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Effects of Vacuum Drying with Infrared Heating on Some Properties of Wood

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Abstract: *Effects of vacuum drying with infrared heating on some properties of wood* **.** Drying of wood is one of the most important industrial processes in wood manufacturing. Mechanical properties of wood are affected from drying process. Heating method of the drying process is the most effective factor on the properties of end product. The aim of this study was to determine the effect of infrared heating in vacuum drying on the drying quality and mechanical properties of wood. For this purpose Oriental beech (*Fagus orientalis* L.) and Scots pine (*Pinus Sylvestris* L.) samples were dried by vacuum drying with infrared heating at $41^{\pm}1$ $^{\circ}$C temperatures and at $110^{\pm}10$ mbar ambient pressure for 48 hours. Final moisture content (MC) distributions, case hardening, modulus of elasticity (MOE), modulus of rupture (MOR) and compression strength (CS) of dried samples were determined. According to the results of the test, although average MC of the pieces met the requirements of the standard drying class, distribution of the individual MC did not meet the requirements in both pine and beech. Vacuum drying with infrared heating increased the MOE, MOR and CS of Scots pine and only CS of beech. MOE and MOR of beech were not affected from drying with infrared heating.

Keywords: vacuum drying, infrared heating, drying quality, Scots pine, beech, mechanical properties

INTRODUCTION

Drying of wood is one of the most important industrial processes in wood manufacturing. There are many methods, which are widespread used to drying lumber such as air drying, shed air drying, forced-air shed drying, warehouse pre-drying, low temperature kiln drying, conventional electric dehumidification kiln drying and conventional steam-heated kiln drying (Denig et.al., 2000). Drying is the most energy-intensive and time-consuming component of the lumber manufacturing process. Currently, over 80% of the produced lumber has been dried in conventional and vent kilns. Although this operation is simple and inexpensive, the product quality is often low and the drying time is very long, especially for hardwoods (Li et al., 2008).

An incorrect drying process generates cracking problems, rupture of the cellular structure of the wood, folding in the piece, and in general an inadequate drying stage. These alterations devalue the final product and important losses for the wood industry take place. Drying influences the mechanical properties of wood in three ways, namely through the direct effect of moisture loss, the internal drying stresses and strains. (Taskini 2007)

Many studies have been carried out on vacuum drying of wood. Water in wood at the sub-atmospheric pressure can be vaporized and moved at a temperature below 100 ^{0}C as rapidly as for high temperature drying at the atmospheric pressure. Therefore, vacuum drying has the benefits of high temperature drying without the danger of developing defects with some susceptible species. (Jung et al. 2004)

Generally, there are two basic processes (continuous or discontinuous) and three type of heating (by convection, heating plates or microwave) in vacuum drying. In discontinuous vacuum drying the wood undergoes repeated changes, first being heated at atmospheric pressure then demoisturised at low pressure without any heat. There is considerable risk of discoloration owing to the presence of a high oxygen component during heating phase. In continuous vacuum drying there is simultaneous heating and demoisturising most of the time, at reduced pressure; external air is excluded. With convection heating the air speed must be suitably high owing to the low density of the drying agent. With direct heating no fans at all required but there are serious problems: heating plates are only used individually and only for small useful volumes owing to their limited size and the very laborious, time consuming job of stacking and removing from the stack. The other direct heating method is the use of microwaves. Apart from the comparatively high capital cost and greater likelihood of malfunctioning it is very difficult to obtain homogenous intensity distribution over the whole stack. (Brunner 1993)

Jomaa and Baixeras (1997), Chen (1997), Audebart et al. (1997) and many other researchers studied on vacuum drying with heating by convection or heating plates. Recently, researchers have focused on vacuum drying of wood with radio frequency and microwaves. Koumoutsakos (2001) investigated the energy dissipation coupled with heat and moisture mechanisms in wood during radio frquency/vacuum drying. Li et al. (2008) established a one-dimensional mathematical model to describe the process of wood microwave-vacuum drying based on the mechanism of moisture and heat transfer in wood. Hansmann et al. (2008) used the high-frequency energy assisted vacuum drying to improve drying quality of fresh *Eucalyptus globulus*. Abubakari (2010) studied on the effect of RF heating as pre-conventional kiln treatment on the drying characteristics and quality of sub-alpine fir lumber. Jung et al. (2004) compared the vacuum drying characteristic of radiate pine using contact heating, radio frequency heating and the combination of both. Möttönen (2006) compared the conventional low temperature drying with vacuum drying in terms of variation in drying behavior and final moisture content. Unlike these studies Perre et al. (2004) used infrared (IR) heating in vacuum drying of wood. They noted that IR heating could be used successfully in the vacuum drying. In most of these studies drying rate and moisture distributions were reported. Very little studies included the effect of drying specifications on the drying quality and mechanical properties of wood. Taskini (2007) made a comparison between microwave, infrared, and convectional drying effects on wood strength and reported that drying time of the microwave heating is significantly reduced, while the strength stays higher than that obtained in convectional and infrared drying.

RESEARCH OBJECTIVE

The aim of this study was to determine the effect of infrared heating in vacuum drying on the drying quality and mechanical properties of wood. For this purpose Oriental beech (*Fagus orientalis* L.) and Scots pine (*Pinus Sylvestris L.*) samples were dried by vacuum drying with infrared heating and final moisture content (MC) distributions, case hardening, modulus of elasticity (MOE), modulus of rupture (MOR) and compression strength (CS) of dried samples were determined.

MATERIAL AND METHODS

In this study Oriental beech (*Fagus orientalis* L.) and Scots pine (*Pinus Sylvestris L.*) were used as a wood material. Samples were sawn with a thickness of 25 mm, a width of 100 mm and a length of approximately 3000 mm. The samples were of best quality without any cracks, cell collapse, warp, or obvious discoloration. Then they were divided into two parts and one part of each sample was dried in a conventional kiln by a commercial lumber supplier according to their professional experience. These samples were used as the control group to determine the mechanical properties. Other parts of samples were dried with vacuum drying with infrared heating in a laboratory scale vacuum chamber. Before drying, 200 mm were cut off on both ends of the boards in order to remove any pre-dried wood and due to manipulation damaged material. A sample with a width of 50 mm was cut of at the middle of each board for determining the initial moisture content (MC) by oven drying at 103 $^{\circ}$C and for determining the density. Because of smallness of the pilot vacuum drying chamber, samples were cut into a length of 500 mm before drying. Oven dry densities, initial and final MC and drying rate of the samples were given in Table 1.

Samples were dried in a sealed vacuum chamber. Heating for drying were supplied by 4 ceramic infrared heaters having 2-10 µm wavelength and 16 kW/m^2 surface ratings and were placed at the two sides of the stack. Ambient temperature of the chamber was measured at the top of the stack, and core temperature of the wood was measured from samples in the middle of the stack. Measuring probe was inserted into half of the thickness of the sample. It was measured 10 °C difference between chamber and core temperature of samples during drying. Vacuum was supplied by an oil vacuum pump.

Table 1. Oven dry densities, initial and final MC and drying rate of the samples

Wood	Oven dry density (g/cm^3)	Initial MC %	Final MC %	Drying time h	Drying rate %/day
Beech	0,663	47	13	48	17
Scots pine	0,457	46	10	48	18

Stack was placed in the chamber and dried at 110±10 mbar absolute pressure and 41±1 °C (core temperature of wood) temperature for 48 hours. After drying, each wood sample was weighed and inspected for occurrence of any drying defects in the form of surface checking.

Drying quality of the process was assessed according to TS EN 14298 (2006) standard. Samples were marked and cut into wood sections to determine the average final moisture content, the MC distribution, for internal checking and case hardening. Wood sections were quickly weighed with a digital balance having sensitivity 0.01 g to determine the individual MC. Case hardening of the samples was determined according to TS ENV 14464 (2005) standard.

Effects of vacuum drying with infrared heating on the mechanical properties of wood were investigated. Modulus of elasticity (MOE), modulus of rupture (MOR) and compression strength were determined according to TS 2478 (1976), TS 2474 (1976) and TS 2595 (1977), respectively.

RESEARCH RESULTS

Beech and Scots pine wood were dried by using vacuum drying with infrared heating for 48 hours. No visual defects were detected on the surface of the dried samples. After sectioning of the samples, each section was inspected and there was no internal check. For beech and pine, the average final MC values were measured as 12% and 10% and drying rate were calculated as 17 %/day and 18 %/day, respectively. The individual MC distribution was between 7.2% and 12.9% in pine samples and between 6.5% and 18.5% in beech samples. The MC distribution across the length and width of the vacuum dried samples are given in Figure 1.

According to TS EN 14298 standard, allowable range of average MC around the target MC (12%) is ±1.5% and 93.5% of the pieces should have individual moisture content between 15.6% and 8.4%. According to measurements 87.5% of the pine pieces and 75% of the beech pieces had individual MC between this ranges. Although average MC of the pieces met the requirements of the standard drying class, distribution of the individual MC did not meet the requirements in both pine and beech. As can be seen in Figure 1, average MC at the middle of the beech samples was much higher than that of at the end of and outer side of the samples. That is why the distribution of the individual MC exceeded the allowable range for the standard drying class. Although the MC difference between inner and outer side of pine samples was relatively low, it was also out of allowable rage.

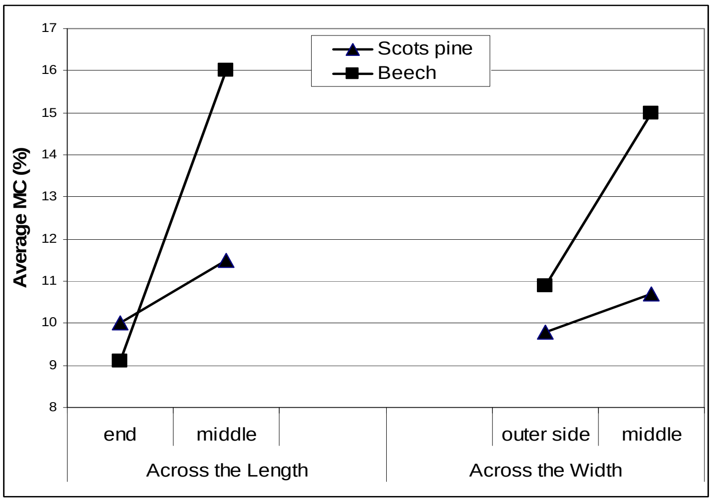

Figure 1. MC distribution across the length and width of the vacuum dried samples

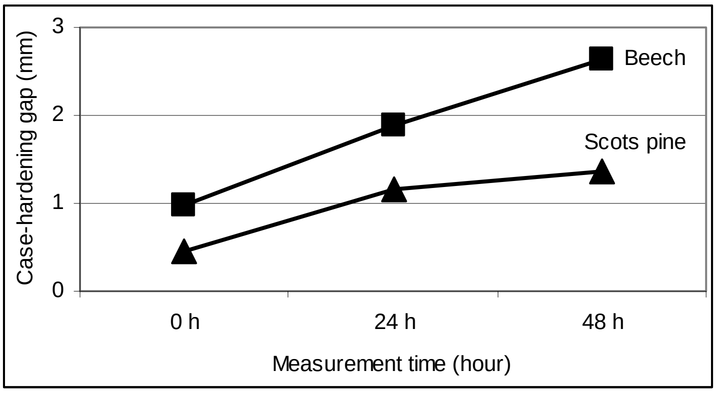

Figure 2. Casehardening gap values of vacuum dried wood samples

Casehardening gap values of vacuum dried samples with infrared heating are illustrated in Figure 2. Casehardening gap of beech was higher than that of pine. The gap increased with time. According to Abubakari (2010) casehardening is a condition of stress and set in wood in which the outer fibers are under compressive stress and the inner fibers under tensile stress, after drying. Casehardening is caused by too rapid or uneven drying as a result of too high temperature or too low relative humidity or large fluctuation of both. According to these results it can be said that vacuum drying of Scots pine and beech with infrared heating is not proper enough in terms of drying quality assessment.

Mechanical properties of wood are affected from drying process. Because of this, the selection of drying process is very important. The most important mechanical properties of wood are modulus of elasticity (MOE), modulus of rupture (MOR), and compression strength (CS) in the many applications. According to the test results, mean and standard deviation values of these mechanical properties are given in Figure 3.

It has been seen that the drying process used in this study affected the MOE, MOR and CS values. It has been found that the MOE, MOR and CS values of the test samples varied between 9504.82-10551.49 N/mm^2, 99.29-130.83 N/mm^2, and 51.53-66.69 N/mm^2, respectively. The variance analysis was applied on data belonging to these mechanical properties of samples, and the results were shown in Table 2.

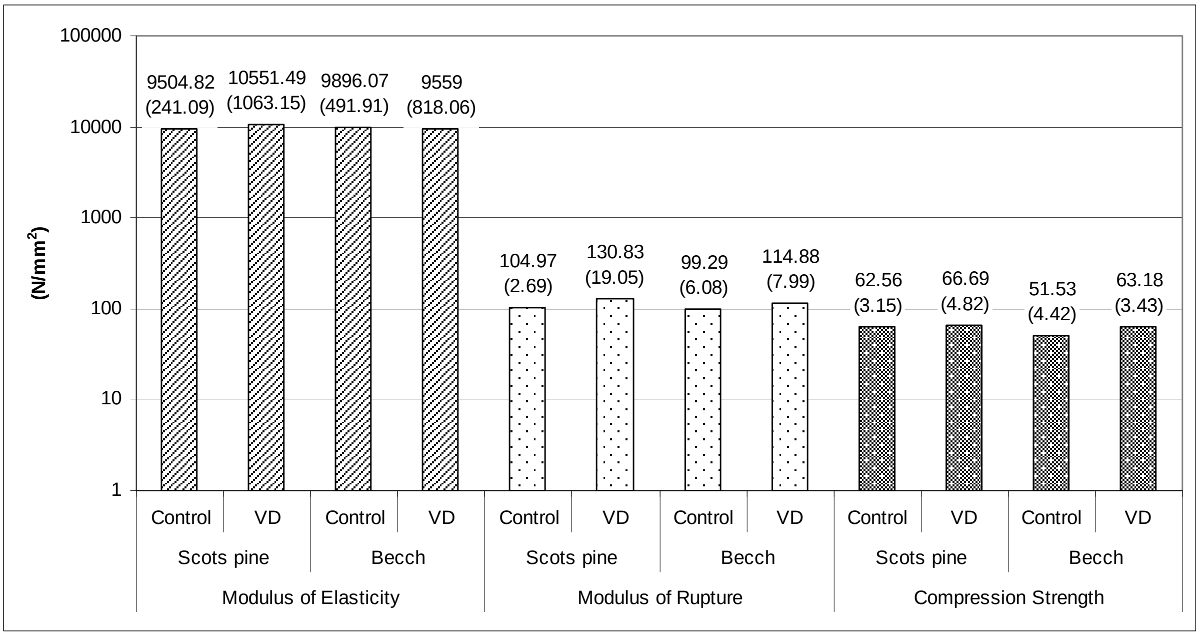

Figure 3. Mechanical properties of Scots pine and Beech wood
(VD indicates Vacuum Drying and Values in the parenthesis indicate standard deviation)

Table 2. The results of variance analysis

	MOE (N/mm^2)		MOR (N/mm^2)		CS (N/mm^2)	
Source	F	P<0,05	F	P<0,05	F	P<0,05
Corrected Model	30529	0,000	32.44	0,000	53.39	0,000
Intercept	14870.86	0,000	8600.55	0,000	18454.1	0,000
A: Wood species	16132	0.07	19.88	0,000	65.5	0,000
B: Drying types	40759	0.03	72.95	0,000	77.11	0,000
AxB	18.24	0,000	17989	0.04	17.57	0,000

According to the variance analysis, it has been seen that while the effects of drying types, wood species and interaction of them on both modulus of rupture and compressive strength properties of wood were found statically significant at 95% significance level. However, just only the effect of wood species used in this study on the modulus of elasticity value of test sample was not found at 95% significant level. To comparisons of these means were done by employing a Duncan test and the results are given in Table 3.

Table 3.The results of Duncan Test

MOE (N/mm^2)			MOR (N/mm^2)			CS (N/mm^2)		
Experimental design	Mean	HG	Experimental design	Mean	HG	Experimental design	Mean	HG
Scots pine-control	9504.81	A	Beech-control	99.29	A	Scots pine-control	51.53	A
Beech-vacuum drying	9559.00	A	Scots pine-control	104.97	A	Beech-vacuum drying	62.56	B
Beech-control	9896.06	A	Beech-vacuum drying	114.87	B	Beech-control	63.18	B
Scots pine-vacuum drying	10551.49	B	Scots pine-vacuum drying	130.83	C	Scots pine-vacuum drying	66.68	C

It was shown that vacuum drying with infrared heating did not affect the MOE of beech wood. According to the Duncan test there was no statistical difference between MOE values of vacuum dried and control of beech specimens. Because of the fact that MOE values determined from Scots pine-Control, Beech-Vacuum drying, and Beech-Control was seen much closer to each other; they were given the same homogenous groups. Vacuum drying with IR heating increased the MOE of Scots pine, statistically. It can be said that according to the result of Duncan test, vacuum drying with IR heating increased the MOR values in both Scots pine and beech specimens. Although MOR values, which were obtained from both Beech-control and Scots pine-control were given at the same homogenous group, the others were shown at different homogenous groups. It can be seen that CS values of beech were not affected from vacuum drying with IR heating. However, CS of Scots pine had dried with IR was much higher than that of control. Vacuum drying with IR increased the CS of Scots pine significantly. Contrary to these findings, Taskini (2007) reported that the infrared drying can reduce the strength of the spruce woods significantly. This contradiction may be explained by the ambient pressure. Drying under vacuum might eliminate the decreasing effect of IR heating.

CONCLUSIONS

Drying of wood is one of the most important industrial processes in wood manufacturing. Drying conditions influence the properties of wood. Effects of vacuum drying with IR heating on drying quality and mechanical properties of Scots pine and beech wood were investigated.

1) Vacuum drying with infrared heating can be used to dry Scots pine and beech, successfully. Vacuum drying decreased the drying time significantly compared to conventional drying.
2) Average MC of the Scots pine and beech after vacuum drying with IR heating for 48 hours was acceptable according to standard drying quality class. But distribution of the individual MC did not meet the requirements of the standard drying class in both Scots pine and beech.
3) Casehardening of beech was much higher than that of Scots pine after vacuum drying with IR heating.
4) Vacuum drying with IR heating increased the MOR value of beech while the MOE and CS values of beech were unaffected. It increased the MOE, MOR and CS values of the Scots pine, significantly.

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Streszczenie: *Wpływ suszenia próżniowego z ogrzewaniem za pomocą podczerwieni na niektóre właściwości drewna.* Metoda ogrzewania w procesie suszenia drewna ma duże znaczenie dla właściwości uzyskanego produktu. Celem pracy było określenie wpływu suszenia próżniowego z ogrzewaniem za pomocą podczerwieni na niektóre właściwości drewna. Stwierdzono między innymi, że ogrzewanie za pomocą podczerwieni powoduje wzrost modułu Younga, wytrzymałości na zginanie oraz ściskanie drewna sosny oraz wytrzymałości na ściskanie drewna buka.

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