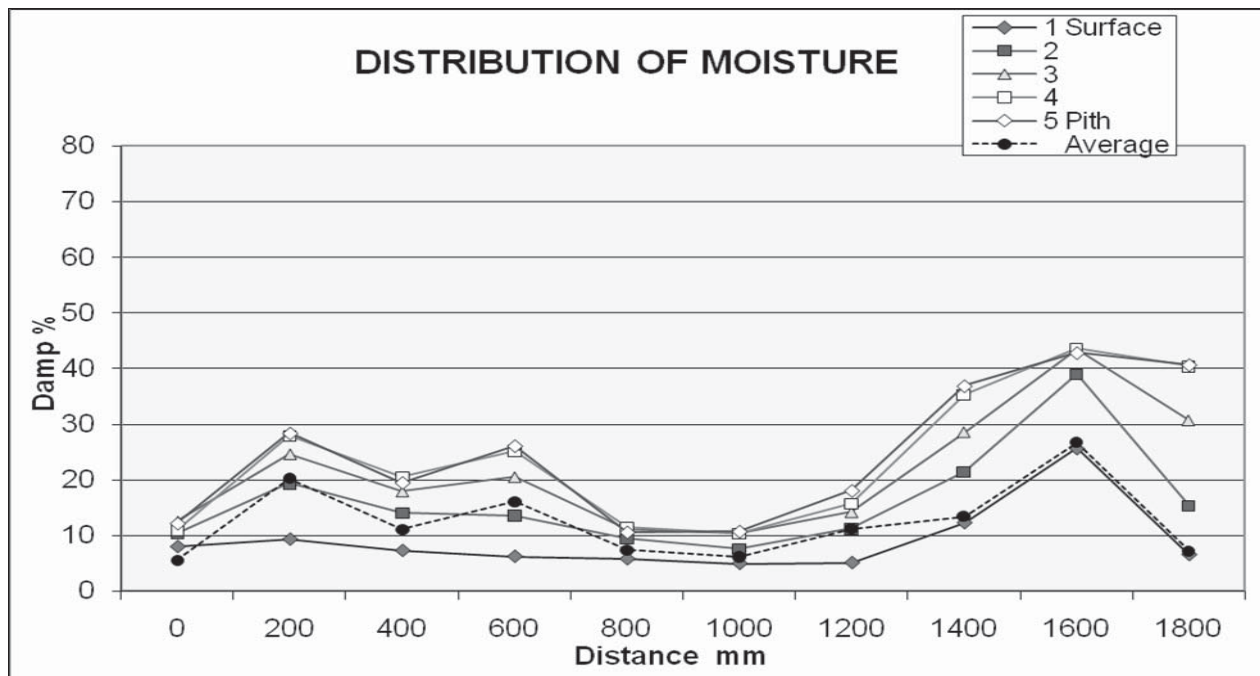
FURTHER ACTION

The attachment of electrodes is worth developing, so that the drying process does not need to be stopped when current reaches value 0 mA.

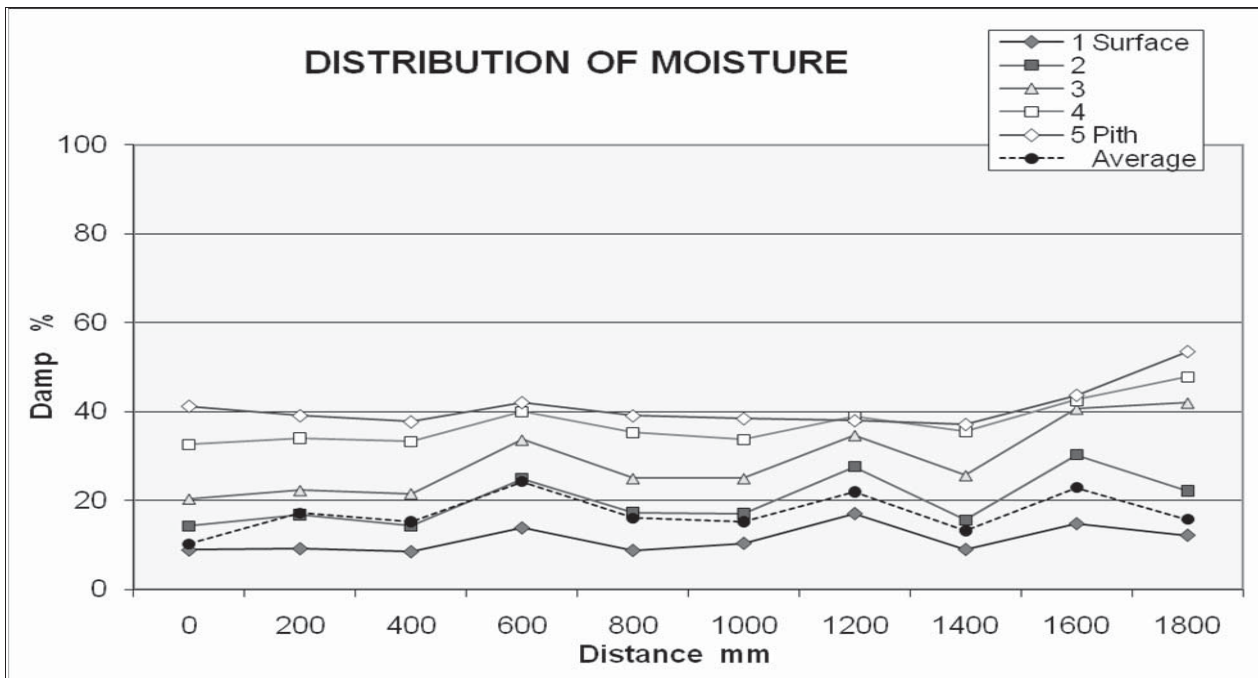
Good research topics would be to study the programming of electrokinetic drying and to examine at which stage electrical current should be used to get the best benefit from vacuum drying and electrokinetic drying.

A topic for further research is also to examine the drying of eucalyptus, which is a difficult species to dry. In these tests the pieces had too low initial moisture. Successful results here would have great significance.

Another interesting research subject is the drying of large-dimensioned logs and beams.



Picture 3. The final moistures of dried birch specified as shown in Picture 2. The dimensions of the test specimens were 1800 x 100 x 100 mm and initial moisture 74 %. The plus electrode (+) was at point 0 and the minus electrode (-) at point 1800. The test specimens were heated by circulating warm water in a coil of flexible hose surrounding the wood. The pressure in the drying chamber was 0.06 bars and the temperature of the wood was 35 °C, i.e. very close to the evaporating point (35.84 °C). Drying time was 60 hours. The diagram shows that moisture has transferred from the pith to the ends and there is a higher accumulation towards the minus electrode. The flow of electric current has continued until the end of the test, declining to value 0.3 mA. Voltage was set at 1800 V. Moisture differences between the surface and the pith are only about 20 %, which is less than the differences presented in Picture 4.



Picture 4. The final moistures of dried birch specified as shown in Picture 2. The dimensions of the test specimens were 1800 x 100 x 100 mm and initial moisture 80 %. Drying was done without electricity, using efficient vacuum drying. The test specimens were heated by circulating warm water in a coil of flexible hose surrounding the wood. The pressure in the drying chamber was 0.07 bars and the temperature of the wood was 41 °C, i.e. clearly above the evaporating point (38.51 °C). Drying time was 96 hours. The diagram shows that moisture has been removed from the wood relatively evenly. However moisture differences between the surface and the pith are about 30 %, i.e. the centre of the test specimen is relatively moist.

Redistribution of moisture in pre-dried pinewood using microwave power, a preliminary study

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ABSTRACT

Commonly, during air-circulation kiln drying moisture gradients within wood cross-sections are developed, i.e. the surfaces become drier than the interior. To minimize these gradients a conditioning step subsequent to the drying is needed. The aim with this study was to investigate the possibility to use microwave power for redistribution of moisture within pinewood planks after air-circulation kiln drying to the average moisture content 0,14. Two dimensions of pinewood were tested; thickness 50 and 63 mm, in two different plants, generating 5 and 12 kW microwave power respectively. Results show that microwave energy give rise to a fast and advantageous moisture redistribution i.e. equalization of moisture content within the wood. The higher microwave power density the faster heating and moisture equalization in these wood dimensions. Required time for heating and redistribution of moisture was found to be as short as 3 minutes at the power density 500 kW/m³. In addition, split-tests indicate decreased or almost no gap in the investigated specimens.

Introducing a new method of veneer drying

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ABSTRACT

In Finland 1.4 million m³ of plywood was produced in 2006. The share of export of production was 87 per cent. Plywood sheets are processed by gluing thin veneers into each other under mechanical pressure. The plywood manufacturing process consists of the following sub-processes: Soaking, peeling, drying, sorting, layup, gluing and hot pressing.

In existing manufacturing process drying is based on direct convective dryers. The existing convective dryers have several problems. Main problems are uneven moisture distribution and uncertain drying result, other quality problems in veneer, big energy consumption and problems in process control.

At Helsinki University of Technology a new kind of contact drying method for veneer has been developed. The drying system consists of the hot upper plate, cold bottom plate, vacuum inside the drying chamber and a mechanical press. The new method has been tested with experimental device that dries 48 * 48 cm veneers. Effect of the drying method on the drying time and final moisture content and moisture distribution of the veneer have been studied both theoretically and experimentally. In veneer drying the moisture variation in wet veneer is large and the target moisture level after drying is very low. Because of the technology used in the convective dryers the drying conditions have to be set to artificially low level in order to insure sufficiently low moisture average. The final moisture distribution is uneven both between individual veneers and also within a veneer sheet. Too high moisture content creates problems in later stages of plywood manufacturing process. As a result, a large proportion of the veneers are over dried, which has an adverse effect on the veneer quality.

The goal of this paper is to introduce the new method and discuss its potential in improving veneer drying as a whole. The drying results, such as final moisture content, moisture distribution and drying times are discussed. The results will be compared to a conventional convective drying.

SESSION 6

WOOD MODIFICATION RELATED TO DRYING

Drying of Wood in Oil Under Vacuum

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ABSTRACT

Use of oils as water repellent impregnation agents has industrial potential and is an environmentally friendly alternative to the traditionally employed chemical wood protection. This study deals with drying of wood in oil under vacuum, i.e. the initial and inevitable technological step prior to impregnation.

Plant oils have significantly higher thermal conductivity than air, thus conducting the heat more effectively to the surface and into wood. The objective of this study was to investigate the suitability of oil drying under vacuum for various wood species using a cheap and available plant oil.

Boards of Scots pine, Norway spruce and oak wood with thickness within 25-30 mm and high initial moisture content were dried in rapeseed oil at temperature of 80°C and permanently applied vacuum (60%). Final moisture content, internal stress, modulus of elasticity (MOE), oil uptake and penetration depth were measured for the studied wood species. Scots pine and spruce boards were dried to less than 20% moisture content with negligible degradation (checks and stress) for 6 h. For identical duration of drying, the oak samples were more degraded and dried to only 30-40% moisture content. MOE of the oil dried samples was measured by a dynamic and static method and compared to air dried control samples. Oil drying had no negative effect on the MOE. The uptake of oil was 36, 25 and 26 kg/m³ and penetration depth was measured to be 2.2, 0.7 and 1.7 mm for Scots pine, spruce and oak respectively. The initial tests showed that drying in oil is a promising process for softwood timber providing short drying time and insignificant degradation. Drying of oak is possible but the temperature and duration of drying must be adjusted to ensure better results. The method facilitates further impregnation of wood with modified oils.

INTRODUCTION

Wood drying is a complex and time extensive process. Beside the oldest, natural and technically easiest way of air drying, several other processes have been developed during the years. Methods like high frequency, high temperature and common kiln drying are much faster and therefore a first choice to provide a steady and fast wood supply for the market. Kiln drying is the most established and economical way to dry wood at present time. It is faster than air drying, but can still take weeks or months depending on the wood species since the schedule has to provide a good quality and avoid undesirable degradation.

A drawback and consequently a trigger for problems is the efficient conduction of heat into wood. Wood's heterogeneity and specific structure cause serious difficulties and, thus wood is a poor conductor of heat. Commonly the heating process is achieved with heated water steam. Other possibilities to heat up wood are rare at present time. An alternative method to achieve the fast and efficient heat conduction to wood is the immersion in oily liquids. The main idea is that these oils should have a higher boiling point than water and need to be water-insoluble. Oils have a significantly higher thermal conductivity than humid air, thus conducting energy more efficiently into the wood.

With this approach in mind researchers have carried out investigations to develop oil drying processes under vacuum. The first report on oil drying of wood was published by FPL (McMillen 1947). In the suggested process, oil was heated up considerable above the boiling point of water. The vaporising water formed a protective layer of water steam bubbles around the wood surface as was patented and reported in details by Fies and Johnston (1965). As water vaporised, heat was absorbed and the temperature was kept around the boiling point of water. This protected the wood from harsh drying and degradation by high temperature. The evaporating water limited the oil uptake in wood and maintained certain moisture content on the surface. When the free water was removed, the protective layer became very thin and the wood was exposed to high temperature of the oil. Uneven temperature and pressure distribution during the process caused varying wood moisture content through the charge. The process involved circulation of the oil to provide an even temperature distribution (120-150 °C). During the recovery stage of the oil, the vessel was filled with superheated steam at a temperature and relative humidity that provided an even equilibrium moisture content of the wood. Vacuum was recommended during the whole process (about 0.5 bar or deeper) to get an acceptable oil recovery rate and limit the oil uptake.

The average wood moisture content were reported in the range 2-7% by maintaining vacuum at 116°C and a final oil uptake from 0.5% (on weight basis) after the oil recovery stage. An arrangement of vessels, pumps, valves and pipelines in two drawings of the pilot plants for veneer and lumber drying are presented in the patent.

Bror Olaf Hager (1971) integrated a similar process after impregnation of wood (full-cell process) to remove the water (so-called Royal Process). Hager mentioned several possible combinations of chemicals and agents that could be included in the boiling-in-oil drying process to get a quick and efficient treatment of wood. Hager suggested high-temperature boiling liquids like non-drying and drying oils or mixtures of those. According to the author, almost any commercially used oil like paraffin oil (non-drying), linseed oil (drying-oil) or melted wax could be used. McDonald (1958) mentioned petroleum oil and creosote to be considering for the process.

The FPL report (McMillen 1947) showed some interesting examples of possible problems during the boiling-in-oil process. The protective layer, consisting of superheated steam, protected the wood from overheating, but on the other hand it was also shown that this layer became very thin at the end of the process

when the oil was still heated about 100°C. The presence of this layer was also questionable when the diffusion rate was disturbed by some wood anomalies, e.g. knots. In that case, the wood would be exposed to severe drying condition and is susceptible to checking, honeycombing and discolouration. The FPL report also included some cases of severe casehardening and stresses that could cause warping. These were just possible problems that could occur in the worst drying case. Further tests mentioned in the report, have shown that only a few samples were severely degraded by the process. The problem of uneven temperature distribution was eliminated to a great extent by circulation of the oil (Fies and Johnston 1965). The moisture content was reduced from 77 to 22% in 16 h. The high oil uptake could be greatly reduced by a following recovery stage with vacuum and steam leading to retentions of about 0.3%. Lasting problems were the control of the wood final moisture content. No stress measurements or results regarding the mechanical properties of wood after the oil drying process were mentioned.

Drying in oil under vacuum is a promising way to dry wood but due to lack of experience, missing realistic test-plants and limited interest of the industry the development of the method slowed down and hindered further research. The objective of this study was to investigate the suitability of this method for various wood species using cheap and available plant oil, e.g. rapeseed oil. This investigation was further encouraged by the general stagnating progress in the field of new, more effective and faster techniques for wood drying.

MATERIALS AND METHODS

Material

Wood species studied were Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* L. Karst) and oak (*Quercus rubra* L.). The wood material was purchased directly from sawmills as fresh as possible. The logs were through-and-through sawn to boards with dimensions of 25×125 mm for spruce and pine and 29×130 mm for oak. All samples were stored in a freezer (-20°C) immediately after purchasing, cutting and initial measurements to avoid moisture loss. Polyurethane was used to end-coat the samples to prevent evaporation of water from the ends. After end-coating the samples were stored in a fridge to harden the polyurethane for 24 h. The initial moisture content (MC) for pine 80-145%, for spruce 30-40% and for oak 75-80%. The MC was determined by oven-drying and calculated on wood dry basis (DIN 52183). Control samples were cut from each board and air dried in room climate (20°C/65% RH) for 4 weeks. Wood density at

12 % MC was measured according to DIN 52 182 and shown in Table 1.

Rapeseed oil was purchased and used for the tests. Properties like density (892 kg/m³) and boiling point (≈200°C) were determined experimentally. Linseed oil was also tested for this process but later excluded.

The test runs were performed in a small test plant at the Swedish University of Agriculture and Science, Department of Forest Products (App. 1). The arrangement consisted of two cylinders, equipped with heating coils, connected through numerous pipes and valves. Two condensers collected the evaporated water. The whole system was attached to a vacuum pump. The temperature during the drying process was measured by a data logger using four thermo couples. Two couples were placed in drilled openings in one wood sample; one approximately 1 mm underneath the surface; the other one in the wood core. The remaining two cables were placed in each cylinder. During the drying process the temperature and time were recorded for later analyses and calculations. (App. 2).

Process and procedure

The setup for a drying procedure consisted of 4 frozen wood samples that were placed in a cache of mesh wire in the lower cylinder. The cache was placed on two glass sticks to facilitate the later oil recovery and minimize direct contact to the inner cylinder wall. After the lid was screwed and the oil (2800 ml) was poured in the upper cylinder the process started. Heating coils for both cylinders were switched on simultaneously. The oil was heated up to approximately 80°C. When the temperature in the wood core had reached 20°C the oil was drained to the lower cylinder to heat up the wood and initiate the drying process. Vacuum (60%) was applied directly after the lower cylinder was properly filled with oil. The heating was switched on and off manually to maintain an average temperature of about 80°C in the lower cylinder containing the wood samples. Heating for the upper cylinder was switched on when it was necessary to evaporate the condensed water and keep the system warm. The vacuum pump worked only to maintain the negative pressure and was switched on and off manually. Reliable indicators for the vacuum level were the intensity of the air bubbles coming out from the wood samples and the vacuum measuring gauge attached to the upper cylinder. After 4

h for spruce, 6 h for pine and 8 h for oak the oil was drained back to the oil store and a final vacuum was applied for 15 min to recover some oil from the samples. The dried samples were placed in seal plastic bags to cool them down to 30-40°C and weighted. Two samples from each drying charge were cross-cut into smaller samples to determine the final MC, penetration depth of the oil and for prong test samples. The other two samples were used for mechanical testing. A magnification glass and a digital caliper were used to measure penetration depth of oil on the sanded crosscut surfaces of the samples. Final oil uptake was calculated by the difference between the amount oil used and amount of recovered oil, corrected by 10 ml (amount of oil remaining in the cylinder and pipes) and then calculated per m³. Internal stress was visualized by prong test samples (Fig. 1). The method was used to compare the stress after drying process among all test runs and wood species. The samples for the test were cut immediately after the cooling stage from 2 of the 4 samples. When the initial gap was measured the samples were stored for 24 h in a sealed plastic bag. Decisive for the stress (D_{24}) calculation is equation 1.

$$D_{24} = \frac{h - h_{24}}{2 * L} * 100\% \tag{1}$$

h - prong gap direct after the cutting, mm
 h₂₄ - 24h later, mm
 L - length of one prong, mm

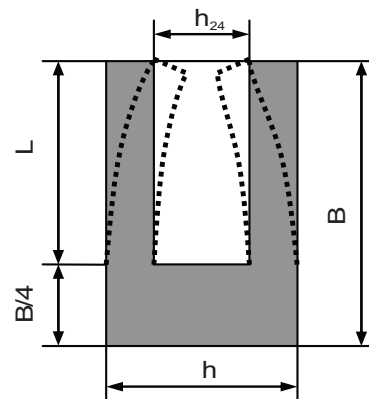


FIGURE. 1. Prong test sample

TABLE 1. Density at 12% MC (mean values)

Wood species	Number of samples	Size (mm)			Volume (cm ³)	Weight (g)	ρ ₁₂ (kg/m ³)
		H	W	L			
Pine	22	14.4	19.9	77.5	22.2	13.7	618.1
Spruce	22	9.9	29.2	70.4	20.4	9.6	472.0
Oak	30	8.5	24.4	50.7	10.4	7.6	732.6

Mechanical tests

Mechanical tests were performed with a dynamic and a static method to determine the module of elasticity (MOE). The dynamic MOE (MOE_{dyn}) was calculated by the frequency measured with the acoustical device Signal Analyzer (SA-77) and the density of the samples (Equations 2 and 3). The static MOE (MOE_{stat}) was measured with a mechanical tester (Alwetron TCT 50). All samples for mechanical tests were conditioned in a climate chamber for two weeks before testing. The tests were carried out according to standard DIN 52186.

For investigation of oil penetration oil dried samples of pine and spruce were sectioned by microtome for microscopy. The sections were taken transversally and had thickness of 20 μm ; the sections were stained with 0.1% aniline blue in 50% lactic acid.

$$S = \frac{l}{1000} * f \quad (2)$$

S - speed of sound, m/s
L - length of sample, mm
F - frequency, Hz

$$MOE_{dyn} = \frac{S^2 * \rho_{12}}{10^6} \quad (3)$$

ρ_{12} density at 12% MC, kg/m^3

RESULTS

Pine

The average final MC after 6 h drying was 17%. Due to high initial moisture contents the water evaporation was a steady and intensive throughout the process. The average oil uptake was 36.1 kg/m^3 (Table 2). The penetration depth (Pd) varied depending on the direction of the grain. The average value of 2.2 mm was measured on the transverse sections. The deformations determined by prong test samples showed moderate stress of 6.8% (Table 3). No prong gap was completely closed due to tensions after 24 h.

Only two among the twenty pine samples were degraded by twisting and checking during the rapid drying process. The wood surface colour became slightly darker because of the oil uptake.

TABLE 2. Drying results (Scots pine)

Test no.	Initial MC (%)	Final MC (%)	OU* (kg/m^3)	Pd* (mm)
1	95.9	11.2	41.1	1.1
2	145.1	16.2	46.5	1.8
3	80.8	12.5	38.3	2.3
4	82.0	19.7	16.4	3.6
5	98.4	25.6	38.3	2.3

*OU - oil uptake; Pd - Penetration depth

TABLE 3. Prong test results (Scots pine)

Sample no.	h* (mm)	h ₂₄ * (mm)	L* (mm)	D ₂₄ * (%)
1	26.3	19.4	38.1	9.1
2	25.1	18.5	36.4	9.1
3	28.5	23.8	40.7	5.7
4	27.3	22.9	37.3	5.9
5	27.4	21.7	39.2	7.3
23	26.2	22.0	39.2	5.3
24	29.1	23.4	40.0	7.1
25	28.2	23.6	40.3	5.7
26	27.3	21.8	39.6	6.9
27	27.0	22.5	38.3	5.9
28	28.3	23.2	39.7	6.4
Mean value				6.8

*h- initial gap; h₂₄- gap after 24h; L- length of one prong; D₂₄- Deformation

Spruce

The spruce samples were oil dried from the initial to the final MC of 14 % in 4 h. (Table 4). The penetration depth of oil was 0.7 mm. Some samples showed no oil penetration. The average oil uptake was 25.0 kg/m^3 . Oil on the surface dried very fast similarly to pine. Prong test showed similar deformations as after Scots pine drying (Table 5). Only one sample out of 12 had small checks.

TABLE 5. Prong test results (Norway spruce)

Test no.	Initial MC (%)	Final MC (%)	OU* (kg/m^3)	Pd* (mm)
1	39.8	14.3	17.3	0.8
2	29.5	13.0	37.6	0.7
3	29.4	14.7	20.2	0.5

*OU- oil-uptake; Pd- Penetration depth

TABLE 4. Drying results (Norway spruce)

Sample no.	h* (mm)	h ₂₄ * (mm)	L* (mm)	D ₂₄ * (%)
1	21.42	15.30	35.47	8.6
2	20.38	15.25	35.43	7.2
3	20.35	16.40	35.92	5.5
4	21.12	15.00	35.21	8.7
5	21.42	15.30	35.47	8.6
17	22.06	17.12	38.40	6.4
18	21.46	17.63	37.17	5.2
19	23.08	18.55	36.18	6.3
20	21.50	16.03	34.96	7.8
22	21.06	16.57	35.75	6.3
21	20.44	15.52	38.01	6.5
Mean value				6.7

*h- initial gap; h₂₄- gap after 24h; L- length of one prong; D₂₄- Deformation

Oak

Oak samples were dried from the initial to the final MC of 35% in 8 h. The average oil uptake was 26.8 kg/m³. The average penetration depth was 1.7 mm (Table 6) but significantly deeper along the rays. Prong test samples indicated an average deformation of 8.7% (Table 7). The whole process with oak samples was less intensive regarding the air bubbles and condensing water. Three samples were severely degraded by cracks along the grain and around knots. Small checks occurred in all samples. After cutting the samples it was visible that the wood core was almost not dried; only the outermost 5 mm were dried properly. The samples for the mechanical testing had also small checks.

TABLE 6. Drying results (oak)

Test no.	Initial MC (%)	Final MC (%)	OU* (kg/m ³)	Pd* (mm)
1	80.5	30.8	33.7	1.4
2	75.2	33.2	20.7	2.0
3	78.7	40.9	25.9	1.8

*OU- oil-uptake; Pd- Penetration depth

TABLE 7. Prong test results (oak)

Sample no.	h* (mm)	h ₂₄ * (mm)	L* (mm)	D ₂₄ * (%)
1	24.66	18.72	36.91	8.0
2	25.19	17.33	37.26	10.5
3	24.66	18.02	36.36	9.1
4	26.24	18.04	37.11	11.0
5	24.55	18.14	36.57	8.8
22	25.49	17.56	36.87	10.8

23	25.63	16.85	38.89	11.3
24	25.44	19.47	38.22	7.8
25	25.98	19.75	37.78	8.2
26	26.41	18.12	38.21	10.8
27	25.49	17.56	36.87	10.8
Mean value				8.7

*h- initial gap; h₂₄- gap after 24h; L- length of one prong; D₂₄- Deformation

Mechanical tests

The MOE_{dyn} showed always a higher value than the MOE_{stat} for the same sample; especially for pine a correlation between these values was found (Fig. 2). Furthermore, the correlation between the density and the MOE_{dyn} and MOE_{stat} was significant for Scots pine wood (Fig. 3). No correlation was found for spruce and oak. The determined average MOE_{stat} were lower compared to the literary values despite of the higher density (Table 8).

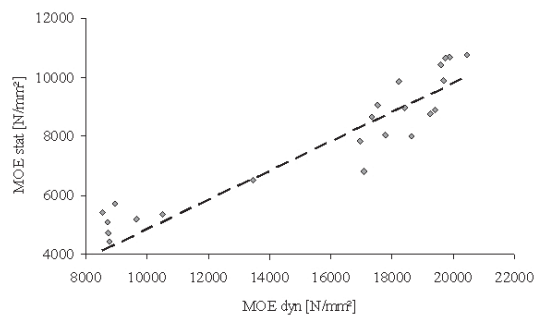


FIGURE 2. Correlation between MOE_{stat} and MOE_{dyn} (Scots pine)

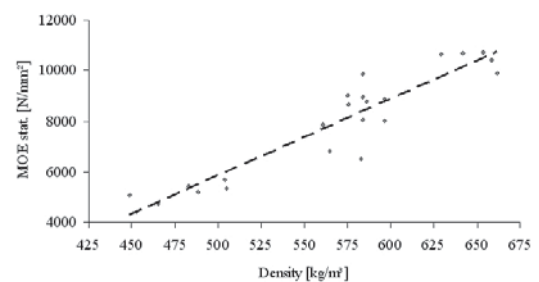


FIGURE 3. Correlation between density (at 12% MC) and MOE_{stat} (Scots pine)

Comparison between the mechanical properties of the air and oil dried samples (from the same board) was carried out by dividing the MOE of the latter samples with the MOE of the control samples and expressed in percent. The results showed four distinct groups due to strength loss. The group “< 0%” means that the MOE of the oil dried sample was higher compared with the control sample (Fig. 4).

TABLE 8. Measured mean density, MOE_{dyn} and MOE_{stat} compared to literary values

Wood species	ρ_{12} (g/cm ³)	MOE _{dyn} (N/mm ²)	MOE _{stat} (N/mm ²)	Literature ρ_{12} (g/cm ³)	values* MOE _{stat} (N/mm ²)
Pine	0.62	15317	7812	0.49	12000
Spruce	0.47	10775	6645	0.43	11000
Oak	0.73	11654	7510	0.66	12500

*Lohmann (1998)

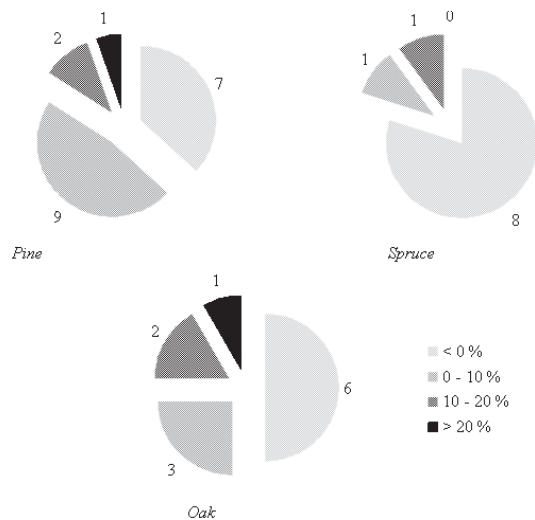


FIGURE 4. Number of samples with certain strength losses after the oil drying compared with the control samples

DISCUSSION

Pine and spruce

The higher oil uptake in the Scots pine samples compared to Norway spruce samples was predictable. It is well known fact that spruce is significantly less permeable for liquids than pine due to less and smaller bordered pits in the structure but also less pores in the ray tracheids. The target final MC (20%) was reached for both wood species with only one exception in pine test run 5. The reason for this exception could not be explained and reflexes the heterogeneity of wood even when small samples are used. Severe degradation did not occur for spruce or pine samples. Stress (prong-test) was in an acceptable range indicating only little external and internal casehardening during the fast drying process. Two weeks after the experiment some of the pine samples showed small radial cracks. This late occurrence of cracks could be explained by a further drying in obvious to dry room conditions (MC≈8%).

Thus, it should not be interpreted as a consequence of the oil drying procedure. The control samples, air dried under standard conditions (20°C/65% RH) showed small checks on the ends and small deformation in the prong test (0.6% for spruce).

Oak

Oak was the only hardwood tested during this investigation. The results achieved were not satisfying. Even with the time extension to 8 h the samples were not dried to 20% and showed partly severe degradation by superficial and internal checking. This checks occurred mainly in radial direction along the numerous rays. The interior layers were only partly dried while the exterior layers were dried down to 10% MC. This uneven drying of oak can be explained as follows. Oak is one of the wood species with high density in Europe. The diverse and inhomogeneous cell structure, tyloses makes it difficult to evacuate the water from the structure. Ring porous wood species like oak have an extraordinary high difference in density between the annual rings, whereas the late wood rings are the denser zones. The density contrast can reach a ratio from 1 to 2.21. Consequently the major part of the evaporating water during the drying process has to pass through early wood rings, namely the vessels, in longitudinal direction. In radial and tangential directions the water can pass through the rays. Due to high density the wood cell walls are less permeable. Under moderate air drying conditions with normal atmospheric pressure and low temperatures the waters vapour pressure is gradual and much less than it is during the oil drying process under vacuum. Thus, the water can evaporate smoothly through the rays and vessels. Due to a steeper pressure and moisture gradient, drying in oil process forces water to evaporate faster than during air drying. Furthermore, the ends of the short samples were sealed with polyurethane what prevented the water to evaporate in longitudinal direction. The remaining possibilities for the water to evaporate were obviously not enough to provide a fast water removal as demanded by the surrounding conditions. These reasons lead to steep moisture gradients and consequently uneven shrinkage

between the core and outer layers and finally cracks. Nevertheless, four samples were nearly free of cracks and the MC was halved in 8 h. The stress indicated by the prong test was moderate and only slightly higher than for spruce and pine. The explanation could be that the drying process in the oak samples was not finished when the samples were cut and measured and therefore the tension were not grown to full extend. The relatively high final MC prevented also a higher oil uptake because of the evaporating water and water remaining in the cell lumen.

Drying oil

The same rapeseed oil was used for several test runs and only exchanged completely one time. No significant changes in the oil properties were noticed. Only the oil colour was darker after a few runs probably discoloured by the extractives removed from the wood. This had no influence on the process. The oil odour after drying was hardly detectable. Rapeseed oil is more suitable compared to linseed oil. One drying test was started with linseed oil but aborted after a few minutes. Immediately after the vacuum was applied a thick bubble layer occurred on the surface of the oil resulting in oil leaking out in the pipes, filling the separator and making the further process impossible. The reason for this phenomenon was not investigated further.

Mechanical test

The implementation of the standard (DIN 52186) was not completely possible because of limitation in sample length due to the test plant size. The samples used for mechanical testing were not free of defects, e.g. knots and fibre angle was not exact for most samples as suggested in the standard (DIN 52186). This also explains the deviation of the measured MOE compared to the literally values.

Significant correlations ($r^2 > 0.9$) were found between MOE_{stat} , MOE_{dyn} but also wood density (Figures 2 and 3). The determined modulus of elasticity was insignificantly lower for the oil dried samples compared with the air dried samples. This indicates that the oil drying process at approximately 80°C has no negative effect on the mechanical properties of wood. Furthermore, some oil dried samples had higher values especially for spruce and oak but it is debatable to assume the process had a positive effect on the mechanical properties. The variation between the MOE was probably additional affected by the numerous knots in the pine and spruce samples. It was found the acoustical method is significantly affected by knots and resin pockets because the sound waves are deflected by

these anomalies, thus delivering inaccurate results compared to the 3-point-bending method.

CONCLUSIONS

Drying in oil under vacuum is a fast method to dry wood to moisture content below 20% as shown in this investigation. The additional final permanent vacuum is beneficial to shorten the time and lower the temperature to evaporate the water from the wood and to evacuate the vapour from the chamber. The results show that the settings and process schedule used for this investigation are suitable for softwoods like pine and spruce. For denser wood species like oak the process needs to be modified to get reasonable results. One suggestion to achieve this could be to perform the oil drying process in intervals of oil heating and conditioning stages at lower temperatures to get a slower drying progress and equalize the moisture gradients in the wood.

The superficial oil residue was beneficial for the further processing with the wood working machines according to the reduced friction and caused no further problems. Additional it should be investigated for which wood products this oil uptake could be beneficial. The enclosed oil has much in common with a superficial wood impregnation or painting. Using a drying agent with fungicide properties the impregnation and drying of wood could be combined in one process, where the oil uptake could be increased by a pressure stages. In this case the further processing should exclude any planing or routing. Markets for this kind of wood products could be for instance panels for building facades.

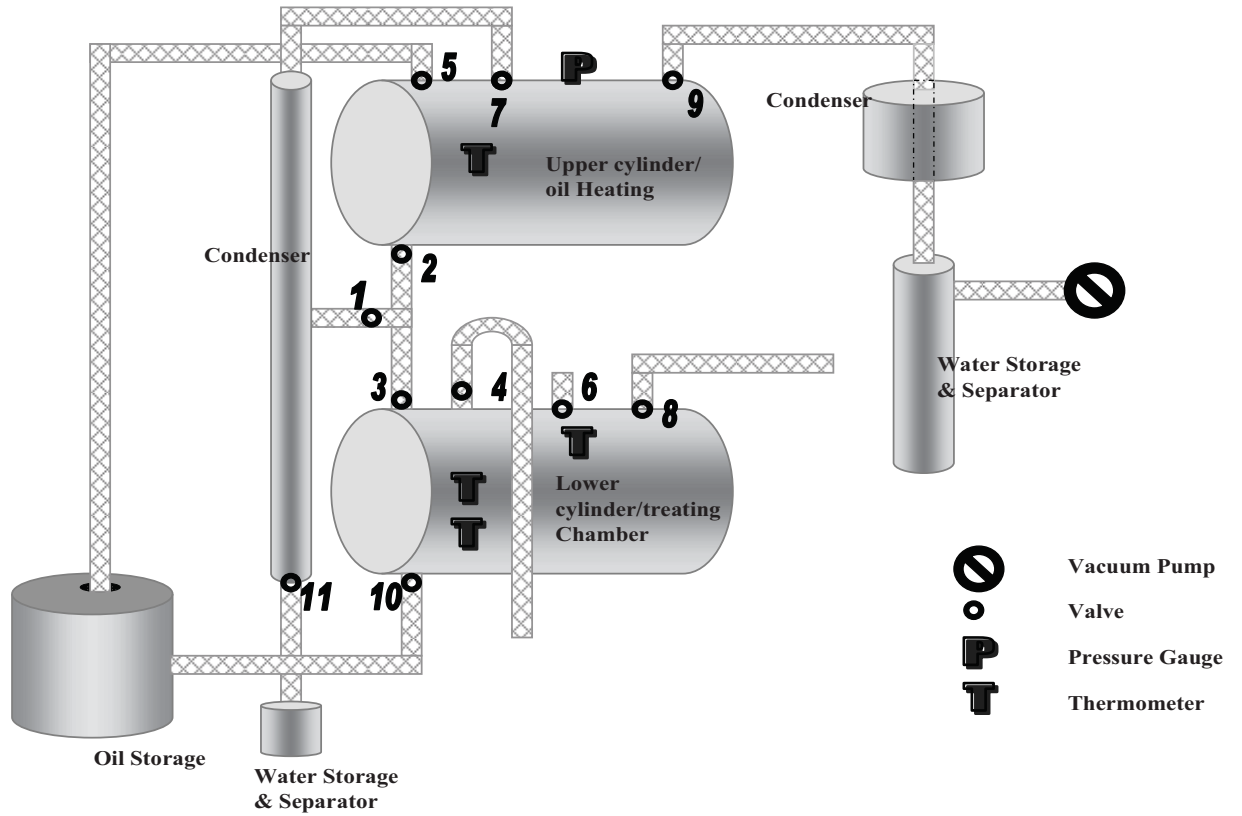
Drying of wood by immersion in oil has limitations regarding the suitable dimensions of the timber. It is to expect that large size timber, e.g. beams, will be severely degraded when dried with this process due to steep moisture gradients and following checking during the fast drying progress even for softwoods. Furthermore, the enclosed oil causes some lasting odour and occasionally leaching from the wood, depending on the oil type, which excludes an indoor use of these products.

From the economical point of view the drying in oil process can barely compete with the better established methods, e.g. kiln drying. This drawback can be offset depending on the specific process and for what kind of products this method is used for instance by the reduction in drying time. No cost calculations are available at this time. The potential of this process for future utilisation is not to deny and should undergo further investigations to find a technical and economical suitable field of application.

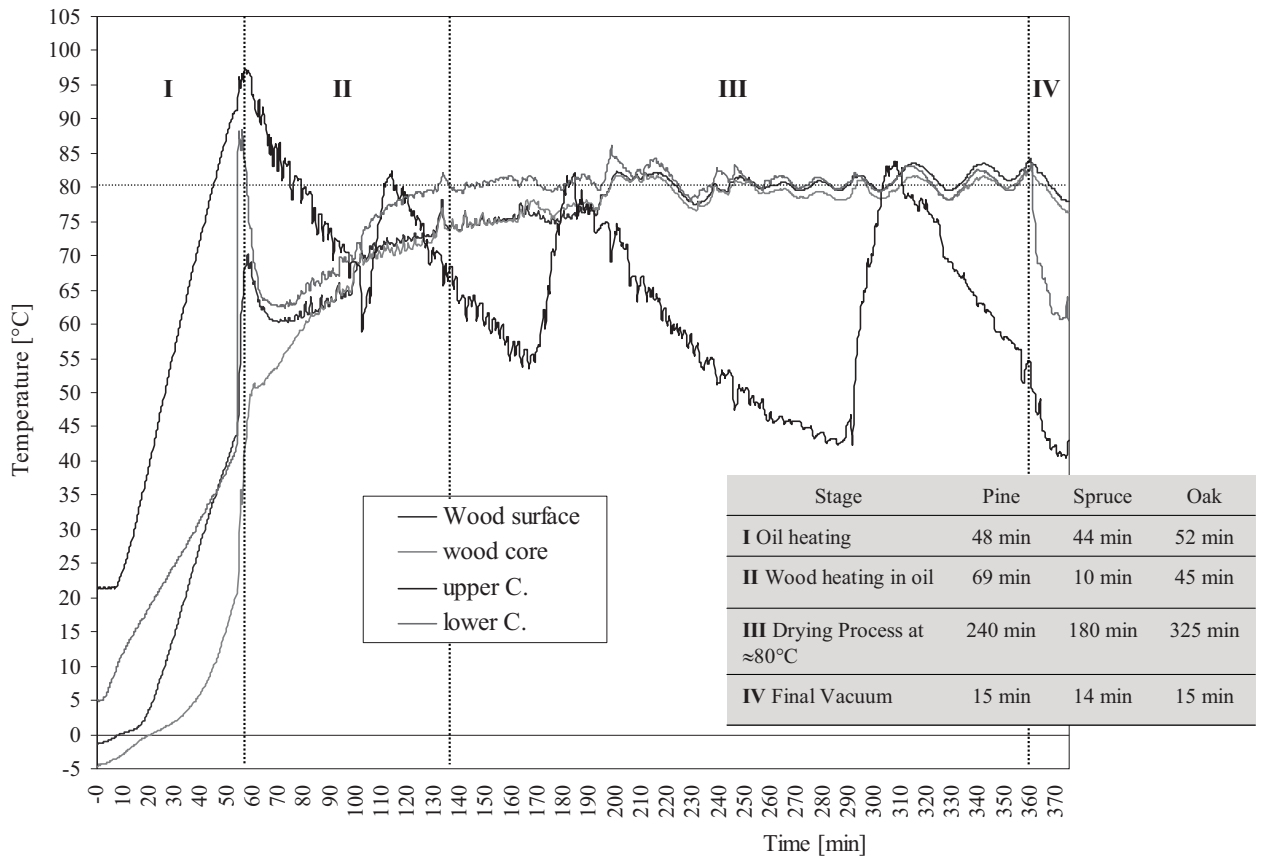
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APPENDIX 1 Arrangement scheme of the test plant



APPENDIX 2. Temperature-time course during the drying procedure divided in stages with the average time for each wood species .



Investigation of chemical changes in the structure of wood thermally modified

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ABSTRACT

Thermal modification beneficially alters several technological parameters of wood. The changes in the physical parameters are due to the significant alterations of the structure and the chemical composition of wood, which take place during the modification process. These changes are complex and some aspects/processes are still far from being completely understood. What is known, is that by increasing the temperature the nature of reactions taking place changes. Still it is unknown the exact point where the individual reactions become dominant. Various industrially important hardwood and softwood have been treated in autoclave in N₂ atmosphere and with Vacuum Press Drying. The physical (density, L-value, moisture content, bending strength, MOE) and chemical (pH, hemicellulose-, totalphenol-, soluble carbohydrate-, and volatile organic compound content) parameters have been measured and evaluated. Correlations between physical and chemical parameters have been established and discussed.

INTRODUCTION

Thermal modification beneficially changes the dimensional stability, hygroscopicity and biological durability of wood (Boonstra et al. 2007). The modification treatment is always performed between the temperatures of 180 °C and 240 °C. Increasing temperatures result in the transformation of solid into volatile compounds (degradation of extractives, production and transformation of radicals originating from lignin) (Burmester 1975, Hakkou et al. 2005). Between ranges of 100 °C to 250/280 °C a mild pyrolysis generally takes place. Above 300 °C the rapid degradation of cellulose (Pfriem 2006) also contributes to the formation of the degradation products.

Various wood species with distinct chemical compositions also behave differently during the thermal modification process (Zaman et al. 2000, Militz 2002) and it is sometimes hard to interpret or interconnect physical changes with exact chemical transformations.

Chosen physical (density, L-value, moisture content, bending strength, MOE) and chemical (pH, hemicellulose-, totalphenol-, soluble carbohydrate-, and volatile organic compound content) properties have been measured in samples of industrially significant wood species that have been thermally modified in autoclave in N₂ atmosphere. The modification process has been carried out in two steps as described by Giebler (1981) (Step 0: untreated; Step 2, Step3: increasing treatment).

Through investigating linear correlations, relationships between chemical parameters (wood structure) and physical/technological features have been established and discussed.

MATERIAL AND METHODS

Material und Treatment

Wood samples (beech, spruce, pine and Douglas fir) were treated thermally in an autoclave in N₂ gas according to the method described by Giebler (1981). Intensity of the modification increases with the number of steps. The two steps of the modification process differ in terms of pressure, residual oxygen content, temperature and duration. The reference samples were not modified (Step 0). After closing the autoclave, the vacuum is generated, which is followed by the establishment of an overpressured atmosphere using N₂ gas. The initial moisture content of the wood is between 8-10 %. The mixture of nitrogen, residual oxygen and steam, which is produced during the treatment, remains in the autoclave during the whole process. Untreated wood (Step 0) and wood samples treated in two steps (Step 2 and Step 3) have been investigated. The physical/mechanical properties were measured

approximately 6 months after production, and the chemical parameters after 12 months. Tab. 1 summarizes the samples investigated.

Measurement of Physical Properties

All the properties investigated have been measured under normal conditions, at 20°C/65% relative humidity using wood probes with the dimensions 400 x 20 x 20 mm. Density has been measured according to DIN 52182, the moisture content according to DIN 52183 and has been indicated in g/cm³ and in percentage units respectively. Bending strength and modulus of elasticity (MOE) were measured according to DIN 52186 and given in N/mm² units. The lightness parameter perpendicular to the wood fibre (L-value) was evaluated according to colour measurement using Minolta Chroma-Meter CR 200 device.

Tab. 1: The wood samples investigated and their nominations

Species	Symbol	Treatment steps
Hardwoods		
Beech I	Bu	0, 2, 3
Beech II	Bu	0, 2, 3
Softwoods		
Douglas fir	Dk	0, 2, 3
Pine	Fk	0, 2, 3
Spruce	Fi	0, 2, 3

Approximately 200 g of each of the wood samples were ground and sieved. The fraction with particle sizes between 0.2-0.63 mm was used in all the measurements.

Dry mass content determination

3 g of each of the wood samples was heated at 105°C until constant weight. The dry mass content was calculated and used in the evaluation of the results.

pH

The pH of the wood samples was determined using the method of Roffael and Kossatz (1981).

Ethanol-Toluene soluble extract content

The Ethanol-Toluene soluble Extract content was measured according to the Tappi-standards T 264 cm-97 and T 204 cm-97. The extractive content relates to dry weight (dw.) and has been indicated in percent.

Total phenol determination

0.025 g of wood sample was extracted over 6 consecutive steps with 80% methanol using an ultrasonic bath with a temperature of 25°C. Extraction was carried out by applying 8 ml of extraction solvent for 30 minutes during each step. The extracts were collected into a flask and made up to a final volume of 50.0 cm³. The total phenol content was determined with spectrophotometry according to the method of Folin-Ciocalteu (Singleton and Rossi 1965) using quercetin as standard. The results have been given in mmol quercetin/100g dry wood. The measurements were carried out in triplicate.

Soluble Carbohydrate content

The soluble carbohydrate content was determined from the same extract from which the total phenol content was measured. The determination was carried out according to the method of Dubois et al. (1956) using glucose as standard. The results were given in mg glucose/g dry wood. The measurements were carried out in triplicate.

Hemicellulose determination

The measurement of the hemicellulose content was carried out using the method of Polyak (1948). The hemicellulose content was related to dry wood weight and indicated in percent.

Tab. 2: Physical Properties – beech samples

In upper index behind the name of the samples: Numer of samples.

Confidence interval is indicated at p=0.05

Sample	Density [g/cm ³]	Moisture content [%]	L-value	Bending strength [N/mm ²]	Modulus of Elasticity [N/mm ²]
Bu0 ²⁷	0.738 ± 0.007	10.9	72.0 ± 0.7	132.8 ± 2.2	13140 ± 293.5
Bu2 ³⁵	0.692 ± 0.010	8.7	47.9 ± 0.8	76.7 ± 7.5	11092 ± 612.3
Bu3 ⁴²	0.656 ± 0.010	8.3	35.9 ± 0.5	53.8 ± 4.1	11776 ± 397.5

RESULTS AND DISCUSSION

Physical Properties

Tab. 2 summarizes the physical properties of the investigated hard wood samples, table 3 for softwood.

After the treatment the equilibrium moisture content, the bending strength of the wood samples decrease. The density and MOR of the treated wood samples also decreases significantly compared to the untreated samples. It can also be recognized that the thermal treatment has not had any important impact on the resulted MOE parameters. The bending strength decreases drastically with intensified treatment (table 2 and 3). Although with increasing treatment intensity the L-value is reduced, which means that the colour becomes darker. No significant relationship between the colour and the bending strength could be established. Generally it can be said that with increasing treatment intensity the bending strength lowers. While the intensification of the treatment correlates with the colour of the wood it can be generally established that the darker the wood the poorer is the bending strength (Junghans und Niemz 2005). The strength of wood however is also influenced by many other parameters.

Differences have been noted amongst the different wood species as to the way they respond to heat treatment. The most important differences were reported between softwoods and hardwoods (Zaman et al. 2000, Militz 2002, Callum Hill 2006). Due to these facts, the

wood samples investigated have been grouped and discussed as softwood and hardwood species. The lignin fraction takes up 20-25% of hardwood and 28-30% of softwood. The composition is also different: the lignin of softwoods is mainly built-up from coniferyl- and p-coumaryl-alcohol, while in the case of hardwoods the major components are coniferyl- and sinapyl-alcohol (Németh 1997). The hemicellulose fraction of hardwoods is mainly composed of glucuronoxylans which are thermally and hydrolytically more instable than the glucomannans which are dominant in the hemicellulose of softwood. A fraction of the hydroxyl-groups in hemicellulose is acetylated (Pfriem 2006). Considering cellulose there are no significant differences mentioned between woods, regarding the structure and composition (Németh 1997).

The largest differences between the chemical compositions of different wood species are in the quality and concentration of extractives.

Tab. 3: Physical Properties – softwood samples

In upper index behind the name of samples: Number of samples; s. Confidence interval is indicated at $p=0.05$.

Sample	Density [g/cm ³]	Moisture content [%]	L-value	Bending strength [N/mm ²]	Modulus of Elasticity [N/mm ²]
Fi0 ⁴⁵	0.462 ± 0.015	11.6	61.2 ± 1.6	90.6 ± 4.8	12204 ± 646.9
Fi2 ⁴⁵	0.481 ± 0.024	9.3	29.3 ± 0.7	63.7 ± 4.6	13123 ± 734.6
Fk0 ³⁹	0.552 ± 0.017	11.9	79.7 ± 0.6	87.4 ± 3.8	12138 ± 713.0
Fk2 ³⁰	0.543 ± 0.016	9.7	56.4 ± 1.0	68.0 ± 7.5	12514 ± 944.2
Fk3 ⁸¹	0.516 ± 0.009	7.2	47.2 ± 1.3	57.2 ± 5.0	12540 ± 402.4
Dk0 ⁵²	0.484 ± 0.013	13.4	72.9 ± 3.0	75.6 ± 3.8	11305 ± 446.3
Dk2 ²⁰	0.477 ± 0.016	7.5	57.8 ± 1.0	73.1 ± 3.8	12181 ± 548.0
Dk3 ⁹⁶	0.466 ± 0.010	6.8	47.5 ± 0.5	67.5 ± 2.3	12166 ± 390.9

Chemical Analyses

The decrease in pH (table 4) can be observed when comparing samples from Step 0 and Step 2 for **beech**. The differences between the values of Step 2 and Step 3

of beech do not indicate further acidification of the wood, but instead a slight increase of the pH. There is a remarkable change in the totalphenol content in all of the samples. The concentration of the phenolic

compounds consistently increases from Step 0 to Step 3. A very good correlation can be established between totalphenol concentration and the ethanol-toluene extractive content ($R^2=0.955$, fig. 1). The correlation proves that phenolic compounds are produced during the treatment, these also have good solubility in the ethanol-toluene mixture; for this reason, these compounds are presumably simple phenols with low molecular weight. The only explanation for this could be the transformation of lignin, which stretches over wide temperature ranges. A decrease in the hemicellulose concentration can be observed with progressive intensity of the treatment (or just ‘progressive treatment’) in all the hardwood samples.

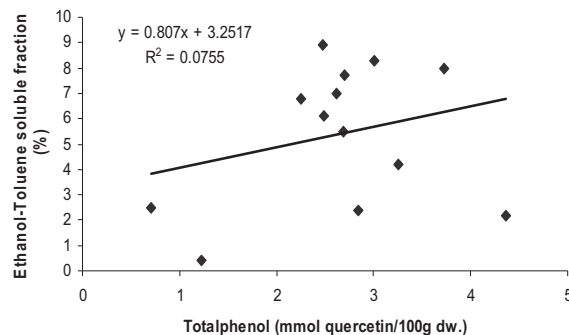


Fig. 2: Correlation for softwood samples

Tab. 4: The pH, the Ethanol-toluene soluble extract content, the totalphenol content, the soluble carbohydrate content and the hemicellulose fraction of the investigated beech samples,. Confidence interval is indicated at $p=0.05$

	Bu0	Bu2	Bu3
pH	4.16	3.57	3.62
Ethanol-Toluene s. extract [%]	3.6	8.5	11.9
Totalphenol [mmol/100g dw.]	2.59 ± 0.1	6.95 ± 0.25	9.78 ± 0.64
Soluble Carbohydrates [mg/g dw.]	23.2 ± 2.2	199.2 ± 27.1	65.1 ± 7.3
Hemicellulose [%]	13.6	10.4	5.6

During the modification process the hemicellulose content also changes in softwood samples. While comparing softwood and hardwood samples, it can also be concluded that the phenolic compounds in the hardwood samples are more readily transformed (an increase of the totalphenol level from Step 0 to Step 3) while in the softwood samples it is the soluble carbohydrate content that shows extensive changes. The **softwood wood** samples showed a decrease in pH values with the progression of the thermal treatment. Thus, a good correlation as found for hardwood can not be established between totalphenol concentration and the ethanol-toluene soluble extractive content ($R^2=0.0755$) in softwood samples (fig. 2).

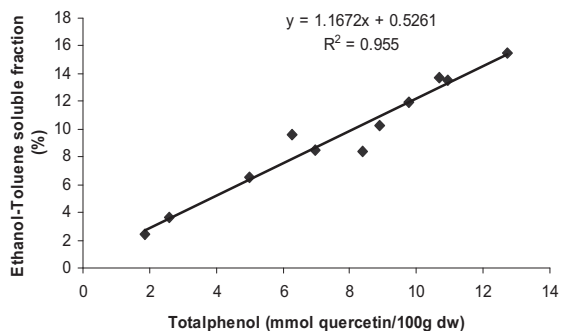


Fig. 1: Correlation for hardwood samples (for correlation other hardwood species (ash and maple) also were used)

Tab. 5: The pH, the ethanol-toluene soluble extract content, the totalphenol content, the soluble carbohydrate content and the hemicellulose fraction of the investigated softwood samples. Confidence interval is indicated at $p=0.05$.

	Dk0	Dk2	Dk3	Fk0	Fk2	Fk3	Fi0	Fi2
pH	3.64	3.63	3.52	4.10	3.92	3.59	4.15	3.56
Ethanol-Toluol extract [%]	2.2	8.9	8.3	6.8	7	8	2.4	4.2
Totalphenol [mmol/100g dw.]	4.36 ± 0.07	2.47 ± 0.08	3.01 ± 0.03	2.25 ± 0.02	2.62 ± 0.11	3.72 ± 0.12	2.84 ± 0.05	3.25 ± 0.07
Soluble Carbohydrates [mg/g dw.]	27.99 ± 2.04	118.9 ± 23.3	102.6 ± 15.5	15.84 ± 1.96	66.46 ± 1.56	55.64 ± 8.37	24.89 ± 2.41	45.05 ± 1.84
Hemicellulose [%]	17.2	13.3	4.9	6.8	8.7	7.3	6.9	8.0

Correlation between physical and chemical properties

The physical, technological features of the wood are altered during the treatment. The change in the physical properties of the wood is realized through the transformation of chemical components and through the alteration of the wood structure. Yet, which physical feature is influenced by which chemical parameter can only be guessed on the basis of woodchemical- and woodphysical knowledge.

Possible relationships can be quantified well by using mathematical tools (i.e. Linear correlations) and this way

the influence of the treatment regarding attaining the desired technological features could be well prognosticated. In table 6, information can be seen regarding the most important correlations found between the measured physical and chemical parameters. Due to the previously discussed differences between softwood and hardwood, the two groups are evaluated separately.

Tab. 6: Linear Correlations between physical and chemical parameters for hardwood (acer and maple samples also were used) samples. R: correlation coefficient

Parameter 1	Parameter 2	R
Ethanol-toluene extract	Totalphenol	0.9773
Totalphenol	Bending strength	-0.9297
Totalphenol	Moisture content	-0.8923
Totalphenol	Hemicellulose	-0.8776
Hemicellulose	Bending strength	0.8383
Totalphenol	Density	-0.6574
Hemicellulose	Moisture content	0.6319

The bending strength decreases ($R=-0.9297$) in **hardwood samples** (Tab. 6) with increasing totalphenol content. While heating up wood, the lignin is first softened (70-80 °C) then radicals are formed in the depolymerisation reactions (120-130 °C) that in turn are condensed (140-200 °C) to compounds that presumably have lower polarity. In this process the hygroscopicity of lignin decreases significantly (Pecina 1985). During the depolymerisation reactions, simple phenolic compounds can be formed that are also very soluble in ethanol-toluene mixture, as discussed above. This could be the

cause for the increasing totalphenol concentrations of the wood samples. The transformation of lignin (i.e. increasing amounts on phenolic extractives in the wood) seems to be closely connected with the poor/degrading bending strength parameter in the investigated hardwood species.

The transformation of lignin and the increase in the concentration of the produced phenolic compounds also contribute to the reduced water adsorption (equilibrium moisture content) in the thermally modified hardwood samples ($R=-0.8923$). The reduced amount of equilibrium moisture-uptake, and thus the swelling and shrinking, is characteristic to thermally modified wood (Pfriem, 2006). A reduction in the hemicellulose content is measured (-0.8776) with an increase in the totalphenol concentration.

During the thermal degradation of hemicellulose the lignin-carbohydrate connections are also cleaved. The cleavage leads to the easy depolymerisation of this non-carbohydrate-bonded lignin fraction (Pfriem, 2006), which can also result in the production of simple phenolic compounds.

It seems that there is also a clear connection between a reduction in bending strength and hemicellulose content ($R=0.8383$), which proves the physical changes that take place during the degradation of hemicellulose in hardwood samples. The intense degradation of hemicelluloses, through thermal modification of wood, has already been proven by several authors (Sweet and Winandy 1999, Winandy and Lebow 2001, Pfriem und Wagenführ, 2007).

There are not so many good correlations between physical and chemical parameters in the **softwood samples** (Tab. 7) compared to hardwood samples (e.g. hemicellulose-bending strength $R=0.0520$ for softwood samples, $R=0.8383$ for hardwood samples). Softwoods have more thermally stable hemicelluloses that are mainly built up from glucomannans and besides that they also have different types and quantities of extractives than hardwoods. With increasing soluble sugar concentration, the MOE ($R=-0.7330$) and also the bending strength ($R=-0.6695$) decrease. Through the degradation of hemicellulose, soluble carbohydrate compounds are produced in the wood. The structure of the wood is altered which probably results in the reduced MOE and the bending strength. The correlation between totalphenol and bending strength ($R=-0.5852$) is also lower than in hardwood samples ($R=-0.9297$). Nevertheless, it will take further investigations to reveal other possible relationships between physical and chemical parameters concerning thermally modified softwood.

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Tab. 7: Linear correlations between physical and chemical parameters for softwood samples. R: correlation coefficient

Parameter 1	Parameter 2	R
Soluble carbohydrates	MOE	-0.7330
Soluble carbohydrates	Bending strength	-0.6695
Totalphenol	Bending strength	-0.5852
Totalphenol	L-value	-0.5272
Hemicellulose	Bending strength	0.0520

CONCLUSIONS

Softwood and hardwood samples behave differently during the thermal modification process carried out in a N_2 atmosphere autoclave. The different behaviour can be assigned to the distinct composition of the wood of each species. The chemical composition also influences the physical, technological features of wood.

Using correlations, the chemical reactions that take place during the thermal modification process can be better tracked and the physical properties, as well as changes of the wood material, can be better related to various stages of the process. These correlations are different for softwood and hardwood samples. Not only are different transformation reactions of the various wood types taking place during the modification treatment, but the chemical parameters investigated also contribute differently to the establishment of the physical and technological properties of the product. The results can serve as a basis for further research of the behaviour of different types of wood tissues during thermal treatment.

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Colour stabilization of heat modified Norway spruce exposed to out-door conditions

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ABSTRACT

Wood boards from Norway spruce (300 mmx125mmx10mm) were heat modified in a pilot chamber corresponding to Thermowood-D quality. The surface of boards was sprayed with diluted solutions of ferrous sulphate alone or in combination with subsequent spraying of a 30% solution of hydrogen peroxide. The boards were exposed to outdoor conditions during summer 2009 (45° facing south). Colour coordinates were measured using a colorimeter.

Only small changes in colour of boards were observed directly after the surface treatments. Lightness increased for boards with no surface treatments during out-door exposure (seven weeks). Increase in lightness was delayed when ferrous sulphate was applied to the board. Lightness was essentially unchanged during the out-door exposure period when ferrous sulphate and hydrogen peroxide was used to modify the wood surface (at low hydrogen peroxide charge a small increase of lightness was, however, observed). Chroma decreased for boards with surface treatments but levelled out after a couple of weeks. On the other hand a decrease in chroma of boards with no surface treatments started after about four weeks exposure. Hue increased for all the boards until the fourth week. After that hue of untreated boards and boards treated with both ferrous sulphate and hydrogen peroxide continue to increase.

INTRODUCTION

Heat modifying processes (such as Thermowood) could be characterized as a mild pyrolysis of the wood resulting in a reduction of hygroscopicity and increased dimensional stability. Although hardness of the product is increased a reduction in (surface) strength takes place during heat modification. The brownish colour formed by degradation reactions of wood components during heating is bleached on exposure to sun-light. Application of unpigmented or low-build stains and oils were found not to be able to give a weather stable coating (Jämsä et al. 2000). Lignin contributes to the colour of wood and if such structures and/or other colour giving groups could be stabilised it could reduce bleachability of heat modified wood surfaces towards sun-light. The UV-stability of lignin in wood was increased by blocking of phenolic groups with for example benzophenone groups (Kiguchi and Evans 1998) or by addition of UV-absorbers (Schaller and Rogez 2007). Increase in UV-stability of wood can also be performed by addition of ferric chloride and it is well known that increase in greying of wood can be

done by addition of ferrous sulphate. However, the influence of the iron-salts on colour and stability of heat modified wood to out-door exposure is, at least to us, not known. In this paper we present results on stabilizing effect of ferrous sulphate and ferric chloride on surface of heat modified Norway spruce during exposure to out-door conditions. This was done by performing colour measurements with colorimeter. Importance of oxidation of wood surface by application of ferrous sulphate and hydrogen peroxide was also investigated.

EXPERIMENTAL

Wood from Norway spruce (sapwood side) were cut from a 25 mm thick board into 300x125x1.0 mm. Wood was heat modified in pilot chamber (Valutec) corresponding to Thermo-D properties and stored indoor at 20 °C. Before application of chemicals board surface was sanded. A 10% water-solution of ferrous sulphate ($\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$) was prepared by dissolving 10.3 g of the salt in 100 ml water (pH of the solution was 4.8). A 30% hydrogen peroxide solution was prepared by mixing 20 ml water with 25 ml of hydrogen

peroxide (50%). About 10 mg of ferrous solution was sprayed on the surface of samples using a spray gun. A high (ca 50 mg) and a low (ca 10 mg) charge of hydrogen peroxide were applied to boards. The boards were dried in air and put out on a rack in 45° tilt and facing south direction. Colour measurement was performed with a Minolta Chromameter CR 310 colorimeter before and when exposed to sunlight. Colour coordinates: Lightness (L), chroma (C) and hue (H) was measured. A decrease in chroma indicates a less saturated colour (grey) whereas a decrease in hue indicates (in this paper) a shift from red to yellow colour.

RESULTS

This paper presents results on colour (lightness) stabilisation of heat modified boards from spruce by addition of iron ion containing solutions with or without addition of hydrogen peroxide. Surface treated boards and boards with no surface treatment were put onto a rack in the summer of 2009. As could be expected considerable bleaching of the heat modified board surface took place within a couple of weeks. This is indicated in figure 1 showing the decrease in colour greying of the boards after out-door exposure. It is well known that a ferrous sulphate solution can be used to speed up greying of wooden surface, however, only a minor darkening of the heat modified board could be observed when the solution was applied to the board. On exposure to out-door conditions brightening of surface was substantially smaller for a board that had been treated with ferrous solution than a board that had not been surface treated (Fig. 1).

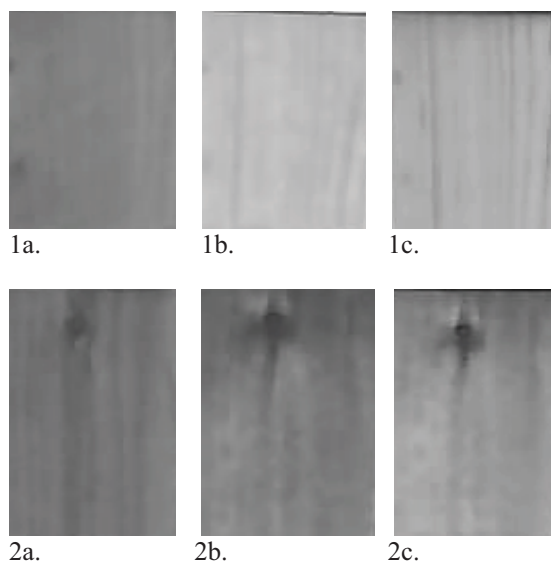


Figure 1. Effect of surface treatment with ferrous sulphate (2) or no surface treatment (1) on heat modified spruce wood. a. before exposure to outdoor conditions, b. after two weeks of exposure, c. after four weeks of exposure.

Analysis of colour coordinates during the first weeks of exposure to sun-light showed that lightness was essentially unchanged for boards that had been treated with the ferrous solution but increased for boards with no additions (Fig 2.). Lightness of the surface treated board started to increase when exposure was continued (Fig.2). A “delay” and increase in lightness was also observed with a board surface treated with Lewis acid catalyst, ferric chloride. Chroma decreased for the boards treated with ferrous solution whereas chroma was more slowly decreased for a board with no surface additives. Hue increased for both types of boards which mean that a shift towards yellow colour coordinate took place during the exposure. Increase for board treated ferrous sulphate, however, seemed to level-out at the end of exposure period

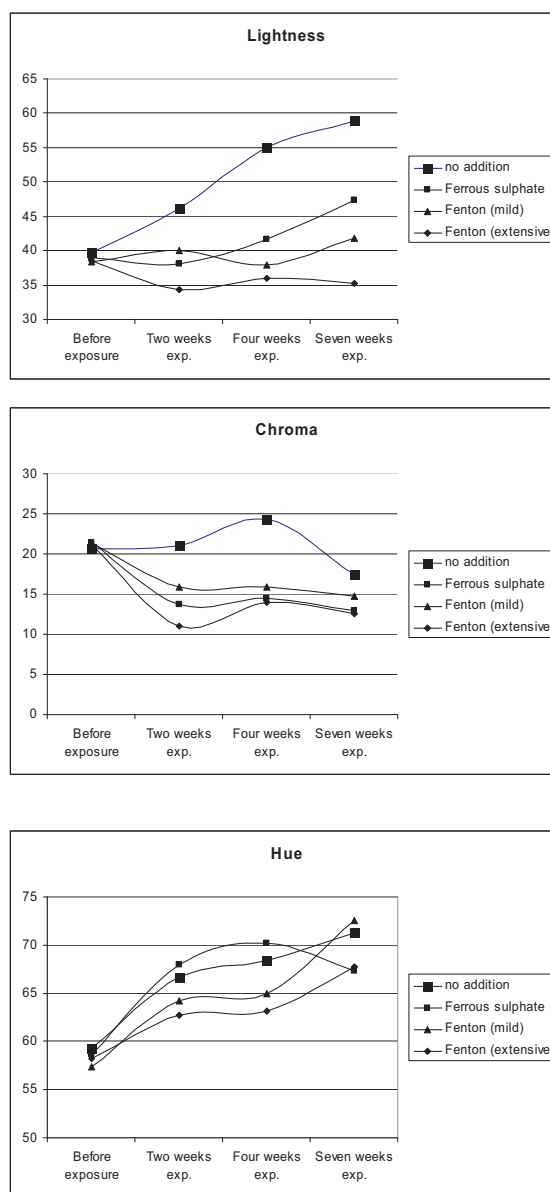


Figure 2. Colour measurements of heat modified boards exposed to sunlight. Effect of application of ferrous sulphate with or without hydrogen peroxide.

Ferrous sulphate is a mild reducing agent, however, when combined with hydrogen peroxide it forms a strong oxidising agent (also called Fenton's reagent) that has the ability to modify or introduce new chromophoric groups in the wood surface. Surprisingly, only small changes in colour coordinates could be observed for heat modified boards treated with Fenton's reagent. It can be seen in fig 2 that the lightness of oxidised surface was more stable than a board that had been treated with only the ferrous solution. After four weeks of exposure lightness, however, started to increase (Fig. 2). Decrease in chroma took place but levelled out after a few weeks. Hue increased during the exposure. The extent of surface activation was increased by addition of larger amounts of hydrogen peroxide and the typical formation of oxygen gas was observed. Still the colour of the board was not much altered by the extensive treatment and the measured lightness after seven weeks of exposure was essentially the same as before start of exposure (Fig.2). Hue was increased during the out-door exposure.

DISCUSSION

Lignin is brown in native state but deepen in colour in many industrial processes. Carbohydrates are more or less colourless but can form coloured compounds, by caramelisation reactions when heated. Detailed structure of chromophores in heat modified wood is still rather poorly described (González-Peña and Hale 2009). The chromophores generated during the heat modification of wood are not stable in sun-light and finally a greyish surface similar to weathered wood will appear. The retardation of bleaching of the board treated with ferrous solution in our experiments was quite unexpected. It is difficult to speculate on the reason for the retardation of bleaching based on the limited amount of experimental data but a few possibilities will be presented in the following sections.

During photodegradation of lignin radicals are formed and as ferrous ion has a reducing capability it may hinder further chain reactions of formed radicals. This does not mean that new chromophores are not formed during the exposure. The increase in hue and thus shift to more yellow colour in Fig. 2 points to that chromophores becomes modified during light exposure. Ferrous ion can also oxidise in air and this could be a reason why the lightness retardation of the treated boards was not stable and started to decrease after a couple of weeks.

Catechol (*ortho*-hydroxyphenols) structures can be involved in colour formation and may form during heat modification; an increase in phenolic content during heat modification by cleavage of beta aryl-ether bonds and methoxyl groups in lignin has been reported (Tjeerdesma 1998, Wikberg and Maunu 2004). Ferrous ion can form strong complex with

catechols in lignin. One well known example is discoloration of tannin-rich heartwood of oak by ferrous ions. However, when ferrous solution was sprayed over the heat modified board only small differences in colour could be observed.

When ferrous sulphate was applied to an untreated wood surface a greying of the surface in the sun-light occurred only within a few days. Such a greying process was difficult to observe with the naked eye for the surface treated heat modified board. However, a decrease in the colour coordinate chroma was observed already in the beginning of the exposure for the surface treated boards (Fig. 2).

Fenton's reagent is a reactive and unselective oxidising system and reactive radicals can be formed when hydrogen peroxide is decomposed in presence of iron ions such as presented in figure 3.

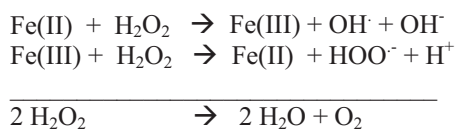


Figure 3. Reactions of hydrogen peroxide in presence of Fe(II)/Fe(III) catalyst.

In presence of wood the radicals can react with wood components and introduce new functional groups instead of terminating into oxygen and water. This could involve formation of organic peroxides and radicals, hydroxylation of aromatic nuclei of lignin as well as further oxidation to quinones and acids. Surprisingly, lightness of the modified board after the oxidation with Fenton's reagent was affected only to a small extent. On the other hand, a darkening can be observed when untreated wood is oxidised with this reagent. It is, however, striking that lightness of heat modified board treated with the Fenton's reagent was essentially the same even after seven weeks of out-door exposure (Fig. 2). Hue increased, however, during out-door exposure (Fig. 2). This is an indication that the structure of chromophores in the surface oxidised board changes during exposure but that it still absorb light to a similar degree as before exposure.

Quinones are likely to be involved in the yellowing of paper but can under certain conditions have photostabilising properties. It has been proposed that weather stability of wood treated with strong oxidant chromic acid is due to formation of insoluble complexes with Cr (III) and quinones similar to the ones formed by chromic oxidation of guaiacol (Schmalzl et al. 2003). On the other hand, Evans and Schmalzl 1989 reported that a quinone-complex with relatively high solubility was formed when wood was treated with ferric chloride. In our experiments we found that treatment of wood with Lewis acid, ferric chloride led to a darkening but the lightness of the heat modified board started to increase in the end of the exposure period.

Quinones are not stable and could be oxidised further to acids that may form stable ferrous complexes. Also, heat modified carbohydrates can form strong complexes with ferrous ion (Benjakul et al. 2005, Natsuume and Ueda 1987). It is, however, questionable if such structures can really contribute directly to the colour stability of the oxidised heat modified board.

The current study was limited to a seven weeks period and gives only indications on the initial photo-degradation reactions of surface treatment of heat modified wood. The effect of prolonged exposure will be subject for further studied where also greying of the material will be focused in more detail. The effect of combination with oil surface treatments is also of interest as well as stability of potential chromophores in the process.

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Wooden Material Under Extreme Climate Changes

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ABSTRACT

The heat treated (HT) ThermoD and untreated species were tested for the extreme climate changes. The experimental contained five cycles of soaking in water, freezing and warming. After experimental all samples degraded in colour more or less and some started to crack. ThermoD beech showed the best results. The colour did not change significantly and the material did not crack.

SESSION 7

MISCELLANEOUS DRYING TECHNOLOGIES

Moisture Diffusion Coefficient of Low Density Fiber Board Determined Under Steady and Unsteady State Conditions

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ABSTRACT

Low-density fiber board ($< 300 \text{ kg/m}^3$) offers a good thermal insulation for housing construction. However, few works deal with the mass diffusivity of this product, though it is essential for characterizing the drying kinetics of the wood fiber sheets during the wet-manufacturing process, or for determining the moisture buffering capacity of the product directly exposed to an indoor climate in the building.

The diffusivity of wood fiber insulation board is measured in this work under steady state conditions (cup method) and under unsteady-state conditions (sorption in the relative humidity range [37%-75%]). The mass diffusivity is measured for different sample thicknesses (~24 and 2 mm) and different board densities (160 and 270 kg/m^3).

Results indicated that the diffusion coefficient measured under steady-state conditions (cup method) has a value different from the one obtained under unsteady state conditions. Additionally, the diffusivity depends on the sample thickness, which constitutes a failure of Fickian's law. Discussion emphasizes on the effect of the double porosity of the material to explain this macroscopic non-Fickian behavior.

Heat Sterilization of Ash Firewood – Heat Treating Options, Temperature Monitoring, and Thermal Verification

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ABSTRACT

Due to the potential risk associated with moving emerald ash borer (EAB) infested firewood, the interstate movement of all hardwood firewood in US is currently restricted under the Federal quarantine. Communities and firewood producers are now faced with decisions on how to treat their firewood for interstate commerce. The new regulations for heat sterilization of ash firewood require holding a core temperature of 71 °C for 75 min, which is higher than current international standard for heat treating solid wood packaging materials (ISPM 15). A study funded by the U.S. Forest Service Wood Education and Resource Center (WERC) has recently been conducted to examine the efficacy of different heat treatment schemes for meeting the new regulations and develop empirical models for estimating heating times at various heating conditions. This paper focuses on some practical aspects of the heat treatment process in terms of meeting the current heating standard for EAB, monitoring temperature changes during heating process, and providing thermal verification after the heat treatment operations.

Key words: Emerald ash borer (EAB), ash firewood, heat treatment

INTRODUCTION

Emerald ash borer (EAB), *Agilus planipennis*, is a non-native bark- and wood-infesting insect of Asian origin that poses an enormous threat to North American urban and rural forests. Since its discovery in southeastern Michigan in the summer of 2002 (Haack et al. 2002), EAB has killed millions of ash (*Fraxinus* spp.) trees in Canada and the United States. As of September 2009, the infested area includes two Canadian provinces (Ontario and Quebec) and 13 states (Illinois, Indiana, Kentucky, Maryland, Minnesota, Michigan, Missouri, New York, Ohio, Pennsylvania, Virginia, West Virginia, and Wisconsin) in the United States (<http://www.emeraldashborer.info>). The U.S. Forest Service estimates that if EAB is not contained or eradicated, it has the potential to cost local governments and homeowners approximately \$7 billion (present dollars) over the next 25 years to remove and replace dead and dying ash trees (USDA 2008). This scenario would also result in extensive environmental damage and long-term changes in the North American forest structure. To stop further spread of EAB, quarantines are currently in place to prevent infested ash firewood,

logs or nursery trees from being transported and starting new infestations.

Heat sterilization is currently the most practical and environmentally friendly treatment to kill pest in solid wood materials and prevent the transfer of pests between regions and states. Current international regulations for heat sterilization of solid wood packaging materials require a minimal core temperature of 56 °C for 30 minutes (FAO 2006, CFR 2004). To deal with the potential of EAB moving in firewood, the U.S. Department of Agriculture (USDA) Animal and Plant Health Inspection Service (APHIS) has implemented a new heating standard for treating ash firewood. The new regulations require that the core of the firewood be heated to at least 71 °C for a minimum of 75 minutes (APHIS 2009). Comparing with heat treating wood packaging materials, firewood industry are faced with bigger challenges in heat treating firewood for EAB. This paper focuses on some practical aspects of the heat treatment process in terms of meeting the current heating standard for EAB, monitoring temperature changes during heating process, and providing thermal verification after the heat treatment operations.

FACTORS AFFECTING HEAT TREATMENT

From a practical standpoint, the times required for the center of a piece of firewood to reach the kill temperature are dependent on many factors, including the type of energy source used to generate the heat, the medium used to transfer the heat (for example, wet or dry heat), the effectiveness of the air circulation in the heating facility, the species and physical properties (configurations, specific gravity, moisture content, initial wood temperature) of the firewood. These factors will determine if the heat treatment standard can be met and how fast the treatment process can be done.

Heat Energy

Energy is the amount of heat supplied during the heat treatment process. Heat treating chambers typically employ systems that utilize steam, hot air (direct fire), electricity, and hot water or hot oil as mechanisms to generate the heat necessary to sterilize the wood. The choice of heat energy primarily depends on the heat treating method, energy resources available, and the cost of the energy.

Heating Medium

The temperature and humidity of the heating medium significantly affects the heating times. Higher heating temperatures obviously yield shorter heating times and heating wood in saturated steam (wet heat) results in the shortest heating times. When the heating medium is air that is not saturated with steam, there is a wet-bulb depression (the relative humidity is less than 100%), and drying occurs as water evaporates from the wood surface. As the heating medium changes from wet to dry heat, the time needed to reach the required temperature increases.

Air Circulation

Maintaining adequate air circulation is also important in heat treatment process. The circulating air performs two functions as it does in kiln drying: it carries heat to the wood to effect evaporation, and it removes the evaporated water vapor. Good air circulation insures uniform heat distribution in the chamber and keeps the wood surface temperature high so that the surface-to-center temperature gradient is as high as possible. This is usually accomplished with fans and baffles in a treatment chamber. Poor air circulation is one of the causes that some heating facilities failed to pass heat treatment certification.

HEAT TREATING OPTIONS

There are three possible options to heat treat firewood in field operations. Selection of the heat treating methods depends on the type of heating facility, energy sources, and the market needs.

Heat Treating Green Firewood with Moisture Reduction (Dry Heat Schedule)

This heat treating strategy integrates the heat treatment procedures with a kiln drying process and is considered as a primary option by many firewood producers who have dry kiln facilities. The heating medium used is typically dry heat (no additional moisture added). The firewood pieces are first heated to the target core temperature of 71 °C and held for at least 75 min (heat treatment stage). After the heating standard is met, the firewood loads are continuously heated and kiln dried until the moisture content of the firewood reaches 20% or below (kiln drying stage). The heating capacity of dry kiln facilities for firewood businesses varies widely. Maximum kiln temperature can range from below 71 °F to over 138 °C, depending on the types of kiln and energy sources used.

Table 1 summarizes the heating times to the core temperature of 71 °C at various heating conditions. The heating time for ash firewood ranged from a few hours at kiln temperatures of 116 and 138 °C to over 10 hours at a kiln temperature of 77 °C. The effect of kiln temperature on heating time is also shown in Figure 1.

Table 1. Heating times to a core temperature of 71 °C for green ash firewood with dry heat schedules.

Kiln temp setting (°C)	Actual kiln temperature (°C)		Initial temp of firewood (°C)	Heating times (min.)		
	Dry bulb	Wet bulb		Avg.	Min.	Max.
77	75	47	-11	471	370	672
			2	411	290	635
			21	396	333	484
82	80	49	-3	251	199	325
			6	232	199	271
			21	198	176	257
93	91	53	-10	198	164	231
			1	161	143	208
			17	144	94	173
116	112	68	-12	133	92	185
			1	126	109	157
			21	118	89	138
138	133	71	-9	142	103	185
			2	139	104	159
			18	129	83	146

Our laboratory study showed that initial temperature of firewood has a practical effect on heating times when kiln temperature was 93 °C and below, as shown in Figure 1. The lower the initial wood temperature, the longer the heating time, as was expected. This implies that heat treating operations in the winter season should take into account initial

firewood temperature and plan for longer heating times than in warmer seasons.

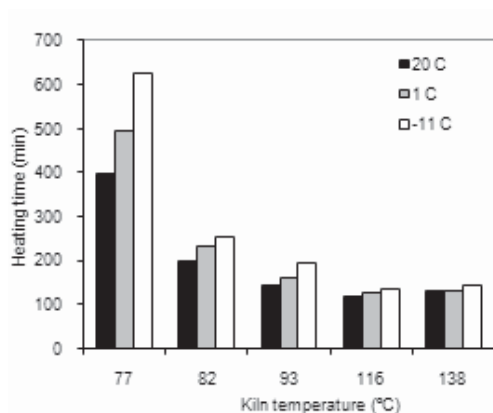


Figure 1. Average heating times for green ash firewood with dry heat at different kiln temperatures and different initial wood temperatures.

Heat Treating Green Firewood without Moisture Reduction (Wet Heat Schedules)

This heating strategy applies to situations where firewood only needs to be heat treated to meet the Federal regulations and no drying is required. Heating with wet heat (no or low wet-bulb depression (wbd)) is the most efficient way to accomplish the heat treatment goal in this scenario. Heating with wet heat yields much shorter heating times than heating with dry heat

Tables 2 shows heating times for green ash firewood under several different wet heat conditions, which were a combination of three kiln temperatures (71, 77, and 82 °C) and two wet-bulb depressions (0 °C and 5.6 °C). The heating times to a core temperature of 71 °C were generally in the range of 2 to 4 hours in a fully saturated heating medium with a kiln temperature of 71 to 82 °F. Heating time increased significantly as wet-bulb depression increased from 0 to 5.6 °C (p<0.012). As an example, Figure 2 shows the effect of heating medium on average heating times to core temperatures of 71 °C for green ash firewood at 77 °C kiln temperature. Note that under similar initial wood temperature conditions, the heating times for wet-heat schedules (0 and 5.6 °C wbd) were significantly lower than the heating times for dry-heat schedule (p<0.001) and the heating medium with 0 °C wet-bulb depression resulted in the shortest heating time.

Heat Treating Seasoned Firewood (Dry Heat Schedules)

Another scenario for commercial firewood producers is heat treatment of firewood after it has been air-dried. This procedure would only be used to meet the Federal regulations in order to freely move firewood

from EAB quarantine areas. Although both dry heat and wet heat schedules can be used to heat treat seasoned firewood, dry heat schedules are more likely to be used as firewood producers who air-dry firewood typically don't have a traditional steam kiln.

The experimental heating times for seasoned firewood with dry heat schedules are shown in Table 3. The comparison of heating times between green and seasoned firewood is illustrated in Figure 3. The results indicated that heating time for seasoned firewood is significantly less than that for green firewood (p<0.009). In the case of 77 °C kiln runs, it took about 2 to 4.8 hours to heat the seasoned ash firewood to a core temperature of 71 °C, compared to 5.6 to 8 hours for green ash firewood.

Table 2. Heating times to a core temperature of 71 °C for green ash firewood with wet heat schedules.

Kiln temp. (°C)	Initial wbd	Initial wood temp. (°C)	Heating time (min.)		
			Avg.	Min.	Max.
71	0	24	200	149	239
71	5.6	23	229	165	273
77	0	18	152	114	196
77	5.6	12	205	160	241
82	0	13	151	119	189
82	5.6	16	159	124	197

Table 3. Heating times to a core temperature of 71 °C for seasoned ash firewood with dry heat schedules.

Kiln temp setting (°C)	Initial temp of firewood (°C)	Heating times (min.)		
		Avg.	Min.	Max.
71	-6	n/a	n/a	n/a
	6	n/a	n/a	n/a
77	19	n/a	n/a	n/a
	20	223	128	290
82	18	169	100	218

TEMPERATURE MONITORING & THERMAL VERIFICATION

APHIS Plant Protection and Quarantine (PPQ) enforcement regulations require that a heat treating facility be inspected and certified by a qualified PPQ official for initial qualification. Certified heat treatment facilities are required to monitor the core temperature of the firewood during heat treatment operation and provide a temperature history record of each heat treatment run as a thermal verification.

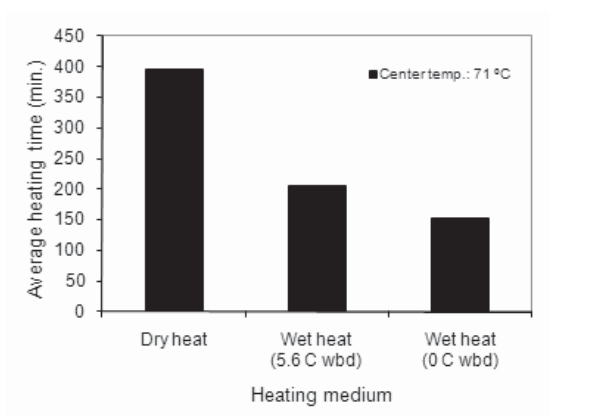


Figure 2. Average heating times for green ash firewood with dry heat and wet heat schedules (dry-bulb temperature of heating medium: 77 °C. Wbd is wet-bulb depression).

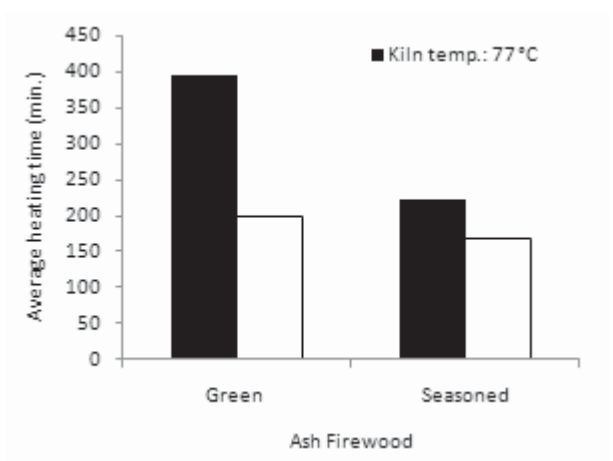


Figure 3. Average heating times to a core temperature of 71 °C for green and seasoned ash firewood.

The temperature sensors used to monitor the firewood temperature need to be calibrated and read within +/- 0.5 °C of the treatment temperature. Sensors should be properly inserted to the largest firewood pieces being monitored and reach the center of the cross section. The firewood samples monitored are required to be placed in the coldest areas of the chamber. The internal wood temperature should be collected at least once every 5 minutes and stored in a data file.

Figure 4 shows a temperature monitoring system used in a field heat treatment operation. The facility in this operation includes a hot water boiler (fueled with waste wood) and a dry kiln with a capacity of holding approximately 51 m³ of firewood. The temperature monitoring system consists of four thermocouple (TC) wires, a four-channel data logger, and a laptop computer. These four TC wires are connected with the

data logger and the data logger can be initiated before a heat treatment run. One of the TC wires is used to measure air temperature (kiln temperature) and the other three TC wires are used to measure the core temperatures of the firewood samples in three baskets that are located in the cold area (back row) of the kiln.

Figure 5 shows the temperature data recorded during a heat treatment run and demonstrated that the treatment has met the heating standard for EAB. This temperature history chart, along with the original temperature data file can serve as the proof of a successful heat treatment for EAB.

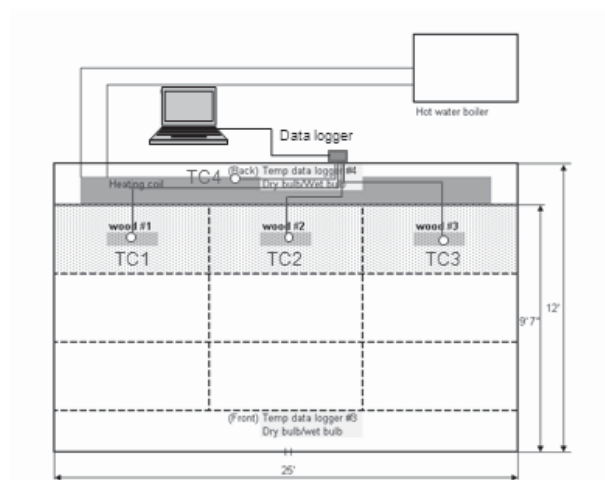


Figure 4. Temperature monitoring system in a field heat treatment operation.

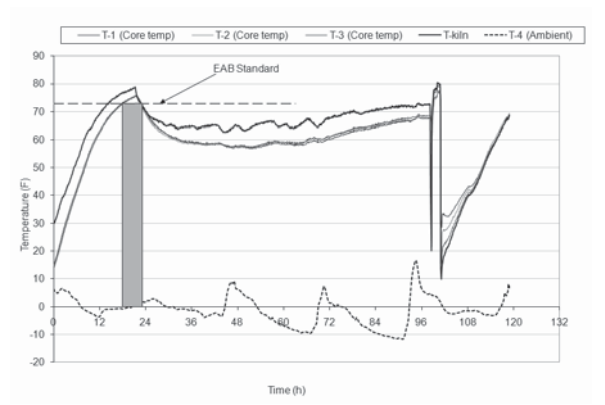


Figure 5. Temperature record of a field heat treatment.

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POSTER SESSION

Planning and Optimising Kiln Operations: - a Sawmill Application Example

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ABSTRACT

Building, maintaining and operating drying kilns is a heavy economic burden for most sawmills. As a consequence, drying capacity is often a bottleneck. Kilns are generally operated 24 h a day, 7 days a week, so there is no spare time to increase the production. Good planning routines are a prerequisite for short as well as long term operational planning. Most established sawmills have a mixture of batch and progressive kilns, some older, possibly upgraded, others more modern. This offers some flexibility in choosing the right kiln for drying a timber lot of defined quality, but also represents operational challenges. Through the years working in and for the sawmill industry, a spreadsheet model tool was made for analysing kiln capacity. The model is put together to examine the available-to-needed capacity balance in each of thirteen four-week periods of a year. Input values are information about the drying kilns and their operations, the sawmill production plans and the requested drying quality. Capacity is given in volume-hours (calculated in the same way as man-hours). The operational plans, i.e. the input values, can and should be adjusted until a reasonable balance for all periods, summed up in a graph, is achieved. A description of the model with a specified sawmill example will be given, illustrating the process from the initial stage to the final plans.

INTRODUCTION

In the sawmill industry, kiln drying regularly is a bottleneck in the production chain. One reason is the cost of building, maintaining and operating the kilns. Consequently, most sawmills tend to maximise the kiln throughput, occasionally leading to overflow and green, still not dried timber stored outdoor for a prolonged period waiting to enter the kiln. A quality loss usually follows, as the timber surface might dry and start cracking at outdoor temperatures, in particular in dry weather. In addition, timber delivery dates will be less predictable, sometimes with the consequence that certain lots are taken out of the production chain for a longer period. On the other hand, underutilising the kiln capacity is obviously also a waste of money.

Versatile models for a variety of aspects of kiln drying have long been available and successfully applied in the sawmill industry, e.g. TorkSim from SP Tråtek. Such models are even incorporated in the process control systems of all modern kilns. Some companies have implemented software to support

production planning and facilitate a smooth flow of sawn timber from the sawmill through the kilns.

The objective of this paper is to describe a simple model for calculating and planning kiln demand and capacity through the year.

DESCRIPTION OF MODEL

The model consists of a set of interlinked spreadsheets:

- An input spreadsheet for the overall available kiln technical capacity (Tab. 1). Each continuous and chamber kiln is described with volume of sawn timber, yearly operating days, down hours and efficiency, which, according to experience, never reaches 100%.
- An input spreadsheet for produced volume sawn timber and seasonal variation in kiln efficiency over the year (Tab. 2). In this example, the year is divided in 12 periods according to weeks. However, other period may easily apply, e.g. months or weeks.

- Input spreadsheets for produced assortments – dimension, final MC and drying quality - of spruce and pine.\, respectively.
 - Input spreadsheets for drying times for spruce and pine, respectively, both for continuous and chamber kilns.
 - Various output tables and graphs, e.g. a graph summing up the balance between kiln demand and kiln capacity for each period (Fig. 1).
- All input values can be manipulated, e.g. drying times can either be those generally applied at the sawmill or simulated times following a new drying schedule.

Table 1. Input spreadsheet for overall kiln capacity

Kiln Technical Annual Capacity

X-mill

Green italic = input value

	Kiln #	# of stacks	Packets per stack	m3 per packet	Volume per kiln	Operated days/year	Lost time hour/day	Efficiency %	Available Cap. 1000m3*h/year
Continuous									
	<i>1</i>	<i>15</i>	<i>3</i>	<i>4.70</i>	212	343	<i>2.0</i>	<i>85 %</i>	1 357
	<i>2</i>	<i>16</i>	<i>3</i>	<i>5.10</i>	245	343	<i>2.0</i>	<i>85 %</i>	1 570
	<i>3</i>	<i>16</i>	<i>3</i>	<i>4.90</i>	235	343	<i>2.0</i>	<i>85 %</i>	1 509
	<i>4</i>	<i>0</i>	<i>0</i>	<i>0.00</i>	0	343	<i>2.0</i>	<i>85 %</i>	0
	<i>5</i>	<i>0</i>	<i>0</i>	<i>0.00</i>	0	343	<i>2.0</i>	<i>85 %</i>	0
Sum					692				4 435
Chambers									
	<i>1</i>	<i>4</i>	<i>3</i>	<i>5.10</i>	61	343	<i>2.5</i>	<i>85 %</i>	384
	<i>2</i>	<i>4</i>	<i>3</i>	<i>5.10</i>	61	343	<i>2.5</i>	<i>85 %</i>	384
	<i>3</i>	<i>6</i>	<i>4</i>	<i>5.10</i>	122	343	<i>2.5</i>	<i>85 %</i>	767
	<i>4</i>	<i>0</i>	<i>0</i>	<i>0.00</i>	0	343	<i>2.5</i>	<i>85 %</i>	0
	<i>5</i>	<i>0</i>	<i>0</i>	<i>0.00</i>	0	343	<i>2.5</i>	<i>85 %</i>	0
Sum					245				1 534
TOTAL					936				5 970

Table 2. Input spreadsheet production and kiln seasonal availability

Available Capacity Through the Year

X-mill

Green italic = input value

Period #	Week #	Working	Prod. timber	Kiln days	Season effect *)	Available Cap. 1000 m3*hour	
		days	m3/day			Chamber	Continuous
1	1-5	<i>22</i>	375	<i>31</i>	<i>98 %</i>	136	393
2	5-9	<i>20</i>	420	<i>28</i>	<i>100 %</i>	125	362
3	10-13	<i>15</i>	616	<i>25</i>	<i>102 %</i>	114	330
4	14-18	<i>23</i>	392	<i>34</i>	<i>104 %</i>	158	457
5	19-22	<i>18</i>	467	<i>27</i>	<i>104 %</i>	126	363
6	23-26	<i>20</i>	392	<i>28</i>	<i>102 %</i>	128	369
7	27-31	<i>10</i>	719	<i>25</i>	<i>98 %</i>	110	317
8	32-35	<i>20</i>	434	<i>28</i>	<i>100 %</i>	125	362
9	36-39	<i>20</i>	428	<i>28</i>	<i>99 %</i>	124	358
10	40-44	<i>25</i>	390	<i>35</i>	<i>98 %</i>	153	444
11	45-48	<i>20</i>	425	<i>28</i>	<i>98 %</i>	123	355
12	49-52	<i>17</i>	492	<i>26</i>	<i>97 %</i>	113	326
Sum		230	444	343	100.0 %	1 535	4 436

*) must add up to 100.0%

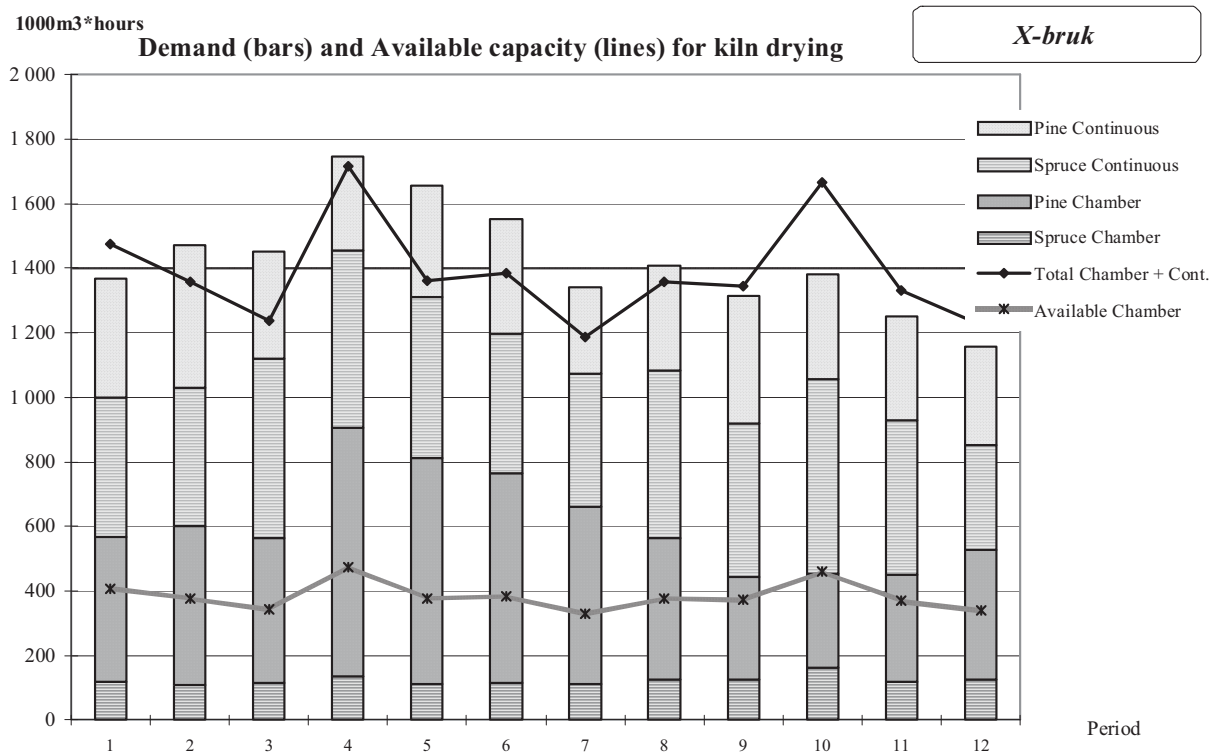


FIGURE 1. Graph demonstrating the balance between demand and available kiln capacity. In this example there is a lack of capacity in the start of the year (periods 2, 3, 5 and 6).

DISCUSSION

The model can be, and has been, used for *ad hoc* analyses like comparing drying capacity between sawmills (benchmarking), assessing the effect of more timber dried directly to customer need, included additional cost for this operation, and for teaching purposes. The model is less suitable for short time production planning.

Spreadsheets offer a flexible environment for tailoring a model to the sawmill in question. It is easy to update the model when the sawing capacity changes or

adjust for varying sawn timber assortments. The model can be easily enhanced and made more sophisticated. However, this will be at a cost as spreadsheet structure is notoriously known to be difficult to overview as the complexity increases. Therefore it is usually recommended to keep the model itself simple, and rather to judge the outcome according to best ability.

CONCLUSION

The outlined spreadsheet model offers a flexible means for analysing the dynamics of the sawmill – kiln production chain.

Modifying Kiln Drying Schedule For 50 mm thick Boland Mazoo OAK (*Quercus Castaneaefolia* C.A.M)

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ABSTRACT

Traverses of **Boland Mazoo Oak** (*Quercus Castaneaefolia* C.A.M) harvested from shah-cheshmeh – e sardabrood stand were sawn comercially in 50 mm thick and dried in semi-industrial kiln with 7m³ capacities in Kelar Abad research campus. This research performance with three different schedules up to ultimate **M.C** of (8±) %. The basic schedule was **T3-D1** suggested by **F.P.L** for 50mm thick red oak (because of similarities between these species). This schedule changed systematically to **T3-D2** and **T4-D2** to obtain the shortest possible time and the best possible quality .for comparing drying process and choosing suitable schedule we used X quality control diagram for bow, crook, twist and surface checks and nP for honey combing and C for total defects. Finally **T4-D2** was choose for 50mm thick **Boland mazoo Oak** .It should also noted pre drying up to **F.S.P** or lower than it , will be much more effective to reduce drying time (about 50%) and the defects which may be occurred due to drying .

KEY WORDS: Boland Mazoo Oak, Kiln Drying schedule, QC Diagrams

INTRODUCTION

Well known wood is a complicated and anisotropic natural material need to dry before use to have fine wood working with good dimensions stability. In other hand wood drying causes some wood drying defects that decreases economical value of wood. Perhaps if wood dried with suitable schedule we can reduce the defects.

In this paper we try to modify wood drying schedule for Boland Mazoo Oak, one of the most sensitive spices of Iranian woods.

In Iran some spices by different thicknesses were modified 50mm thick beech(Madhooshi M. 1995) , 75mm thick beech (Tazakkor –Rezaiee R. 1998) and 32mm thick Boland Mazoo Oak (Nadjafi H. 1999) .

MATERIAL AND METHODS

The traverses of Boland Mazoo Oak (*Quercus Castaneaefolai* C.A.M) harvested in Shah cheshmeh – e – Sardabrood sawn to 50mm thick boards in Kelarabad and then dried in three stages with three different schedules that systematically changed based on FPL suggested schedule for Red Oak because of anatomical similarities with Boland Mazoo Oak.

The basic schedule was T3-D1 that changed in order to T3-D2 and T4-D2.

For inspection of increase or decrease of drying defects board parameters such as dimensions and weight and some important defects such as bow, crook, twist and surface checks were measured before and after drying.

Since thickness is important for kiln drying scheduling all of boards' thicknesses were measured and analyzed with An.O.VA test and it was not significant.

Results of measuring defects before and after drying in each load cases with different schedule were compared and analyzed by quality control diagrams and equals belongs them. For bow, twist, crook and surface checks \bar{X} diagram was used.

$$1. UCL = \bar{\bar{X}} + A_2R$$

$$2. LCL = \bar{\bar{X}} - A_2R$$

Where UCL is upper control level, LCL is lower control level, $\bar{\bar{X}}$ is average of samples average and A_2 is constant ($A_2=0.48$).

For honey combing defect, after drying boards were cut and the results analyzed by $n\bar{p}$ diagram.

$$3. UCL = n\bar{p} + 3\sqrt{n\bar{p}(1-p)}$$

$$4. \quad LCL = n\bar{p} - 3\sqrt{n\bar{p}(1-p)}$$

Where $n\bar{p}$ average of defective samples and P is fraction of defective cases

And finally for choosing the best and suitable schedule for Boland Mazoo Oak for the lowest rate of drying defects we use C diagram based on Poisson distribution

$$5. \quad UCL = \bar{c} + 3Sd$$

$$6. \quad LCL = \bar{c} - 3Sd$$

Where \bar{c} Average of Poisson distribution is calculate by:

$$7. \quad \bar{c} = \frac{\text{Total defects}}{\text{Total unite}}$$

And Sd Standard Deviation calculates by:

$$8. \quad sd = \sqrt{\bar{c}}$$

For drying rate diagrams it should calculate drying rate for each schedule separately with the equal below:

$$9. \quad E = \frac{(M - Me)}{(Mo - Me)} \times 100$$

Equilibrium moisture content dependent on steps Relative humidity Mo is Average in initial moisture content of kiln

DISCUSSION AND RESULTS

By attention to quality control diagram results for schedules T3-D1, T3-D2 (figure: 1,2,3) and drying rates diagrams (figure: 4,5,6), it seems all of this Three schedules are suitable for 50mm thick Boland Mazoo Oak. In QC Diagrams all of defects are close to center line but in T4-D2 closer than the others and steadier. In drying rate graphs we can see steadier curve in T3-D2 than the others.

In economic point of view steady distribution of defects and shortest drying time T4-D2 is the best schedule for 50mm thick Boland Mazoo Oak if it passes pre drying up to F.S.P or below before charging for kiln drying.

CONCLUSION

Because Boland Mazoo Oak is sensitive for kiln drying, it needs to modify F.P.L suggested schedule. For that we use T3-D1 as basic schedule for 50mm thick Boland Mazoo Oak and change it systematically. Results show that all this three schedules (T3-D1, T3-D2, T4-D2) are suitable for 50mm thick Boland Mazoo Oak but T4-D2 is the best. If all boards were pre dried up to F.S.P or below. (As we did it in this research)

Finally suggestion for next researches is redoing this without pre drying to make better decision for the

best and suitable schedule for 50mm thick Boland Mazoo Oak.

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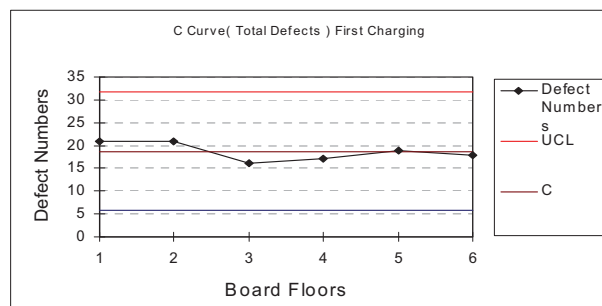


Figure 1. C diagram for T3-D1 schedule

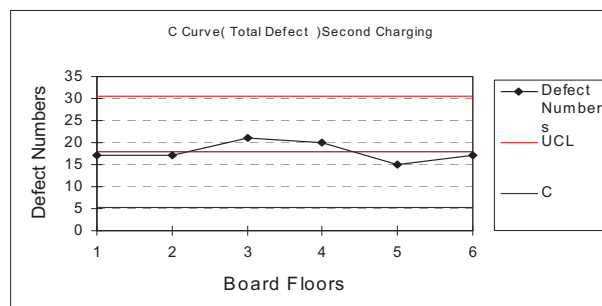


Figure 2. C diagram for T3-D2 schedule

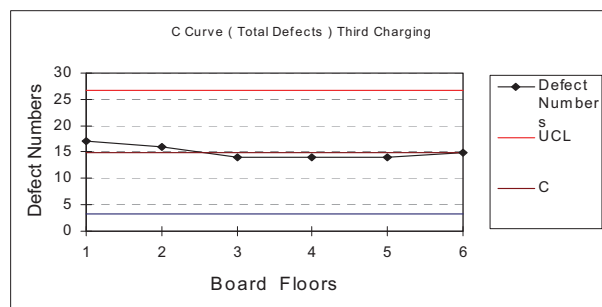


Figure 3. C diagram for T4-D2 schedule

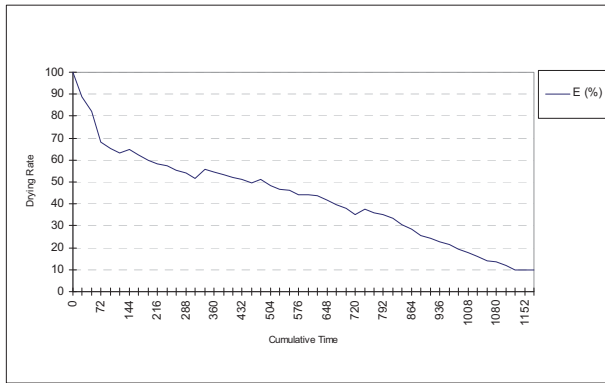


Figure 4. Drying rate diagram for T3-D1 schedule

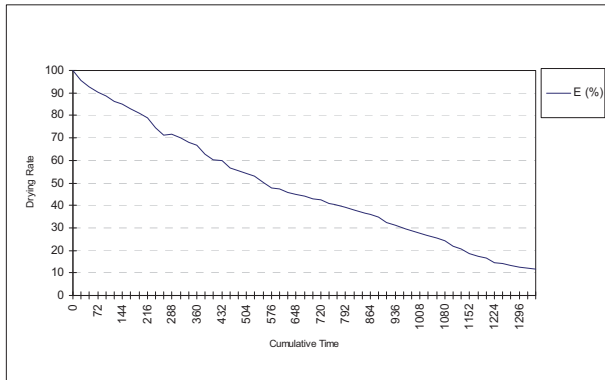


Figure 5. Drying rate diagram for T3-D2 schedule

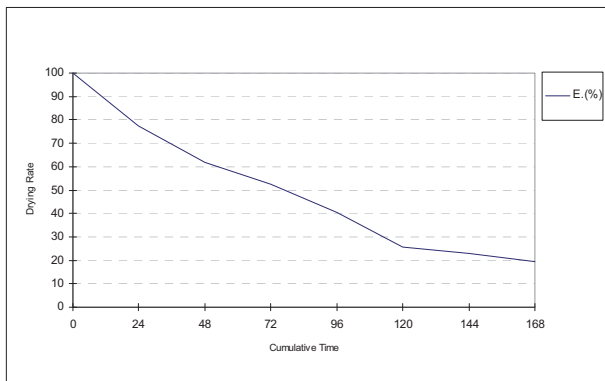


Figure 6. Drying rate diagram for T4-D2 schedule

Superheated Steam Drying of Sugi (*Cryptomeria japonica* D. Don) Boxed-heart Timber - Distribution of Released Strain and Drying Set

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ABSTRACT

Boxed-heart timber from sugi (*Cryptomeria japonica* D. Don) is widely used as structural columns for traditional wooden houses in Japan. It is well known that boxed-heart timber, which has a pith surrounded by juvenile wood, is susceptible to severe drying checks, and that it is difficult to reduce the drying time in the conventional kiln-drying process, which can take as long as 3 weeks. To solve this problem, a high-temperature drying method was developed where boxed-heart timber is dried at a temperature of 120°C and relative humidity of 35%. This method uses a specific drying rate at the surface and dries boxed-heart timber in only 3 days without surface checking; however, there are still many large internal checks because the drying set at the surface hinders the shrinkage of internal layers. This study indicates that the distribution of drying set can be controlled by applying high-temperature, high-humidity superheated steam treatment, and that it is possible to dry sugi boxed-heart timber, having a moisture content of about 100%, in only a few days without either surface or internal checking. Boxed-heart timber measuring 110 mm² × 625 mm long was dried by superheated steam for 72 h at 130°C, 60–100% RH. The results of drying set distribution were compared with the results from the high-temperature drying test. Surface drying was controlled to a smaller rate than in high-temperature drying and the released strain during the drying process was also smaller.

Tension Wood Formation in *Populus nigra* and its Effect on Longitudinal Gas Permeability under Different Drying Conditions

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ABSTRACT

Gas permeability values of tension wood and normal wood of *Populus nigra* were measured and compared under two different drying conditions. Dowel specimens of 14 mm in diameter and 40 mm length were prepared. Epoxy resin was applied all around each specimen to prevent fluid passing through lateral direction. Specimens were then dried under mild condition (50°C, and %63 relative humidity) to reach %11.8 MC, and under severe condition (62°C, and %35 RH) to reach %7 MC. Drying curves of each specimen were designed for free water movement. Once dried, both ends of all specimens were trimmed with a sharp blade before longitudinal gas (air) permeability values were measured. Results showed that under both moisture conditions, longitudinal gas permeability values in normal wood were greater than those in tension wood. Furthermore, lower permeability values in tension wood were accompanied by lower free water movement.

Keyword: Longitudinal Gas Permeability; Normal Wood; *Populus nigra*; Tension Wood.

Sapwood Moisture Content Measurements in Scots Pine Sawlogs Combining X-ray and 3D Scanning

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ABSTRACT

Wood industry of today deals with large volumes in an almost automatic process, which is not fully adapted to the variability of the raw material. Consequently, it is crucial to sort the wood according to material properties in order to process the wood efficiently and to obtain high quality end products. One material property which could be used for sorting is the moisture content of the sapwood, an important parameter for both the processing and the end products.

Most large Swedish sawmills are using 3D scanners for quality sorting of Scots pine (*Pinus sylvestris* L.) sawlogs based on outer shape. Recently, some sawmills have also invested in X-ray log scanners in order to sort the sawlogs based on inner properties. It has previously been shown that, by combining raw data from industrial 3D and X-ray log scanners using path length compensation, green sapwood density and dry heartwood density can be estimated.

In this study, the dry heartwood density was used to find an estimate of the dry sapwood density, thus allowing the calculation of the sapwood moisture content. The log scanner data used in this study was simulated from 560 Scots pine sawlogs which had previously been scanned in a computed tomography (CT) scanner. The estimated sapwood moisture contents were then compared to reference values calculated by drying samples to 9% moisture content.

It was found that the moisture content estimate could be used to separate the logs into two groups with high and low moisture content, correctly identifying all logs with very low moisture content as dry logs. Out of all logs, 70% were correctly classified. The moisture content estimate could also be compared to the dry density dependent maximum moisture content and used to identify logs that have actually started to dry.

INTRODUCTION

Wood is a biological material with great variations in material properties between individual logs as well as within the same log. The wood industry of today deals with large volumes in an almost automatic process, which is not fully adapted to the variability of the raw material. Thus, the sawn wood also shows a great

variability in material properties and a large share of the production carries combinations of dimension and grade not meeting customer demands (Grönlund 1992).

In order to reduce the production of off-grade products, the sawlogs may be sorted according to specific material properties or predicted grade of the sawn goods prior to actual sawing. This enables the sawmill to saw each log into dimensions where the

grade of the log is best utilized, in this way improving the value of the sawn wood.

Sorting of the logs according to certain material properties also helps the sawmill to adjust the process so that the wood can be processed efficiently and the highest possible quality of the end products can be obtained. Examples of such material properties are the sapwood moisture content and the density.

In the drying process, boards with similar density and moisture content distribution show similar behaviour and, by sorting the boards upon those parameters prior to the drying, well adapted drying schedules with respect to time, energy consumption and quality of the final product can be constructed (Johansson et al. 2003). Having known initial moisture content in the batch, over-drying can be decreased when using fixed schedules and the prediction of the finishing time can be done more accurately when using adaptive schedules (Larsson & Morén 2003).

In most large Swedish sawmills sawing Scots pine (*Pinus sylvestris* L.), optical three-dimensional (3D) scanners are used for quality sorting of sawlogs based on outer shape (e.g. Grace 1994, Jäppinen & Nylinder 1997, Oja et al. 1999). Recently, some sawmills have also invested in X-ray log scanners, able to determine inner properties of the logs such as knot structure (Pietikäinen 1996, Grundberg & Grönlund 1998), heartwood content (Skatter 1998, Oja et al. 2001) and density (Oja et al. 2001).

Because most sawmills installing an X-ray scanner already have a 3D scanner present, the combination of both scanners can be used to sort logs with improved precision (Skog 2009). Skog and Oja (2009) showed that the combined 3D X-ray method can be used to predict both green sapwood density and dry heartwood density in Scots pine sawlogs.

It should be possible to use the dry heartwood density to find an estimate of the dry sapwood density and the dry and green sapwood densities could then be combined to obtain the sapwood moisture content in the log. Sorting the logs based on this information would give batches with more homogeneous material properties, which would be helpful when optimizing the processing of the logs.

The aim of this study has been to develop a sapwood moisture content calculation model and to evaluate the feasibility of this method for sorting of sawlogs.

MATERIALS AND METHODS

Calculation of reference values

The development of moisture content calculation algorithms requires a set of sawlogs with well defined green and dry densities. In this study, the CT scanned logs of the Swedish pine stem bank (Grundberg et al.

1995) have been used. The stem bank contains a total of 560 Scots pine sawlogs (165 butt logs and 395 upper logs), for which cross-sectional CT images are available every 10 mm within knot whorls and every 40 mm between whorls, giving a good knowledge of the green density in the logs. For each log, a knot-free cross-section around 400 mm from the log was chosen and a reference value for the green sapwood density $\rho_{u,u}$ was calculated by taking the average over the cross-section.

In the stem bank, CT images of slices cut out from the butt end of every log and conditioned to 9% moisture content are also available. In these pictures, the average sapwood density at 9% $\rho_{0,9}$ was calculated and used to find a reference value for the dry sapwood density $\rho_{0,0}$.

This value was calculated using the relation between the density $\rho_{u,u}$ at moisture content u and the dry density $\rho_{0,0}$:

$$\rho_{u,u} = \frac{m_u}{V_u} = \frac{(1+u) \cdot m_0}{(1+\alpha_u) \cdot V_0} = \frac{(1+u)}{(1+\alpha_u)} \rho_{0,0} \quad (1)$$

where m_u is the mass, V_u is the volume and α_u is the swelling coefficient at moisture content u . The swelling coefficient was calculated using:

$$\alpha_u = \alpha_{\max} \cdot u/u_{FSP} \quad \text{for } u < u_{FSP} \quad (2a)$$

$$\alpha_u = \alpha_{\max} \quad \text{for } u \geq u_{FSP} \quad (2b)$$

where α_{\max} and u_{FSP} are the swelling coefficient and the moisture content at the fibre saturation point. The average values for Scots pine were used, $\alpha_{\max} = 14.2\%$ (Esping 1992) and $u_{FSP} = 28\%$ (Kollman & Côté 1968).

By inserting the reference values of the green sapwood density and the dry sapwood density in equation (1) and using the swelling from equation (2b), the reference value for the green sapwood moisture content was found.

Prediction of sapwood moisture content using the 3D X-ray method

Industrial 3D and X-ray data for the logs was simulated from the CT images. The simulated data files were then combined using the 3D X-ray technique and the average green sapwood density of each log was calculated as described by Skog and Oja (2009).

From the combined data, the dry heartwood density 400 mm from the butt end of each log was also calculated (Skog & Oja 2009) and a linear model predicting the dry sapwood density from the dry heartwood density was developed. Separate linear models for butt logs and upper logs were used.

Finally, a prediction of the green sapwood moisture content was calculated by combining the average green sapwood density and the predicted dry sapwood density using equations (1) and (2b).

Evaluation of results

A linear model between the predicted and the reference sapwood moisture contents was developed and predictability R^2 and root mean square error (RMSE) were calculated. A threshold value at 145% predicted moisture content was used to separate the logs into two groups with lower and higher moisture content respectively.

Calculated moisture contents were also compared to the theoretical maximum moisture content for saturated wood (Esping 1992):

$$u_{\max} = \frac{1560 \text{ kgm}^{-3} - \rho_{0,u}}{1.56 \cdot \rho_{0,u}} \quad (3)$$

To express u_{\max} as a function of dry density, the relation $\rho_{0,u} = \rho_{0,o}/(1+\alpha_{\max})$ was applied*. The average value of the swelling coefficient at FSP was used, $\alpha_{\max} = 14.2\%$.

RESULTS AND DISCUSSION

For all 560 logs, the green density of the sapwood was predicted with a precision of $R^2 = 0.65$ and $\text{RMSE} = 25 \text{ kgm}^{-3}$, Figure 1 (Skog & Oja 2009). For two outlier logs, the green density of the reference cross-section is much lower than the predicted log average, probably due to local drying of the log.

The dry density of the sapwood was predicted with a precision of $R^2 = 0.47$ and $\text{RMSE} = 43 \text{ kgm}^{-3}$ for 553 (98.8%) of the logs, see Figure 2. The logs failing to be predicted were all large butt logs, which was expected, because for very large diameters, the X-ray detector touches bottom. In this study, the dry sapwood density

was predicted from the dry heartwood density using separate linear models for butt logs and upper logs. For the reference data, the predictability between dry heartwood and dry sapwood densities was found to be $R^2 = 0.57$. The dry heartwood density in turn can be predicted with $R^2 = 0.85$ using the 3D X-ray technique (Skog & Oja 2009). This means that most of the observed uncertainty when predicting the dry sapwood density is due to the poor predictability between the dry heartwood and the dry sapwood densities.

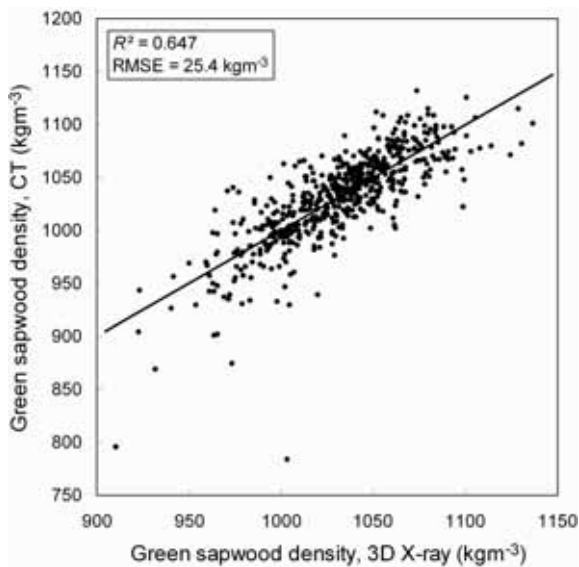


Figure 1: Sapwood green density in 560 Scots pine sawlogs, measurements in CT images versus predictions from simulated X-ray and 3D log scanner data.

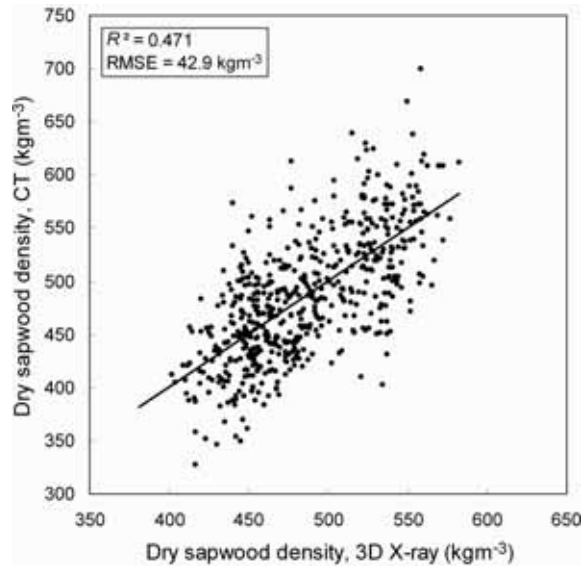


Figure 2: Sapwood dry density in 553 Scots pine sawlogs, measurements in CT images versus predictions from simulated X-ray and 3D log scanner data.

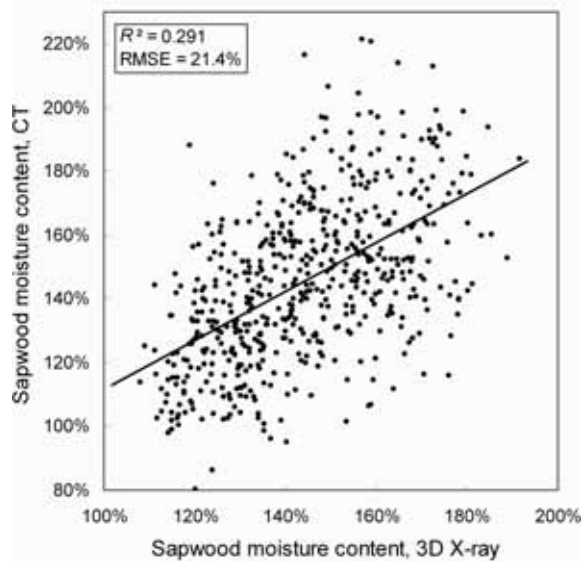


Figure 3: Sapwood moisture content in 553 Scots pine sawlogs, measurements in CT images versus predictions from simulated X-ray and 3D log scanner data.

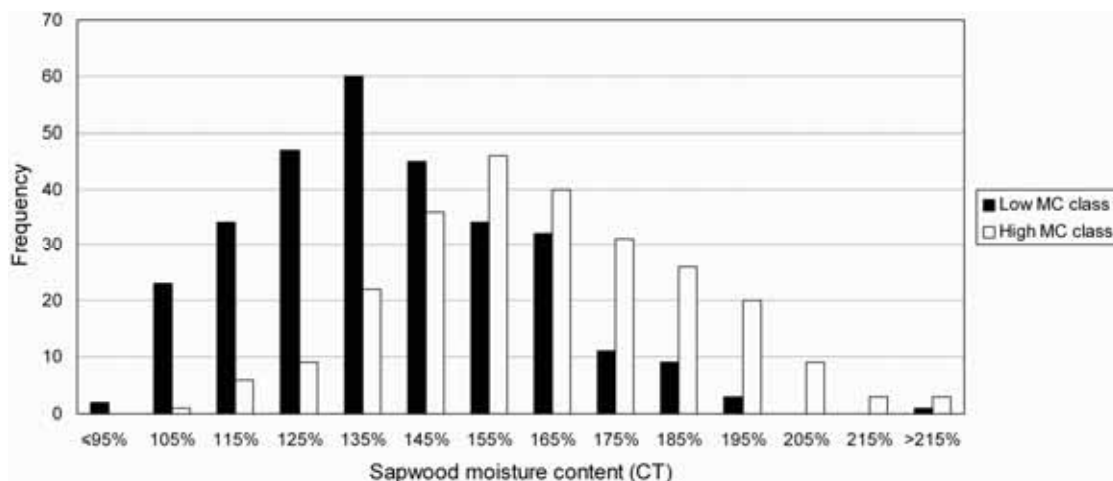


Figure 4: Observed sapwood moisture content (value from CT images) for 553 Scots pine sawlogs, separated into two classes depending on the sapwood moisture content predicted from simulated X-ray and 3D log scanner data.

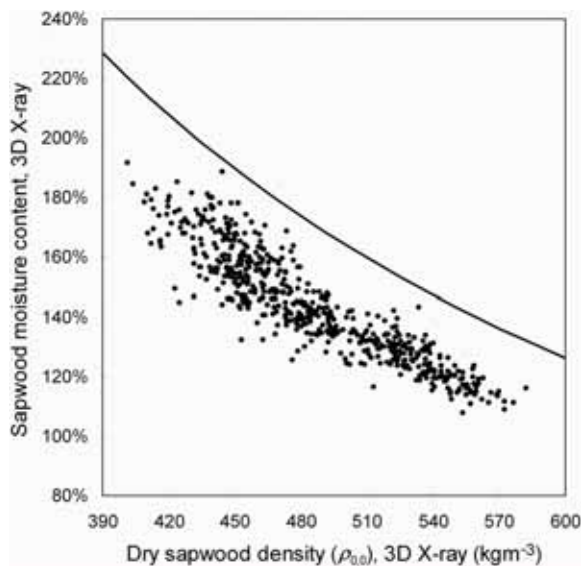


Figure 5: Estimated moisture content as a function of the estimated dry density in the sapwood of 553 Scots pine sawlogs. The solid line represents the theoretical maximum moisture content of saturated wood.

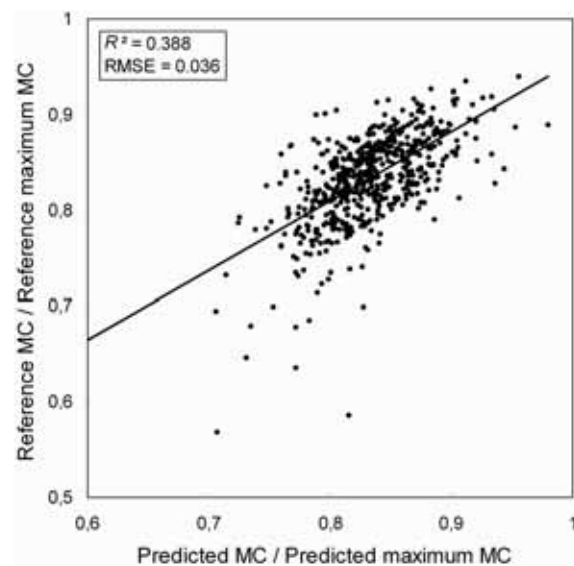


Figure 6: Sapwood moisture content relative to the theoretical maximum moisture content of saturated wood, measurements in CT images versus predictions from simulated X-ray and 3D log scanner data for 553 Scots pine sawlogs.

When combining the predicted green and dry sapwood densities, the sapwood moisture content could be calculated with a precision of $R^2 = 0.29$ and RMSE = 21%, Figure 3.

The reference moisture content was calculated by comparison of the dry density at the butt end and the green density 400 mm from the butt end. Dry CT images were only available at the butt end but due to local drying at the log ends, green CT images could not be taken at the same position. Instead, the position 400 mm from the butt end was chosen for the green images

in order to avoid the log end drying but still to be as close to the end as possible. By choosing this position, the impact of local dry density variations was minimized. However, especially for butt logs there may still be a considerable dry density variation over the distance of 400 mm, causing some uncertainty in the reference values used.

The predicted moisture content was calculated by comparison of a dry sapwood density prediction evaluated 400 mm from the butt end of the log and the average green sapwood density of the whole log. The

average sapwood density of the log was used because it was found to be the best available estimate of the green sapwood density 400 mm from the log end (Skog & Oja 2009). This means that the prediction model tries to predict an average moisture content in the region around 400 mm from the log end whereas the reference value is a mix of two local values taken 400 mm apart. Thus, the local variations near the log end contribute to the uncertainty in the prediction of the sapwood moisture content presented in Figure 3.

The result when using the predicted moisture content to separate the logs into two groups is shown in Figure 4. Because the logs used in this study were all scanned directly after felling, the logs have not dried out and most logs have a moisture content around the used threshold value of 145%. Thus, the separation between the two groups is not very clear, however, all logs with very low moisture content were correctly classified as dry logs. Out of all logs, 70% were correctly classified.

When plotting the moisture content against the dry density, Figure 5, it can be seen that most of the observed variation in moisture content is caused by the varying dry density of the logs and that the moisture content follow a curve of the same shape as the theoretical maximum value, equation (3), as shown by the solid line in Figure 5.

By comparing the calculated moisture content to the theoretical maximum, it should be possible to identify logs that have low moisture content due to drying of the sapwood. Figure 6 shows the ratio between calculated moisture content and maximum moisture content, the reference ratio measured in the CT images could be predicted with a precision of $R^2 = 0.39$ and RMSE = 0.036. The two outliers, with reference values around 0.6, are the two logs with very low green density references, probably caused by local drying at the cross-section of the green CT image.

Comparing calculated and maximum moisture contents could prove to be a very useful way of identifying logs that have been stored for a long time before arriving at the sawmill. A proper evaluation of this method would however require testing on a more diverse population of logs, containing both logs with full sapwood moisture content and logs with reduced sapwood moisture content.

CONCLUSIONS

By combining 3D and X-ray scanning in the log sorting station, it is possible to measure the green sapwood density and to estimate the dry sapwood density and the moisture content in Scots pine sawlogs.

The moisture content estimate could be used to separate the logs into two groups with high and low moisture content, correctly identifying all logs with very

low moisture content as dry logs. Out of all logs, 70% were correctly classified.

The estimate can also be compared to the dry density dependent maximum moisture content and used to identify logs that have actually started to dry. However, this method need still to be evaluated for a population of dry logs because most logs in this study was of full moisture content.

ACKNOWLEDGEMENTS

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REMARK

* In the version of the paper published in the printed proceedings, equation (3) was incorrectly used directly with $\rho_{0,0}$. The mistake has been corrected in this on-line publication and Figures 5 and 6 have been updated.

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***In-situ* Visualization Of Microcracks By CLSM System**

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ABSTRACT

The invisible microcracks occur on the surface of wood at the first stage of drying. It is important to investigate the morphologic changes with time from the generation to propagation in connection with moisture content because microcracks develop to the large scale of cracks causing a serious flaw. In this study, a confocal laser scanning microscopy (CLSM) system with a controlled environment chamber was innovated to visualize the microcracks occurring during drying. The combination was effective way to observe the propagation of microcracks because this microscopy system was enable to visualize the changes with time under given atmospheric conditions.

To reveal the microcrack occurrence and changes from green to dry conditions, small samples of softwood *Cryptomeria japonica*, ring-porous *Melia azedarach*, and diffuse-porous acacia hybrid (*A. mangium* x *A. auriculiformis*) were used in this study. The microcracks occurred on the transverse surface in all of samples with decreasing moisture content. The points in which microcrack occurred were in ray parenchyma or between tracheid or wood fiber and ray parenchyma. Then, the microcracks propagated toward both bark and pith directions along ray parenchyma and stopped at maximum shape. After that, they closed with further drying. In the cases of *Cryptomeria japonica* and *Melia azedarach*, the microcracks almost closed and could not be detected by CLSM. However, those in acacia hybrid did not closed completely at the last stage of drying. From the *in-situ* observation, characteristics of microcrack in relations to moisture content and wood structure were clarified.

INTRODUCTION

Wood drying is a very important process in the manufacturing of high quality wood products because most of flaws occur in this process. In particular, checking due to drying has extreme influence on wood quality. Huge losses arise from large and wide cracks that remain in wood after the drying process. Thus, cracks decrease utility of wood due to deterioration of the physical properties and the obvious disfigurement. To reduce this checking, many scientists have suggested appropriate drying methods in which temperature, relative humidity and drying schedule are taken into account. These studies were aimed at preventing residual checking at the final stage of drying. However, it was pointed out that microcracks invisible to the naked eye might form during the initial stage of drying

(Wallström and Lindberg 1999) and it was observed that the microcracks tended to close at the final stage of drying (Wahl et al. 2001)(Perré 2003). In addition, it has been reported that the drying of wood results in damage at the ultrastructural level (Kifetew et al.1998) (Thuvander et al. 2002). Kifetew et al. (1998) also pointed out that the strength of dried/re soaked woods was generally lower than that of green woods because of cell wall damage due to drying. Therefore, woods might be subjected to some extent of damage in wood drying process even if no checking is detected at the final stage of drying. Therefore, detailed observation throughout the wood drying process is essential. In other words, *in-situ* observation is important to understand the formation of cracks and to reduce their occurrence because they are consistently transforming. Furthermore, it is difficult to detect where and under what conditions

they occurred after they are closed.

In this study, *in-situ* observation system which consisted of a combination of a confocal laser scanning microscopy (CLSM) and a controlled environment chamber was innovated and microcrack propagation was visualized *in-situ* under precisely controlled drying condition. Three kinds of species were prepared. One was softwood *Cryptomeria japonica*, which is the most popular softwood timber in Japan and had a lot of problems to be solved in the aspect of wood drying. The result of this species was reported in previous paper (Sakagami et al. 2009). Others were ring-porous hardwood *Melia azedarach* and diffuse-porous hardwood natural acacia hybrid (*A. mangium* × *A. auriculiformis*), which is one of the fast growing trees. Using this system, the morphological differences of microcracks among them were compared.

MATERIALS

Specimens were prepared from sapwood of softwood *Cryptomeria japonica*, ring-porous *Melia azedarach*, and diffuse-porous natural acacia hybrid (*A. mangium* × *A. auriculiformis*).

• *Cryptomeria Japonica*

Air-dried sapwood of *Cryptomeria japonica* was used. The specific gravity in air-dry was 0.43. Two longitudinal successive 5mm cube specimens were impregnated with distilled water. The growth ring boundary was either positioned parallel or perpendicular to the surface. One was for observation of CLSM and the other was for measurement of moisture content. The transverse surface of specimen was smoothed with sliding microtome. Each specimen's initial moisture content ranged from 200% to 250%.

• Natural acacia hybrid

A diffuse-porous natural acacia hybrid (*A. mangium* × *A. auriculiformis*) was used in this study. The tree was 8 years old and breast height diameter was 12.7 cm. The boundary of the growth ring was not clearly identifiable and specific gravity in air-dry was 0.69. Tangential and radial shrinkage was 7.43 % and 3.23 %, respectively. From the green sapwood, two longitudinal successive specimens (5 mm cube) were prepared and transverse surface was planed with sliding microtome. Two end-matched specimens were used to form a pair of specimens. Each specimen's green moisture content ranged from 75% to 95%.

• *Melia azedarach*

A ring-porous *Melia azedarach* was 13 years old and the growth-ring boundary was visible. The growth

ring width averaged 6.4 mm and specific gravity in air-dry was 0.60. From the green sapwood, two longitudinal successive specimens (9 mm cube) at least including one growth ring were prepared and transverse surface was planed with sliding microtome. As was the case with *Cryptomeria japonica* and natural acacia hybrid, two end-matched specimens were used to form a pair of specimens. Each specimen's green moisture content ranged from 110% to 145%.

CLSM SYSTEM AND DRYING CONDITIONS

To visualize the microcrack transformations, a confocal laser scanning microscopy (CLSM) was utilized. This microscopy has been used in various field of science because of not only its high axial magnification but also more suitability for *in-situ* observation. In contrast to the scanning electron microscope (SEM), in CLSM, it is not necessary to coat the specimen. Thus, like a conventional light microscopy, CLSM enables observation in any conditions with appropriate temperature, relative humidity and barometric pressure. In addition, the laser, which acts as a light source, and a filter enable acquisition of sharper images. Taking these advantages of this microscopy,

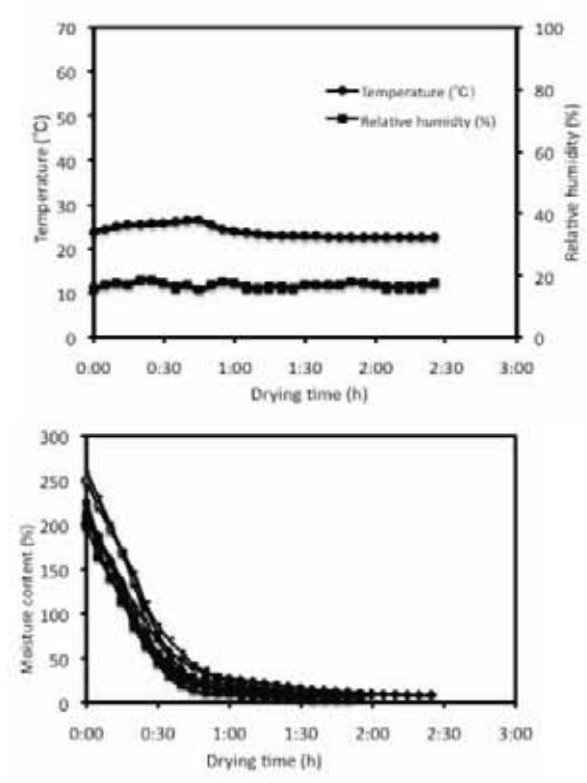


Fig.1. The drying condition of *Cryptomeria japonica* Upper: Temperature and relative humidity, Lower: Change of moisture content

in-situ observation system which combined a CLSM and a controlled environment chamber was devised (Sakagami et al. 2007). Using this system, the specimens of each species were dried under respective conditions in which temperature was between room temperature and around 60°C and relative humidity was between 5% and 20%. Controlled temperature and relative humidity was achieved using thermolamps and humidity generator respectively.

Two prepared end-matched specimens of each species were placed on the stage of a CLSM and then dried. One specimen was observed *in-situ* using a CLSM and the weight of the other specimen was measured for calculating the moisture content.

One of the drying conditions of *Cryptomeria japonica* is shown in Fig.1. The temperature was about 28°C and relative humidity was between 12% and 15%. The rate of decrease in moisture content of twelve specimens is shown in Fig.1, as well. To create the steep gradient of moisture content, a fan was placed near the specimens. The initial moisture content ranged from 200% to 250%. After the drying was started, the moisture content decreased drastically. Therefore, it was assumed that the steep gradient of moisture content

between surface and interior took place in early stage of drying. Under this condition microcracks occurred and transformed.

Fig.2 shows the drying condition and the rate of decrease in moisture content for *Melia azedarach*. Temperature and relative humidity was kept about 50°C and below 5%. Green moisture content was between 110% and 145%. As was the case with *Cryptomeria japonica*, moisture content of specimens decreased drastically at the first stage of drying and the steep gradient of moisture content was assumed to be the reason for microcrack occurring.

The drying condition of natural acacia hybrid and the rate of decrease of moisture content are shown in Fig.3. Temperature was kept about 60°C and relative humidity was below 5%. The specimens were dried with no fan. The green moisture content was between 75% and 95%. As is the case with others, it can be assumed the steep gradient of moisture content caused microcrack occurring on the surface.

RESULTS AND DISCUSSION

CLSM system equipped with a controlled

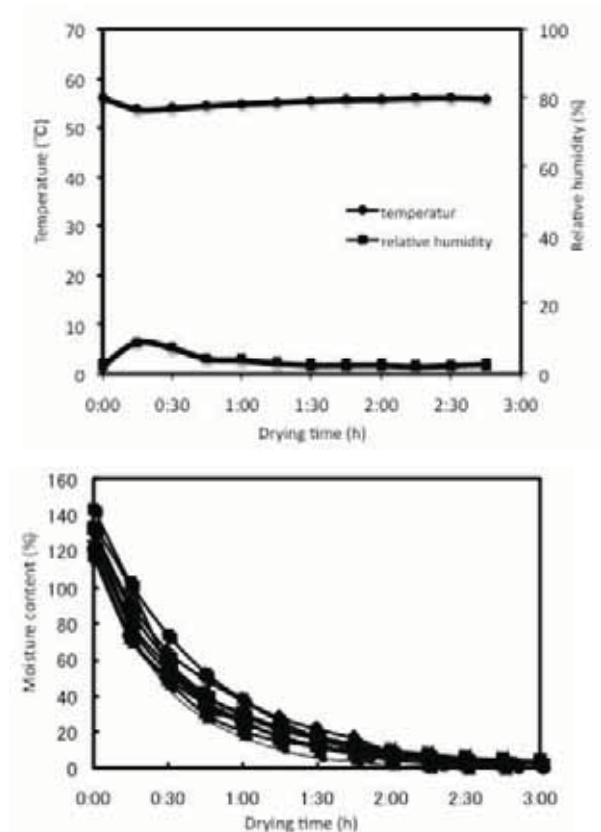


Fig.2. The drying condition of *Melia azedarach*
Upper: Temperature and relative humidity,
Lower: Change of moisture content

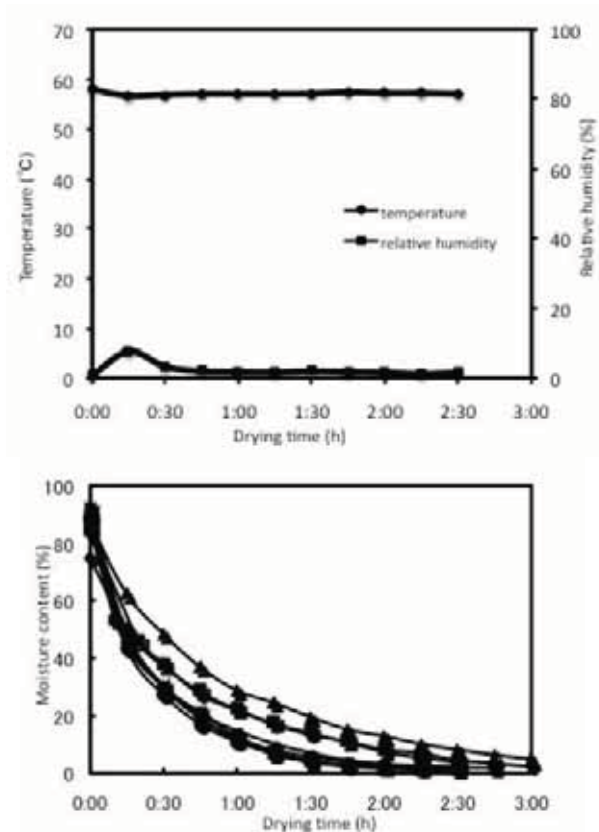


Fig.3. The drying condition of natural acacia hybrid (*A. mangium* × *A. auriculiformis*)
Upper: Temperature and relative humidity,
Lower: Change of moisture content

environment chamber made it possible to reveal microcrack transformation with time from water saturated or green condition to equilibrium moisture content of about 5%. Various types of microcrack emerged on the surface of specimens among three species.

• *Cryptomeria japonica*

The result of *Cryptomeria japonica* was reported in previous paper (Sakagami, 2009). The transformation of microcrack of *Cryptomeria japonica* is shown in Fig.4. Microcracks could not be detected on the surface at the

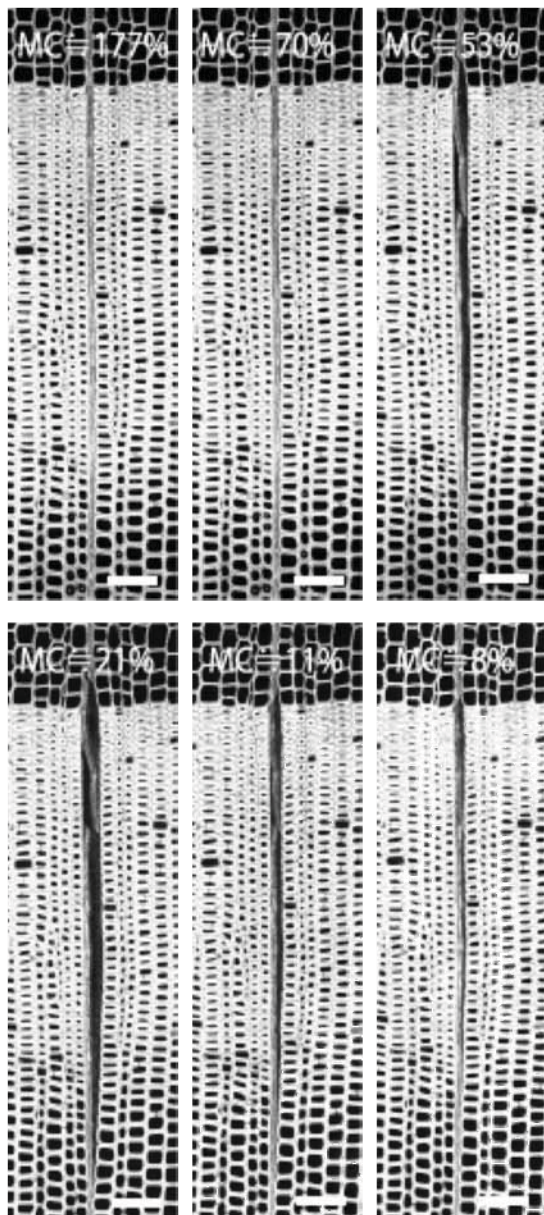


Fig.4. The relationship between moisture content (MC) and configurations of microcracks in *Cryptomeria japonica* Bar: 100µm

first stage of drying (MC=177%). With further drying, microcracks appeared between tracheid and ray parenchyma in the latewood region (MC=70%). After microcrack propagated both toward the bark and the pith along ray parenchyma, its propagation slowed down and halted. This was the largest point (MC=21%). The tip of microcrack toward the bark passed through the growth ring boundary and stopped in the earlywood region of the next ring. The tip toward the pith stopped in earlywood region before reaching the growth-ring boundary. After that, regardless of decreasing of moisture content, microcrack gradually closed and some of them could not be detected by CLSM at the last stage

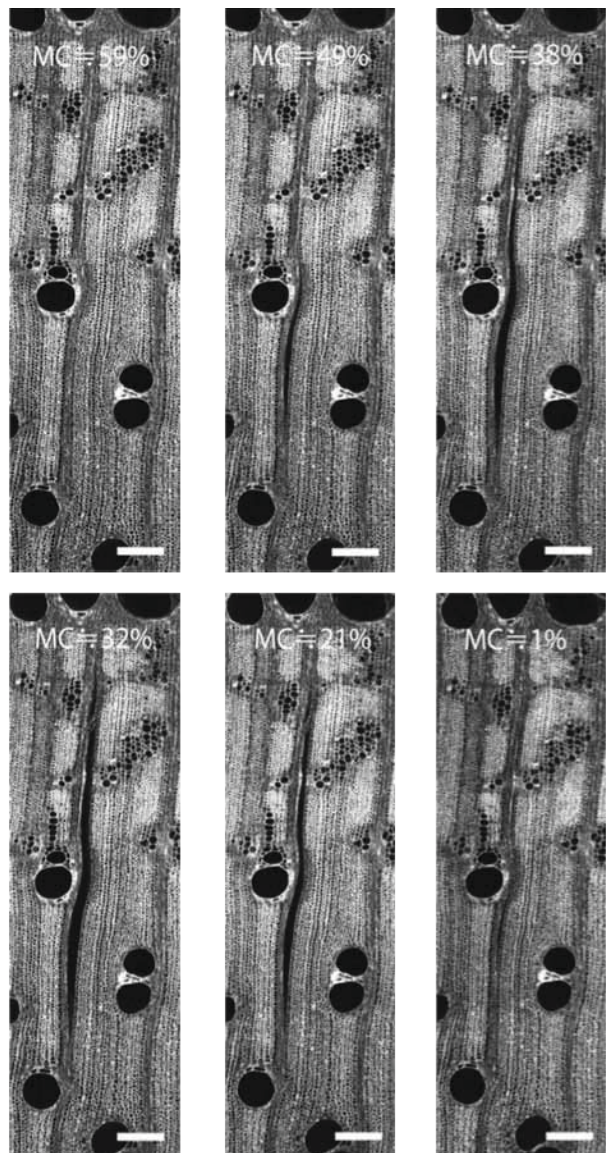


Fig.5. The relationship between moisture content (MC) and configurations of microcracks in *Melia azedarach* Bar: 200µm

of drying.

• *Melia azedarach*

Fig.5. shows the microcrack propagation of *Melia azedarach*. No microcracks could be detected on the surface of specimen in fresh condition (MC=59%). After drying was started, a few microcracks were generated along ray parenchyma in latewood region. After microcrack advanced along ray parenchyma in both the bark and the pith directions, its propagations slowed down and stopped. This was the largest point (MC=32%). The tip toward the bark stopped either at growth ring boundary or just before it. The other tip toward the pith stopped either at the vessel in the early wood or just

before it. After that, with further drying, microcracks were closed and some of them could not be detected by CLSM (MC=1%) the same as *Cryptomeria japonica*.

• **Natural acacia hybrid**

The microcrack propagation of natural acacia hybrid is shown in Fig.6. The distribution of microcracks was different from others. At the first stage of drying, there were no microcracks the same as *Cryptomeria japonica* and *Melia azedarach* (MC=86%). However, a large number of microcracks emerged along ray parenchyma on the surface of specimens and spread among some ray parenchymas. After they propagated toward both bark and pith along ray parenchyma, their propagation slowed down and stopped. This shape was the largest (MC=25%). The tips of the microcracks looked to stop at near vessel elements or neighboring tips of microcracks. Subsequently, with further drying, they gradually closed, but most of them were still observable up to the last stage of drying in contrast to *Cryptomeria japonica* and *Melia azedarach* (MC=1%).

• **Characteristics of microcracks**

From the results of this study, it was detected that microcracks generated between tracheid or wood fiber and ray parenchyma or within ray parenchyma in common for all species. The same tendency of microcrack propagation was reported by Fujita (1969) and Perré (2003). It was also reported by Zink et al. (1994) that ray cells influenced on the shifting of the failure plane in a specimen loaded parallel to grain and ray cells were poor at transmitting tangential tension. Therefore, the weakest point regarding wood structure due to drying was assumed to be ray parenchyma. On the other hand, microcracks appeared in latewood region in *Cryptomeria japonica* and *Melia azedarach* though they generated randomly on the surface of specimen in natural acacia hybrid. The shrinkage in latewood region was found to be greater than that in earlywood region (Pentoney 1953, Nakato 1958, Ma and Rudolph 2006). From the results of this study, it is assumed that the growth ring boundary influenced on the distribution of microcracks.

ACKNOWLEDGMENT

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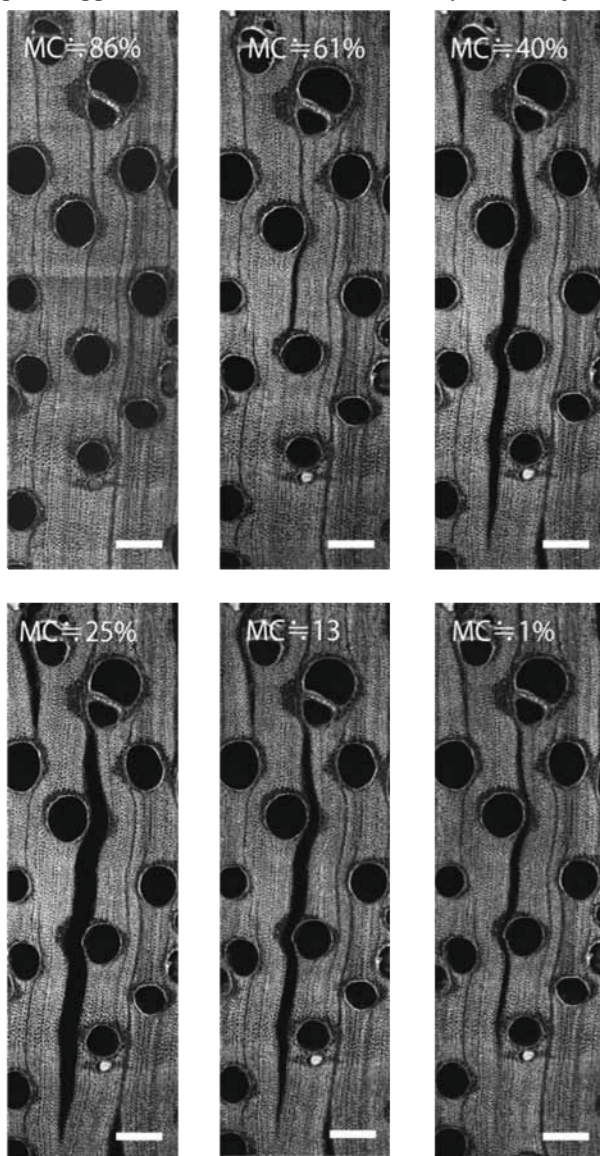


Fig.6 The relationship between moisture content (MC) and configurations of microcracks in natural acacia hybrid
Bar: 200µm

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Digital Image Analysis of Radial Shrinkage of Fresh Spruce Wood

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ABSTRACT

Contact free digital image analysis was performed of the radial shrinkage of fresh, fully saturated small spruce wood beams (*Picea abies* [L. Karst.]). A lot of work is already published regarding the drying of wood and the associated dimensional changes termed shrinkage. However, only few studies show the drying behavior of wood from the fully saturated state to the end of all shrinkage processes. Therefore it was the attempt of this study to analyze any dimensional changes along the whole moisture range. An experimental test setup was developed to ensure constant distance from CCD-camera to the sample surface as well as constant climate and light conditions during the whole experiment. With this setup shrinkage was observed on wood samples with different origin. Dimensional changes were observed immediately after the drying process has started. While an undefined part of the observed dimensional changes could be attributed to drying surface layers, an unexpected distinct effect could be observed which could not be explained by drying surface layers only. After a fast initial radial shrinkage a slowing down of the dimensional changes occurred at high mean moisture contents when the bigger part of the samples was well above fiber saturation. A complete interruption of any dimensional changes followed. Finally even a recovery from shrinkage was observed. It is assumed that besides the drying of surface layers, strong negative pressure occurred in the fully saturated capillaries due to dehydration which led to additional dimensional changes. As a consequence, the break of the water column and aeration in these capillaries finally resulted in a recovery period in the shrinkage rate due to the pressure release. After this effect, the dehydration was characterized by a phase of fast and almost linear shrinkage due to drying surface layers. Finally the shrinkage slowed down to zero when reaching equilibrium moisture content.

The Effect of an Equalizing Phase due to Reduction of Casehardening

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ABSTRACT

In conventional kiln drying of sawn timber, it is sometimes necessary to have an equalization phase after the drying phase to reduce the variation in moisture content (MC) between the planks/boards. Especially at present, where the drying processes become shorter and more effective to increase the kiln capacity and reduce the energy consumption, this may become more and more important. The equalization phase is normally performed by having an equilibrium moisture content (EMC) in the kiln 1 % lower than the desired MC of the kiln batch.

Even though the EMC in an equalization phase is almost the same as the mean MC in the sawn timber, there will be a considerable moisture uptake in the outer layer of the planks/boards due to the steep moisture gradient after the drying phase. This moisture uptake will even out the moisture gradient more or less, but in addition it will give a conditioning effect, with reduced casehardening level as a result. This effect is dependent on moisture gradient, moisture level and the EMC in the equalization phase.

Several laboratory tests are performed where the development of moisture gradient and casehardening during an equalization phase is measured.

The results show that the casehardening level is considerably reduced during an equalizing phase. It seems, however, that it is difficult to reduce the casehardening level below a gap value of 1.0-1.5 mm by using an equalizing phase alone. By an additional conditioning phase, the casehardening level is reduced to values below 1 mm, even by using a short conditioning phase of two hours.

Wood Industry and the Wood Drying Conditions in Kosovo

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ABSTRACT

The main problem of the wood industry in Kosovo is the wood drying. The problems associated with drying of softwood and hardwood lumber, produced in Kosovo and the lumber imported from the other country are discussed in this study. The conditions of the kiln drying and the forms of the lumber drying in the country was also aim of the study. The study was done based on the data collected with a questionnaire among professionals on timber trade and furniture production companies. Mostly, the imported lumber is dry, whereas the domestic lumbars are dried firstly under the air drying, continued with kiln drying. Moisture content from 10 % to 14 % is the most preferable by the end users. Lumber transportation especially by truck is negatively affecting wood moisture content, especially when trucks are not sufficiently covered during the winter. Blue stain development on domestic or imported lumber is a very serious problem for Kosovo.

The Swelling Rate Increases with Decrease of Relative Humidity during the Drying Process of Wood Fiber Composites from the Beech Wood

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ABSTRACT

Background. The wood swelling, which is one of the main problems related to the wood drying, has been studied extensively.

Aim of the study. The objective of this study was to investigate the effect of ambient temperature, relative humidity and polymer content on the hygroscopic thickness swelling rate of drying process of wood fiber composites from the beech wood.

Methods. A swelling model describing the thickness swelling process of composites exposed to water vapor conditions was developed, from which the parameter can be used to quantify the swelling rate.

Results. The results of this study indicated that the swelling model developed in this study was a good predictor of the hygroscopic swelling process of wood composites. The lower the swelling rate, the better prediction was obtained. The polymer content does not show effect on the swelling rate. The swelling rate increases linearly with a decrease in density. Temperature has a significant effect on the hygroscopic thickness swelling rate.

Conclusions. Swelling rate increases as the temperature increases. A poor relationship was found between the relative humidity and the swelling rate. However, the trend shows that the lower the relative humidity, the greater the swelling rate.

Thickness swelling, drying characteristics, vertical density profile, and hardness of thermally modified eucalyptus wood boards by hot-pressing

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ABSTRACT

Thermal treatment techniques are used for modifying wood and wood-based materials to improve dimensional stability and hygroscopicity. This study investigated the effects of press pressure and temperature on density, vertical density profile, thickness swelling, drying characteristics, and surface hardness of eucalyptus wood boards. The experimental wood boards were prepared from Turkish River Gum (*Eucalyptus camaldulensis* Dehn.). The boards with dimensions of 250 mm by 500 mm by 16 mm were thermally compressed at temperature of either 130°C or 150°C, pressure of either 40 or 60 bars for 1 hour in a laboratory type hot press. As one board for each group, totally 5 experimental boards were pressed. Surface hardness value increased with increasing press pressure in the treated groups. The thermally compressing process increased density and decreased thickness of the boards. Final moisture content (MC) and thickness swelling of the samples were not improved when compared to those of untreated samples. This research showed that different initial MC, press pressure and temperature values should be used to improve performance properties of eucalyptus wood so that end-use of the wood materials could be expanded.

Keywords: Thermal compressing, heat modification, dimensional stability, solid wood boards, density, *Eucalyptus camaldulensis*

INTRODUCTION

Turkish river red gum (*Eucalyptus camaldulensis* Dehn.) has been grown as plantation in Tarsus region, Mersin, Turkey. This species has some advantageous such as fast grown and low price. However, it has several undesired properties such as low dimensional stability, and several drying problems limiting its use. Heat treatment of wood and wood composites is known to improve dimensional stability and durability (Burmester 1973; Giebler 1983). Various heat treatment procedures such as Plato Process, Retification Process, Boise Perdure, Oil-Heat Treatment Process, and Thermowood Process are available in forest products industry (Militz 2002). Using compression and temperature on wood purposes to improve its physical and mechanical properties. Thermally compressed wood is known as staypak (Seborg et al. 1945; Stamm, 1964), while compressed wood with phenol formaldehyde (PF) resin pretreatment is called compreg (Stamm and Harris 1953; Stamm, 1964). Further studies were done by Tarkow and Seborg (1968) studying surface densification of wood. After 1980s compressed wood products for low density, and cheaper wood species were produced, especially for utilization some fast growing in Asia (Norimoto 1993; Wang et al. 2000; Norimoto 1994).

Compression in wood is generally considered to be analogous to hot pressing wood composites, except that it takes longer to obtain solid wood compression set without the bonding effect of resins. Wang and Cooper (2004) studied the effects of grain orientation and surface plasticizing methods on the VDPs of compressed balsam fir and spruce. In other study, Wand and Cooper (2005) studied the effects of hot press closing rate, wood initial moisture content, and sample size on the VDPs of thermally compressed fir wood. Density distribution through the thickness of wood composites such as fiberboard and oriented strandboard traditionally exhibits higher surface density and lower core density. Density gradient is affected by the combined influences of pressure, MC, temperature, resin curing, and other factors during pressing and affects physical and mechanical properties of the wood composites (Wang and Winistorfer 2000; Candan 2007; Strickler 1959; Kamke and Casey 1988). Because of differences in material properties and hot pressing parameters compared to wood composite production, densified solid wood boards could show a different density profile. Thermally compressing process might affect drying characteristics, dimensional stability and density, hardness and surface quality.

Esteves et al. (2007) performed steam heating process on eucalyptus wood and found that the equilibrium MC decreased by 61% and dimensional stability increased. However, mechanical properties of

the material decreased. It is reported that modulus of rupture (MOR) decreased by 50% and modulus of elasticity (MOE) decreased by 15%. Unsal and Ayrilmis (2005) used heat treatment process on eucalyptus and determined density and compression strength properties. It is stated that density and compression strength decreased with increasing treatment temperature and time. Unsal et al. (2003) studied effect of heat treatment process on physical and mechanical properties of eucalyptus wood. They concluded that density, swelling and janka hardness values decreased with increasing heat treatment duration and temperature.

Unsal and Candan (2008) studied effects of press pressure and temperature on vertical density profile, janka hardness and MC of pine wood boards. They found that final MC reduced while density and Janka hardness increased. Unsal et al. (2009) used thermally compressing technique on pine wood panels. They used press temperature of 120°C and 150°C while press pressure of 5 and 7 MPa. Thickness swelling values of the boards improved except the boards pressed at 7 MPa and 150°C.

In this research it was studied the influences of thermal modification process using hot-press on final MC, density, VDP, dimensional stability, and janka hardness of eucalyptus wood boards.

MATERIALS AND METHODS

Material

In this study, Turkish River Gum (*Eucalyptus camaldulensis* Dehn.) wood was used. The logs were obtained from Tarsus region in Mersin, Turkey. Experimental boards with dimensions of 250 mm by 500 mm by 16 mm were cut from logs.

Hot pressing procedure

The boards compressed at press temperature of either 130°C or 150°C, press pressure of either 40 or 60 bars for 60 min in a 500 mm by 500 mm laboratory type hot press (Fig. 1).



Figure 1. Hot pres

A total of five board groups with four treatment groups and a control group were investigated. Hot pressing parameters were shown in Table 1.

Table 1. Pressing parameters for experimental groups

Groups	Pressure (bar)	Temperature (°C)	Time (h)
Control	-	-	-
A	40	130	1
B	40	150	1
C	60	130	1
D	60	150	1

Testing procedure

Larger specimens (16 by 250 by 500 mm) were cut into 50 by 50 mm for all tests. All samples with grain angles of around 90 degree (radial) were chosen for this study. As two solid wood panels in one treatment group, a total of ten boards were produced. Density, vertical density profile, thickness swelling, and janka hardness were performed in this study according to international standards. VDPs were measured with an X – ray density profiler (GreCon Measurement Systems, Germany) at Kastamonu Integrated Inc. quality laboratory located in Kocaeli. Janka hardness test was performed according to ASTM D1037 (1999) standard using universal test machine. Initial MC of the samples was measured before pressing to determine drying behavior of the panels. After the treatment, final MC was also measured so that evaluating of the difference.

RESULTS AND DISCUSSION

Thickness swelling

After the hot pressing, thickness of A, B, C and D boards decreased 27.4%, 28.7%, 30.1% and 31.4%, respectively. Decrement in thickness increased with increasing press time and temperature. 2h, 24h and one week thickness swelling values of the boards are illustrated in Table 2.

Table 2. Density, thickness swelling and janka hardness results of boards

Groups	Density (kg/m ³)	Thickness swelling (%)			Janka Hardness (N/mm ²)
		2h	24h	One week	
Control	704	1.39	2.87	4.50	42.95
A	813	2.12	3.71	6.10	40.11
B	698	1.59	3.95	5.74	30.27
C	909	7.95	13.33	18.07	49.14
D	1099	3.14	9.17	13.76	38.15

Among the treated groups, the boards pressed at 40 bar and 150 °C (group B) had the lowest thickness swelling value for both 2h and one week. The highest thickness swelling values were obtained from the boards pressed at 60 bar and 130 °C (group C) for 2h, 24h and one week water soaking time. All thermally pressed panels showed higher thickness swelling values than control group. This result might be explained with springback of the boards densificated with thermally compressing. Thickness swelling values of the treated boards increased with increasing press pressure while the values decreased with increasing press temperature. Increasing in TS values with increasing press pressure could be explained with increasing springback effect. Improving in TS with increasing press temperature could be figured out changing in chemical composition of the wood. In previous study, Unsal et al. (2009) obtained parallel result for pine wood. They reported that thickness swelling and water absorption of thermally hot pressed boards significantly increased with increasing press pressure.

Drying characteristics

Average initial MC of the samples was obtained as 16%. At the end of the process, it was obtained similar MC values. Therefore it was reached that the drying effect of the hot pressing was not remarkable in those conditions. Unsal and Candan (2008) performed thermally compressing technique on pine wood panels and they obtained significant drying effect of the process. Because higher press pressure and initial MC was used in that study. In addition, wood species was pine which is softer than eucalyptus wood.

Density and vertical density profile (VDP)

Mean density values of the boards are shown in Table 2. Group D had the highest mean density value with 1099 kg/m³. Group B showed the lowest mean density value with 698 kg/m³. Mean density values of the boards pressed both at 130 °C and 150 °C increased as press pressure increased.

Peak density (PD) and core density(CD) values as VDP characteristics of boards are shown in Table 3.

Table 3. VDP characteristics of boards

Groups	Peak Density (kg/m ³)	Core density (kg/m ³)
Control	748.0	697.3
A	899.7	788.2
B	829.4	668.9
C	1034.9	902.7
D	1278.2	1097.5

The lowest PD value (748.0 kg/m³) was observed in control group while the highest value (1278.2 kg/m³) was obtained in group D. The lowest CD value (668.9 kg/m³) was observed in group B while the highest value (1097.5 kg/m³) was determined in group D. The VDPs are shown in Figure 2.

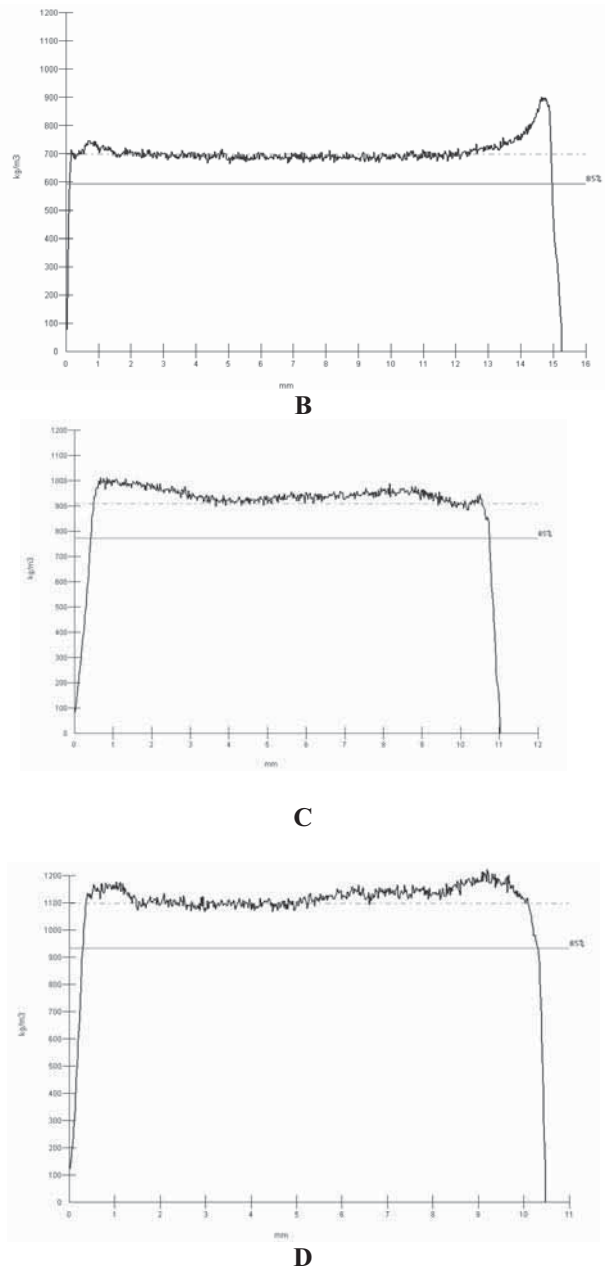
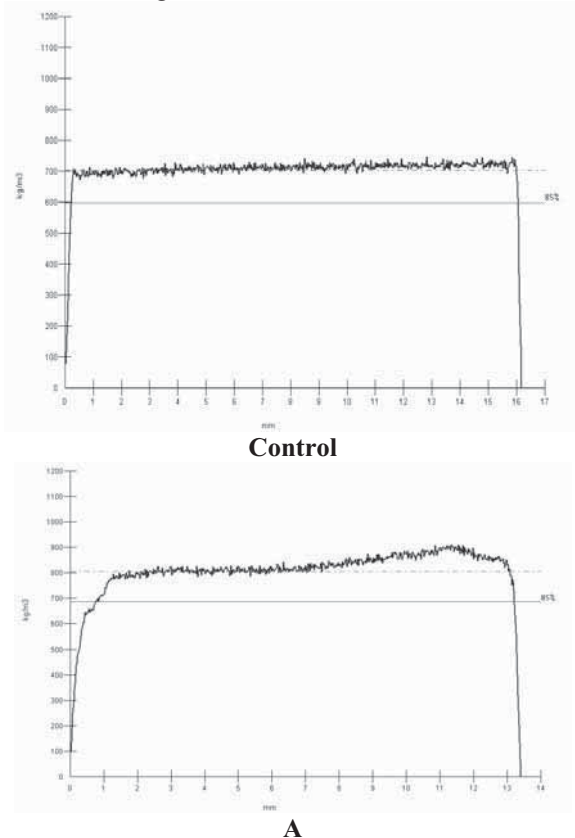


Figure 2. VDPs of boards

PD values of the boards significantly increased with increasing press pressure for both 130 °C and 150 °C. PD values of hot pressed boards were higher than control group. Similarly, Unsal and Candan (2008) found that PD values in pine wood panels increased with increasing press pressure.

Janka Hardness

Janka hardness was evaluated for control and all treatment groups as shown in Table 2. The lowest janka hardness value (30.27 N/mm²) was observed in group B while the highest value (49.14 N/mm²) was obtained in

group C. When hot press pressure increased from 40 bar to 60 bar for 130°C, the hardness value increased from 40.11 to 49.14 N/mm². Similarly, when press pressure increased from 40 bar to 60 bar, the hardness value of the boards pressed at 150°C increased from 30.27 to 38.15 N/mm². Increasing in janka hardness values could be attributed with density increasing. Janka values except group C were lower than control group because brittleness of the boards increased during the hot pressing procedure.

Similar results acquired by Unsal and Candan (2008). It was stated that janka hardness values increased as press pressure increased. The hardness values were negatively affected by press temperature increasing. This result was also supported by Unsal et al. (2003). They reported that janka hardness values of eucalyptus wood significantly decreased with increasing heat treatment temperature.

CONCLUSION

The thermally compressing procedure did not improved thickness swelling of the boards. Moisture movement in wood was not obtained in the treatment conditions because of lower initial MC under 20%. Mean density values of the boards increased as press pressure increased. It was concluded that the VDP in the solid wood panels was closely related with the press pressure and pressing temperature. Increasing in pressure and temperature resulted in improved PD and MD values which are defining factors of VDP.

This research showed that hardness values of Eucalyptus wood boards increased with increasing press pressure for both temperatures. Because of densification on the surface layers of solid wood boards, hardness values were positively affected. The highest hardness value was obtained in the board pressed at pressure of 60 bar and temperature of 130 °C.

Consequently, surface hardness of wood materials from fast growing and low quality wood species could be improved by thermally compressing procedure using hot press. Thus, using areas of these wood species might be extended. Future studies will focus the effects of pressing parameters on bending properties, surface roughness, and decay and termite resistance of solid wood boards.

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The Effect of Season, Site and Culm Height on the Drying Characteristics of the Wood of *Bambusa vulgaris*.

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ABSTRACT

Bamboo wood has been accepted as a good alternative to dwindling commercial timber species in many countries where the resource abound. It has much useful industrial material for both interior and exterior application. In Ghana, native bamboo species are underutilized mainly because of lack of knowledge of the technical properties of the species. Little information exists on most technical properties. The shrinkage in different directions, air and kiln drying properties and schedules of round and split bamboo culms are unknown. As part of a concerted effort to enhance its industrial application, the effect of sites, season and height of bamboo culms of *Bambusa vulgaris* var. *vulgaris* on shrinkage and drying properties were undertaken in southern Ghana. Preliminary results indicated significant difference in drying properties of bamboo samples with sites and height but not with season of harvest. It was recommended among others, that drying properties of bamboo using advances in drying techniques should be further studied for enhanced understanding and industrial application.

Key words: bamboo wood, drying properties, *Bambusa vulgaris*, industrial application

INTRODUCTION

Bamboos are distinct and fascinating plants with a wide range of values and uses. They provide numerous services and products for human survival especially in countries where knowledge of their properties and the dissemination of the knowledge have been thoroughly pursued. The trade in bamboo products is increasing around the world and it is estimated that globally, domestic trade and substitute use worth US\$ 4.5 billion per year and export generating over US\$ 2.7 billion (INBAR,2006). Instead of the use of timber, bamboo wood can be used to produce chairs, sofas, bookshelves, cabinets and tables and is widely regarded as an excellent substitute for wood in the form of laminated bamboo board (FAO,2006; MLF,2005). The market for laminated bamboo furniture, for instance, is growing steadily especially

in Asia. Presently, China is the only place where it is produced on a medium scale level and there is much potential, particularly in exports to more affluent countries. Despite this potential, bamboo processing and utilization is almost non-existing in Ghana compared to the extent of utilization in many countries in South Eastern Asia. Its drying is by air or solar with little or no preservatives. This practice take about two to three weeks to complete and even the desired moisture content of 6-12 per cent is unachievable by current methods. This is partly responsible for the production deficiency in pilot bamboo factory in the country. Drying of bamboo in kiln at controlled temperature minimizes the rapid deterioration of bamboo and can improve many properties of the bamboo. In an earlier work in three sites in Ghana, Tekpetey et al (2007,2008) reported significant variation in some technical properties of bamboo from

different ecological sites. In this present study the drying characteristics of bamboo culms from four sites in Ghana were assessed for enhanced processing and wider utilization.

MATERIALS AND METHODS

Field Procedure/Setting

Matured culms of *Bambusa vulgaris var. vulgaris* were randomly harvested from four sampling areas in southern Ghana: Bamboo culms were be taken from Manso Amenfi (Western Region), Kumasi (Ashanti Region), Assin Akropong (Central Region), and Akim Oda (Eastern Region) of Ghana. The samples were harvested in the dry season (December to February) and raining season (April to June, 2009). Sound internodes of culms were marked and the 4th, 8th, 12th and 16th internodes were selected for the work. A coat of paraffin wax was applied to the cut- surface to minimize or prevent moisture loss. Samples were refrigerated at 5°C to ensure freshness.

Shrinkage determination

Using ISO standard 22157-1:2000E, the shrinkage measurements were taken. The shrinkage sample of 100mm long were obtained from the lower sections of each selected internode. Shrinkage samples were air-dried for about three weeks and dimensional change were recorded regularly (every 24 hours) until constant readings were recorded. The initial and final height (h), outer diameter (D) and culm thickness (t) were measured. On each sample 4 diameters, 4 culm wall thicknesses and 2 lengths were measured. After air drying, the samples were finally dried in electric ovens at 105°C. The final values were recorded and shrinkage percentage were computed using the formula below:

$$\% \text{ Shrinkage} = \frac{(I - F)}{I}$$

Where I - initial dimensions of samples
and F - final dimension of samples

Bamboo drying characteristics

The round and split culms from the 4th, 8th, 12th and 16th internodes from the four sites were dried for the temperature range between 30°C and 100°C. Drying defects like splits, end check, twist, warping and honeycombing which usually occur during kiln drying were assessed and recorded. And the predominant defects were recorded.

RESULTS AND DISCUSSION

Outer Diameter Shrinkage

Table 1 revealed the mean values of shrinkage in the outer diameter and wall thickness from four major bamboo growing areas in Ghana. Generally, there was decline in the mean values in all the four sites from base to top (4th to 16th). The highest shrinkage value in outer diameter was recorded in culms from Manso Amenfi which is located in the Moist Evergreen Forest type of Ghana (11.65 per cent) and lowest value in Kumasi located in the Semi Deciduous Forest types (0.17 per cent). The analysis of variance indicates significant variation exist among culms from the four different zones at P < 0.05. In an earlier work in Ghana, Ebanyenle and Oteng Amoako (2007) also recorded similar findings though the work was carried out in two ecological zones. Shrinkage values according to Ebanyenle and Oteng-Amoako (2007), were 12; 8.7; 0.2 per cent for thickness, diameter and longitudinal in *Bambusa vulgaris* from Wet Evergreen (WE) Forest Type; whilst samples from the moist semideciduous (MS forest types) were 6.8 and 6.4 per cent for shrinkage in thickness and diameter respectively.

As bamboo wood loses moisture, like most timber species, there is reduction in size and dimension. Shrinking of the cell wall occurs as bound water molecules escape from the long-chain cellulose and hemicelluloses molecules in the cell wall. The amount of shrinkage that occurs is proportional to the amount of water removed from the cell wall. In other words, the more bound water removed from the culm wall, the more obvious the dimensional change. Aside the size and shape of the piece, the higher the density of the sample, the more it will tend to shrink.

Table I- Shrinkage variation in Outer diameter, culms wall thickness of *Bambusa vulgaris* from four zones of Ghana.

Site	Shrinkage (%)			
	4 th	8 th	12 th	16 th
Akim Oda (D)	5.22	5.33	5.55	4.43
(T)	7.21	6.79	6.20	3.23
Assin Akropong	8.81	6.95	5.94	4.54
	11.24	7.68	7.49	7.11
Manso Amanfo	11.65	8.17	9.88	6.56
	8.97	3.14	4.94	3.23
Kumasi	1.09	0.24	0.79	0.17
	2.81	3.18	0.10	0.37

shrinkages decrease with the height of the culm since the top portion has lower initial moisture content.

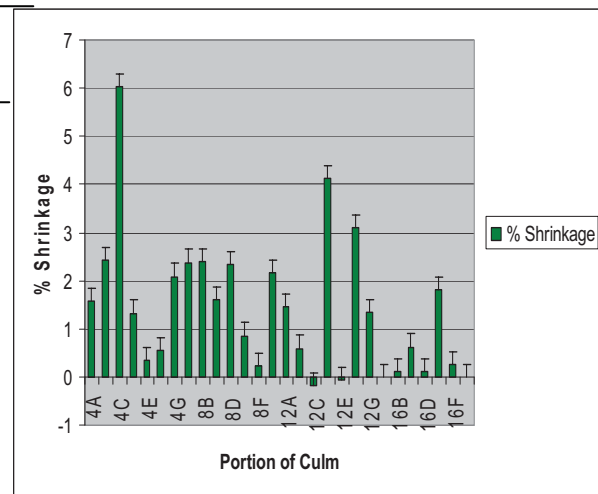


Figure i-Culm wall thickness shrinkage in *Bambusa vulgaris* from Akim Oda.

D- Outer diameter T-culm wall thickness

Culm Wall Thickness Shrinkage

A similar trend in the shrinkage values of culm wall thickness was recorded from base to top of bamboo samples as the outer diameter shrinkage (Table1). However, unlike the outer diameter shrinkages, bamboo samples from Assin Akropong recorded the highest values of 11.24 percent at the 4th internode whilst the lowest value was from Kumasi on the 12th internode (0.10 per cent). At P< 0.05 there was significant variation in shrinkage values of bamboo culms from the four sites. Espiloy (1987) obtained an average of 12.30 per cent and 7.70 per cent for radial and tangential shrinkage of bamboo culms. Also, Mohmod et al. (1991) obtained values ranging between 6.6% and 19.15%.Undoubtedly, the magnitude of shrinkage (tangential and radial) in bamboo decreases with the height of the culm and age (Mohmod et al, 1991). Though specific age of culms where not determined in this work, the within culm variation in shrinkage values in this work may be due to age difference that may exist among the culms in the natural stands. Shrinkage in bamboo is influenced by the stage of fibre maturation and the density of vascular bundles and age of bamboo culms. Older culms are dimensionally more stable than younger ones. The radial and tangential

The trend in shrinkage of individual culm wall thickness of samples fo *Bambusa vulgaris* from Akim Oda in the Moist semideciduous forest zones of Ghana is shown in Fig i .The values represent shrinkage after the air drying to final oven drying stage. The highest values was recorded in 4C-4th internode-(6 per cent) whilst the majority of samples at the top portion(16th internodes) gave relatively lower and sometimes stable dimension in their culm wall thickness.This trend from the base to the top could be attributed to the relatively lower moisture content at the top portion of bamboo culms.

Drying Characteristics Of Bamboo Culms

Air drying of the culms showed no splits at the sections of the samples but rather twisting and deformation of the original cylindrical shape were recorded along the length of the bamboo samples. Since bamboo culms have high moisture content of over 60% moisture and in most cases as high as 150% (Liese,1985) in the culms which was above the fibre saturation point for bamboo culms. As stated earlier, shrinkage begins immediately seasoning begins in most bamboo species.The oven drying method ensured that bound water was completely out of the culm material. Major defects that occurred in the bamboo culms were end checks,surface checks,hoeycombing and splits. The defects arose due to the differential shrinkages that occurred in the culm as a result of its anisotropic nature. In air and kiln drying, drying depends on the formation of a moisture gradient within the bamboo wood and timber.

Many drying defects occur when this gradient is allowed to become too steep. In particular, defects result from uneven shrinkage in the different directions of a board (radial, tangential, or longitudinal) or between different parts of a board, such as the shell and core. In this study, the waxy coat of bamboo samples were not removed, hence moisture movement was faster in inner culm than at the outer surface.

CONCLUSION

Shrinkage properties of bamboo culms from four sites in Ghana revealed there is significant variation in the outer diameter and culm wall thickness but there was significant variation in the properties in relation to season of harvest. It is further important that extensive work on the properties like mechanical properties and drying schedules based on new advances in wood drying will be explored for native and exotic bamboo wood as well as the dwindling traditional economic wood species.

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