DRYING PROCESS IN NORWAY SPRUCE WOOD EXPOSED TO INFRARED RADIATION

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The drying process of Norway spruce (*Picea abies* [L.] Karst) wood exposed to infrared heat radiation was studied by measuring the moisture profiles of the wood samples at controlled temperature during drying. The thermal treatment was executed in a purpose-made industrial pilot-plant containing the heat radiators covered by infrared (IR) transmition filters. The moisture content of the samples was detected at certain stages of the process. Based on the results of exposing the samples to IR radiation for 15, 25, 35, and 45 hours, the drying mechanism of wood is discussed. The moisture transport mechanism was explained by a semipermeable membrane process considering the moisture content as a dilute aqueous solution. If the semipermeable cell wall allows only the passage of water but not that of solute molecules, water diffusing from the region of higher (center) to lower (periphery) water content produces osmotic pressure difference between the two sides of the cell walls. The importance of this osmosis was considered in the approach of moisture migration.

Keywords: IR thermal treatment; Permeability; Osmosis

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INTRODUCTION

Wood is considered a complex composite structure, which consists mainly of cellulose, hemicelluloses, and lignin. Cellulose represents the substantially crystalline part of wood, while the structures of hemicelluloses and lignin are amorphous. The main mechanical function of hemicelluloses and lignin is to buttress the cellulose fibrils.

Since wood is a hygroscopic material, its properties and suitability for further use are determined by its moisture content and the state of its solid framework. According to recent theories, moisture in wood can exist in the following forms: as vapor in the pores, capillary or free (liquid) water also in the pores, hygroscopic or bound water in the solid structure (Siau 1984), and constitutive water in the chemical composition within cell walls (Blasi et al. 2003). Water moves within wood as either liquid or vapor through several types of pathways depending on the nature of the driving force (e.g. pressure or moisture gradient) and variations in wood structure (Nawshadul 2002). In general, it is suggested that transport of water vapor occurs by both convection and diffusion, while capillary water is transported mainly by convection, and bound water can move essentially by surface diffusion (Blasi 1998).

Thermal treatments are often applied to dry wood, and the type of the technique strongly influences the quality of wood and predicts the possible use of the material. The thermal treatment technologies used in the industrial practice are based on the same convective heat transport phenomenon by adding different additional influencing parameters (Pang et al. 1995; Perré and Turner 2002; Surasani et al. 2008; Galgano and Blasi 2004; Brito et al.2008).

Heating wood to high temperatures changes its physical and chemical properties (Windeisen et al. 2007; Mburu et al. 2008; Tsuchikawa et al. 2003; Yildiz et al. 2006). Moreover, the moisture transfer mechanisms above the boiling point of water differ from those that occur below the boiling point. It is necessary to determine some physical phenomena (moisture diffusion; pressure) that directly influence mass transfer during drying at high temperatures (Cai and Oliveira 2010).

In this paper, we used a radiative drying method as an alternative to the conventional, convection-based wood drying process. In contrast to the previously adopted theory that an evaporation process of the drying front is driven by diffusion and capillary forces and ceases upon drying at the fiber saturation point, we hypothesize that the evaporation process under infrared thermal treatment is governed by osmosis due to the semipermeability of the wood structure to aqueous solutions.

EXPERIMENTAL

Experimental Setup

A temperature-controlled experimental furnace was developed using IR heat emitters. The temperature of the heating wires was set to 150 to 180 °C. The temperature of the furnace area was around 120 to 140 °C. The heating blocks were made up of two rows of six IR emitters at two vertical sides of the furnace (Fig.1).

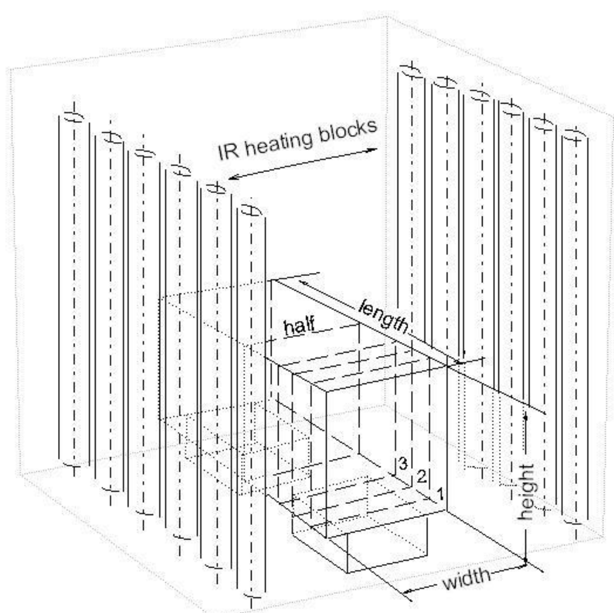

Fig. 1. Schematic of the furnace area with the position and orientation of the sample between the IR heating blocks.

The clearance between the IR emitters could be adjusted to the size of the sample. The IR emitters were adjusted to leave a maximum of 50 mm clearance on either side. A special coating was used around the heating wires that transmits only the IR radiation. The temperature of the heating wires was measured and controlled by a digital temperature controller (Dixell s.r.l, It) involving an on-off control system. Simultaneously, the surface temperature of the heating blocks was measured at the outer side of the transmitting coating. The pressure inside the furnace was atmospheric. The moisture content of the samples was measured by Elbez WHT 860 digital moisture meter (Elbez, Cz). The measuring limit of this device was at around 7% of moisture content.

Sample Preparation

The measurements were executed on Norway spruce (*Picea abies* [L.] Karst) wood. To measure the moisture distribution, rectangular timbers sized 200×200×500 mm were dried. Two replicates were measured connecting to the same treatment adjustment. These samples were exposed to symmetric boundary conditions by being heated on two sides by the parallel IR heating blocks. The position and the orientation of the samples between the IR emitters are presented in Fig. 1. By sealing the butt-edges of the timber with a high temperature resistant, waterproof polymer (silicone), mass loss was allowed only through the surfaces parallel to fiber direction. The initial moisture content of the samples varied between 30 and 70 percent.

Moisture content was measured in two separate ways. On the one hand, 50 mm thick slices were cut off from the butt-edge after 15, 25, 35, and 45 hours of IR irradiation. The cut ends of the piece of the samples were sealed with silicone again after every cut. The actual moisture distribution in the slices was measured along a set of concentric circles centered around the pith. On the other hand, to receive *in situ* moisture data, six moisture sensors were also built in through the top of the samples. These sensors were placed in 10 cm depth measured from the top and in 0.1, 2, 4, 6, 8, and 10 cm distance measured from the irradiated surface. Symmetrically to the fixed moisture sensors, there were six temperature detectors also built in the samples in 0.1, 2, 4, 6, 8, and 10 cm distance from the irradiated surface.

The results for a piece of green (freshly cut without air drying) sample are discussed here.

RESULTS

The moisture distributions in cut slices after 15, 25, 35, 45 hours of irradiation are shown in Fig. 2. The average moisture content of the slice cut after 15 hours (Fig. 2.a.) was 22%. There was a little change in the moisture profile of the slice around the periphery obtained after 25 hours compared to the previous one (Fig. 2.b.). The average moisture content of the slice cut after 25 hours decreased only to 20%. Interestingly, the moisture values in the center of the slice treated for 35 hours increased in contrast to that of the 25 hours slice (Fig. 2.c.). However, the average moisture content of the slice cut after 35 hours were still around 21%. The condition of the last slice was close to the air-dried state with an average 14% moisture content.

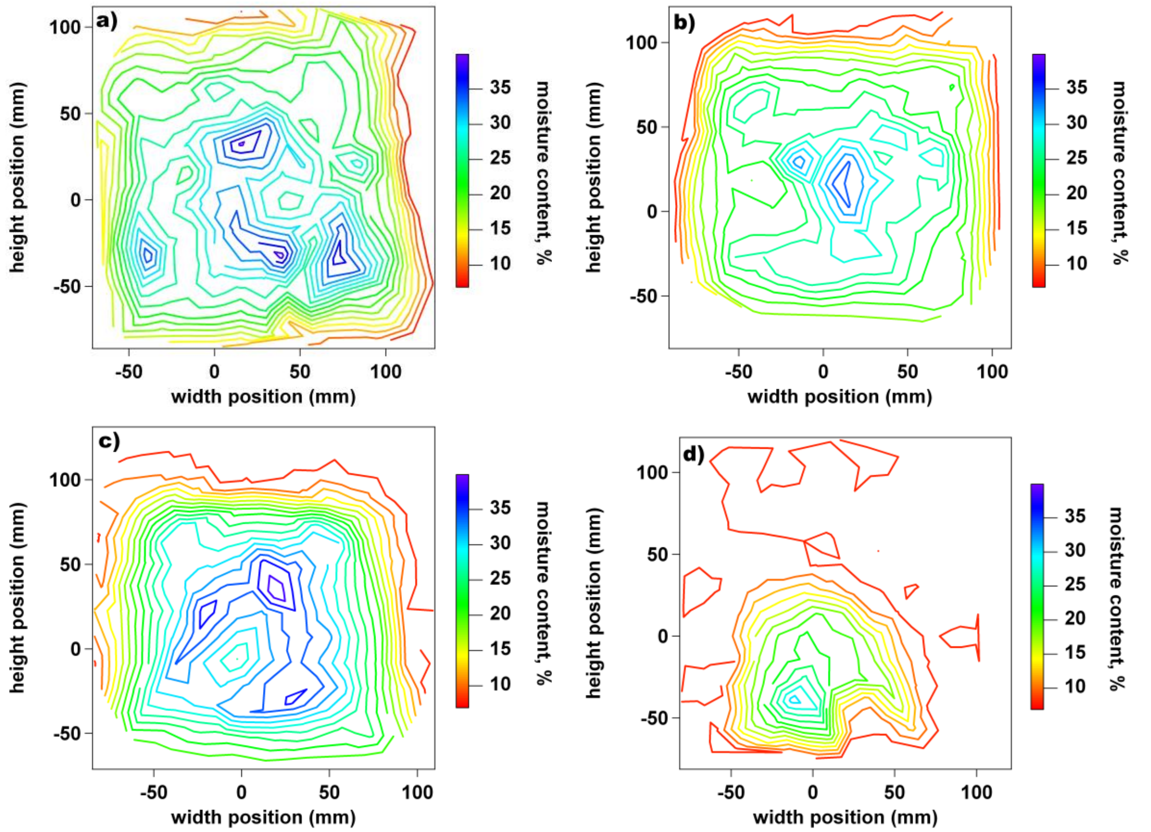

Fig. 2. Moisture distribution of the sample exposed to IR radiation for **(a)** 15, **(b)** 25, **(c)** 35, and **(d)** 45 hours. The colour coding of the contour lines is indicated on the left side. The zero point of the width and height positions was set to coincide with the pith.

A comparison was made among the moisture profiles measured at different time intervals along the cross-line at pith height (70 mm above the bottom) and at 150 mm above the bottom (Fig. 3.). These two heights of sampling were chosen because of the inhomogeneity of the sample as well as the heating conditions in the furnace. Especially, the supporting pillars are intensive heat absorbers. Consequently, the bottom of the sample was always cooler than its top. This tendency can be seen in Fig. 3. The moisture profile in the pith-line (Fig. 3.a.) shows higher values than the data collected in the top-line (Fig. 3.b.) at the same time range of the IR treatment.

After 15-hours of irradiation, a parabolic moisture profile was formed in the pith-line (Fig. 3.a.), as had been affirmed during convective heat treatments (Younsi et al. 2007; Imre 1974). The moisture profile obtained after 25-hour irradiation was similar to the previous one, except for the decreased moisture content around the pith-region. The moisture profile after 35-hour irradiation followed a parabolic shape again. Drastic change in the shape of the moisture profile was obtained from the slice treated for 45 hours. The parabolic shape was retained only in the -40 to 70 mm width range, while the periphery was completely dried.

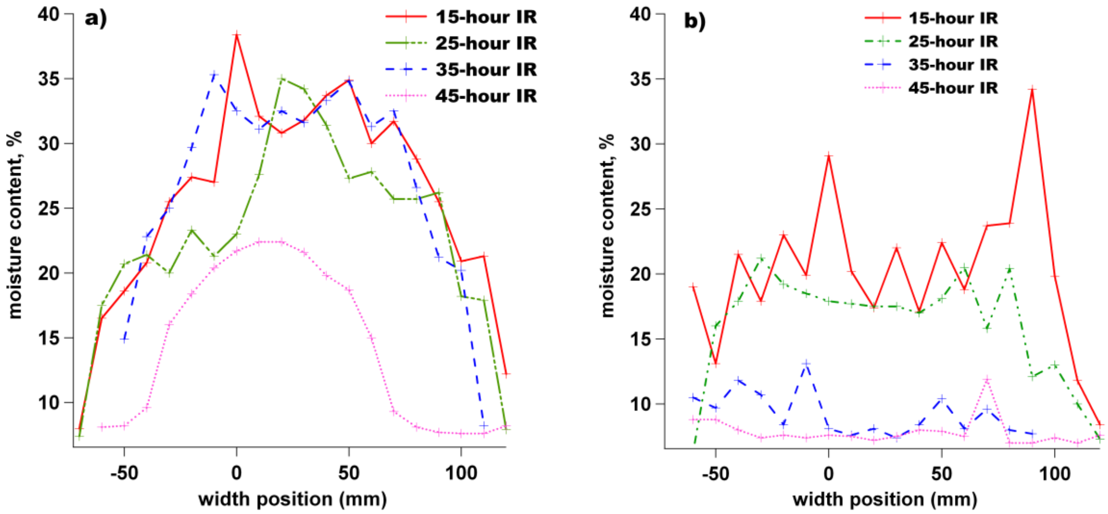

Fig. 3. Moisture profiles of the slices in the cross-line of the **(a)** pith height (70 mm above the bottom) and **(b)** 150 mm above the bottom of the sample. The corresponding treatment time ranges are indicated in the legend. The zero point of the width position was set to coincide with the pith.

The shape of the moisture profiles measured at 150 mm above the bottom (Fig. 3.b) shows more homogeneous values. Although the character of the drying profiles obtained after 15 and 25 hours can be approached by parabola, it is flatter than those obtained at pith height. After 35-hour irradiation, the moisture profile – in contrast to the pith-height profile – shows the dry state. After 45-hours irradiation, the profile shows the end of the drying process.

Data collected by the fixed moisture sensors before and after each cutting process are summarized in Table 1. There was no mode to collect accurate data from the last (45-hour) cutting process, because the direct connection between the sensor and the wood material ceases due to warpage. The moisture content at the periphery is usually less before the cutting than after.

Table 1. Temperature and Moisture Content of the Sample Before and After Cutting the Slices

Position of the moisture and temperature sensors starting from the sample surface (cm)	(Temperature, ºC) Moisture content (%)					
	15-hour IR		25-hour IR		35-hour IR	
	before cut	after cut	before cut	after cut	before cut	after cut
0.1	(99) 10>	(91) 10>	(110) 10>	(83) 10>	(115) 10>	(95) 10>
2	(98) 10>	(85) 14	(109) 11.4	(103) 11.1	(112) 10	(108) 10
4	(95) 39.9	(89) 47.5	(105) 24.3	(101) 29.9	(107) -	(107) 13.2
6	(96) 34.5	(95) 45.3	(105) 22.3	(103) 34.9	(107) 15.7	(107) 16.1
8	(93) -	(91) 42.8	(103) 18.7	(101) 32.9	(104) 13.4	(105) 15.1
10	(88) 24	(88) 44.3	(95) 20.7	(95) 30	(97) 13.6	(97) 17

The temperature values collected before and after the cutting processes are indicated in parentheses in Table 1. The temperature of the periphery was always higher before the cutting than after. In the center region, no significant temperature change was observed.

DISCUSSION

One aspect of the monitoring of the effect of the IR irradiation on the wood drying process is the transport mechanisms occurring within the material. The heat and mass transfer process was followed up by measuring the moisture content *and temperature* of the samples.

Because of the long drying time, drying experiments in pilot plants are not conventionally done on thick timbers. However, to perform accurate investigations of moisture movement, thick samples are required. Therefore, in contrast to the general practice of examining lumbers of approximately 20 to 50 mm thickness (eg., Rozas et al. 2009; Hakkou et al. 2005; Awoyemi and Jones 2010; Ohmae and Makano 2009; Pang 2002; Gonzalez-Pena and Hale 2010), we executed our measurements on rectangular timbers of 200 mm thickness. In this way, it was possible to follow the gradual nature of the drying process.

When comparing the moisture distribution of the slice cross-sections (Fig. 2.) we observed that the air-dried region increased continuously from the periphery while there was a wet central part even in the last slice. Between these two regions, there is a relatively steep moisture content drop. This moisture drop region moves towards the center with time.

An increase of the moisture content was observed directly after each cutting stage (Table 1). Since the measuring device can only detect liquid phase water content, a condensation process must occur during the cutting procedure. It can happen because the cutting procedure included the removal of the sample from the furnace, which inevitably resulted in some temperature loss of the sample. Due to this condensation, the proportion of the liquid phase water content increased inside the wood, while the total moisture content remained almost the same. Consequently, significant amount of immobile gaseous phase moisture had to be produced before the cutting process. The evaporation process has been already observed by other researchers as well (Di Blasi et al. 2003; Pang et al. 1995; Galgano and Blasi 2004; Zhang and Cai 2008).

At this point the logical question arises about the nature of the temporarily phase change of this portion of the water content. The natural gas bubbles occurring mostly in the heartwood and the pith of the Norway spruce can account for only a minimal amount of vapor even at around 100 ºC. Therefore, we assume that the gaseous phase moisture was produced due to the boiling of water.

Interestingly, the temperature values measured parallel with the moisture data are below 100 ºC until 15-hour-irradiation and in the center during the whole IR process. This condition requires that the boiling of water occurs below 100 ºC which is only possible if subatmospheric pressure is produced in the wood. Considering the atmospheric pressure of the furnace, at least one barrier must exist that impedes the equalization of the difference between the atmospheric pressure of the furnace and the subatmospheric pressure generated in the wood. The moisture from the center can only be transferred through this barrier. For this reason, we assume that osmosis must occur between the two sides of the barrier to produce subatmospheric condition inside the wood. Anatomically, this barrier can be identified as the cell walls.

The generation of osmosis can be a sound approach because the moisture is present in the form of a dilute salt solution in the wood. The living wood is able to store nutrients and transfers minerals and water, which have been previously absorbed by the root (Andersson et al. 2006). If the semipermeable cell wall allows only the passage of water but not that of solute molecules, water diffusing from the region of higher (center) to lower (periphery) water content produces osmotic pressure difference between the two sides of the cell walls. Because desiccation due to IR irradiation occurs first at the periphery, the solute concentration of the moisture will increase there. This draws water from the central cells through the semipermeable cell walls by osmosis.

CONCLUSIONS

In this paper, the drying process of Norway spruce exposed to IR irradiation was studied by measuring the moisture of the samples at controlled temperature. The thermal treatment was made in an industrial pilot-plant, in which a special coating was used around the heating wires so that they would transmit only the IR radiation. The moisture of the samples was measured after 15, 25, 35, and 45 hours of IR irradiation. The moisture movement mechanism was approached as a semipermeable membrane process, considering the moisture content of wood as a dilute aqueous solution

The obtained moisture and temperature data refer to the boiling of water at subatmospheric pressure inside the wood. We assume that this subatmospheric condition is produced by an osmotic process. It can occur if the cell wall as a semipermeable membrane permits only the water molecules to pass through, while the larger solute molecules are blocked, and the peripherial drying region of the wood starts to be concentrated by solutes. This increasing salt concentration draws water from the inner cells through the cell walls by osmosis.

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