EVOLUTION OF TEMPERATURE AND MOISTURE PROFILES OF WOOD EXPOSED TO INFRARED RADIATION

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In this article we studied the mechanism of wood drying using infrared (IR) heat transfer. Norway spruce (*Picea abies* (L.) Karst.) samples of 50 mm and 200 mm thickness were exposed to IR radiation, and the temperature and moisture profiles were recorded at the surface and at the core of the samples under controlled experimental conditions. It is proposed that the moisture transport in wood during drying is governed by osmotic effects. Based on such a hypothesis, the temperature stagnation was explained by a lower localized pressure at the core, which reduced the boiling point temperature of water. As moisture is drawn away due to osmosis from the central region, it cannot fill the empty lumens again; therefore, the pressure decreases locally. The evaporation of the internal moisture is brought about by a partial vacuum resulting in the disappearance of the liquid water.

Keywords: Infrared thermal treatment; Wood drying

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INTRODUCTION

Several wood drying techniques that are used industrially are based on the same convective heat transport phenomenon but with the application of different influencing factors, *e.g.* different drying media or pressure conditions (Pang *et al.* 1995; Björk and Rasmuson 1995; Fyhr and Rasmuson 1997; Pang 2002; Bucki and Perré 2003; Stahl *et al.* 2004; Ray *et al.* 2005; Erriguible *et al.* 2007; Poncsak *et al.* 2009). One approach to analyzing drying is based on studying the transport mechanisms that occur within the material in the course of the drying process (Fyhr and Rasmuson 1997).

The dried product has to meet set quality requirements; therefore, the freshly cut wood destined for treatment must be prepared under controlled conditions. On the technical level, the selection of a proper drying method is of utmost importance in order to produce high quality products. Obviously, various drying techniques strongly influence the final properties of wood and determine the possible uses of the material. In order to find the optimal drying parameters, a comprehensive understanding of the drying mechanism of wood is essential. It is necessary to determine the physical phenomena (*e.g.,* moisture diffusion, pressure) that directly influence mass transfer during drying.

This paper analyzes the drying mechanism of wood based on experimental results from an infrared (IR) dryer. We employed this radiant drying method as an alternative to the conventional convection-based drying process. We hypothesize that the evaporation process under infrared thermal treatment is influenced by osmotic pressure differences due to the semipermeability of the wood structure to aqueous solutions.

MATERIALS AND METHODS

The measurements of wood drying were carried out in an IR furnace as described earlier (Cserta *et al.* 2011). The temperature of the IR emitter filaments was set to 165 ± 20 ºC. This temperature was reached either in one step or through gradual increasing from 120 ºC with an approximate 0.3 ºC/min increment.

The temperature of the sample was measured with calibrated K-type thermocouples. Data were read out every 5 minutes. The moisture content was measured with an Elbez WHT 860 digital moisture meter (Elbez, Cz). The lower measuring limit of the device is around 7% moisture content. The moisture was recorded every 20 minutes.

Freshly cut Norway spruce (*Picea abies* (L.) Karst.) samples of 45 to 60% moisture content were exposed to different intensities of IR radiation. This type of wood was chosen because of its prominent use in the timber industry. The drying process was monitored by measuring the temperature and moisture changes in the samples. Drill holes holding the sensors were positioned at the core and at the surface of the sample. These different measuring points enable a depth-dependent description of the process.

First, we measured the temperature changes of boards of 50×200×500 mm in size. The boards were hung in the furnace. The measurements had two subtypes: (1) with intermittent heating, and (2) with continuous heating. Intermittent heating by IR exposure and subsequent cooling to room temperature were alternated at approximately 45 min. cycles for four repetitions. In a number of cases, another 250 min. heating interval was applied. The continuous IR heating exposure did not include cooling intervals; the samples were rather irradiated without interruption for at least 400 min.

Second, simultaneous temperature and moisture content measurements were carried out with timbers of 200×200×500 mm in size. The timbers were positioned on the bottom of the furnace. The treatment time was varied between 800 and 1500 min. The moisture content was followed until the moisture sensors failed due to warping of the wood as it dried. All measurements were repeated at the two different irradiation intensities.

RESULTS

Temperature Measurements

This part of the study considered the most important effect of IR radiation: the heat absorption by the wood from IR exposure. First, samples were exposed to intermittent radiation. However, some of our results required additional experiments to help with data interpretation, so measurements with uninterrupted exposition were also carried out. During the intermittent IR heat exposure, the maximum surface temperature increased with each consecutive cycle until finally achieving 140 ºC. The core temperature changed together with the surface temperature with an approximate10 min. time lag. However, starting from the third cycle, the two temperatures were transiently delinked: the core temperature did not increase over 90 ºC (T_{st}). Below that value the two temperatures were coupled again with the lag mentioned before (Fig. 1a). This stagnation phenomenon persisted for a time in cases when the sample was exposed to the additional uninterrupted irradiation (Fig. 1b). However, after approximately 450 min. cumulative time, the core temperature surpassed 90 ºC and continued increasing -- with a greater rate than the surface temperature -- until the end of the experimental run.

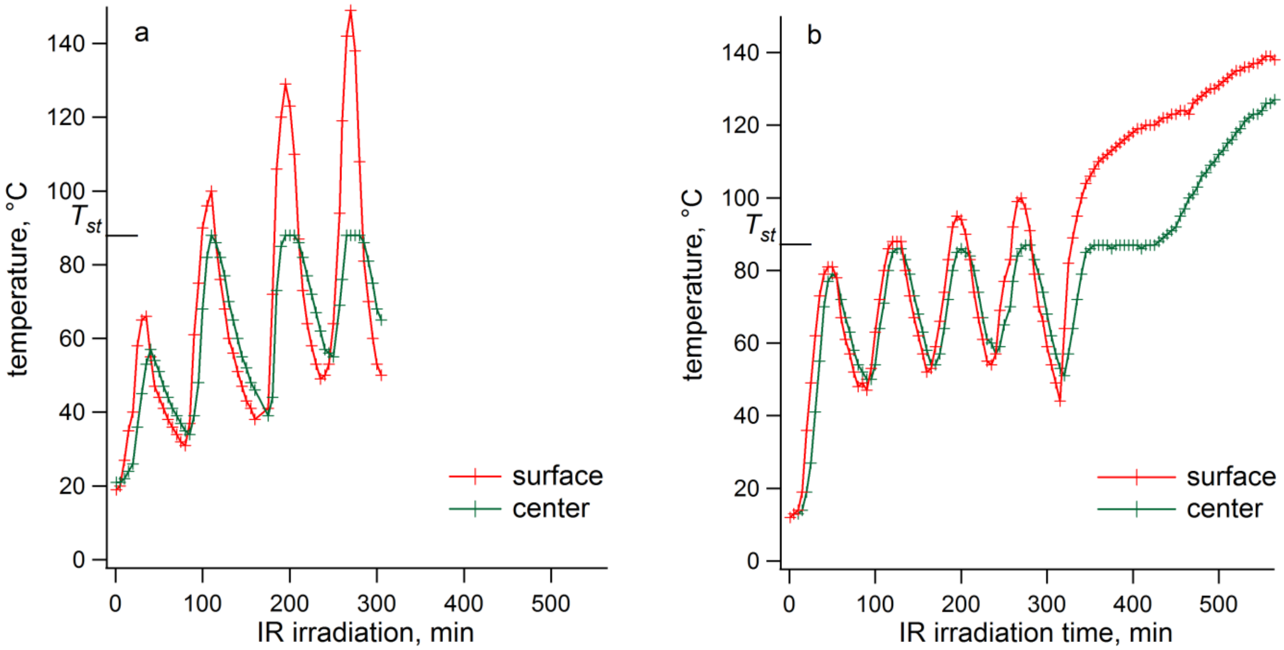

Fig. 1. Temperature profiles of green samples of 45 to 60% initial moisture content as a function of drying time during intermittent IR heat exposure. **(a)** Four heating cycles (maximum emitter temperature (165 ºC) reached in one step). **(b)** Four heating cycles followed by an approx. 250 min. continuous heating interval (maximum emitter temperature (165 ºC) reached through gradual increase)

In the continuous IR heat exposure (Fig. 2), the surface and core temperatures increased together with the temperature lag, as mentioned earlier. The stagnation phenomenon also occurred when the 90 ºC core temperature was reached while the surface temperature was increasing. After 300 min. of cumulative exposition time, the core temperature started to increase to that of the surface temperature (Fig. 2a). However, repeating the continuous heat exposure at different IR intensities (Fig. 2b), the stagnation temperature always appeared at 90 ºC, within experimental error.

Simultaneous Measurements of Moisture and Temperature

The moisture content was monitored as a function of irradiation time by the fixed moisture sensors. The moisture content was followed until the moisture sensors failed due to wood warping as it dried. The moisture change was monitored in parallel with the temperature change in the freshly cut timbers (Fig. 3a and b) in order to compare the simultaneous heat and mass transport effects involved in wood drying. In Fig. 3a and b, the moisture and temperature profiles over time are plotted for two different IR heating intensities.

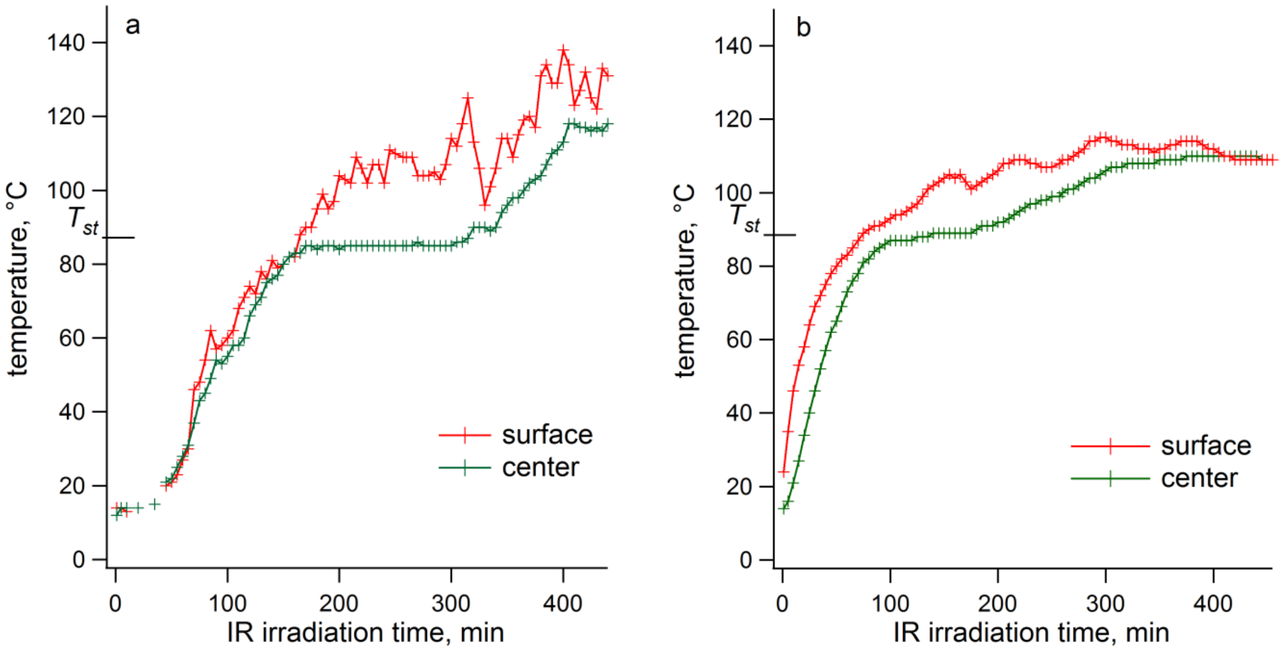

Fig. 2. Temperature profiles of green samples of 45-60% initial moisture content as a function of drying time during continuous IR heating exposure. Maximum emitter temperature: **(a)** 165 ºC; **(b)** 140 ºC

In Fig. 3a, the surface temperature of the IR emitter was 165 ºC. At the beginning of IR exposition, the core temperature of the sample started to increase with a lag relative to the surface temperature.

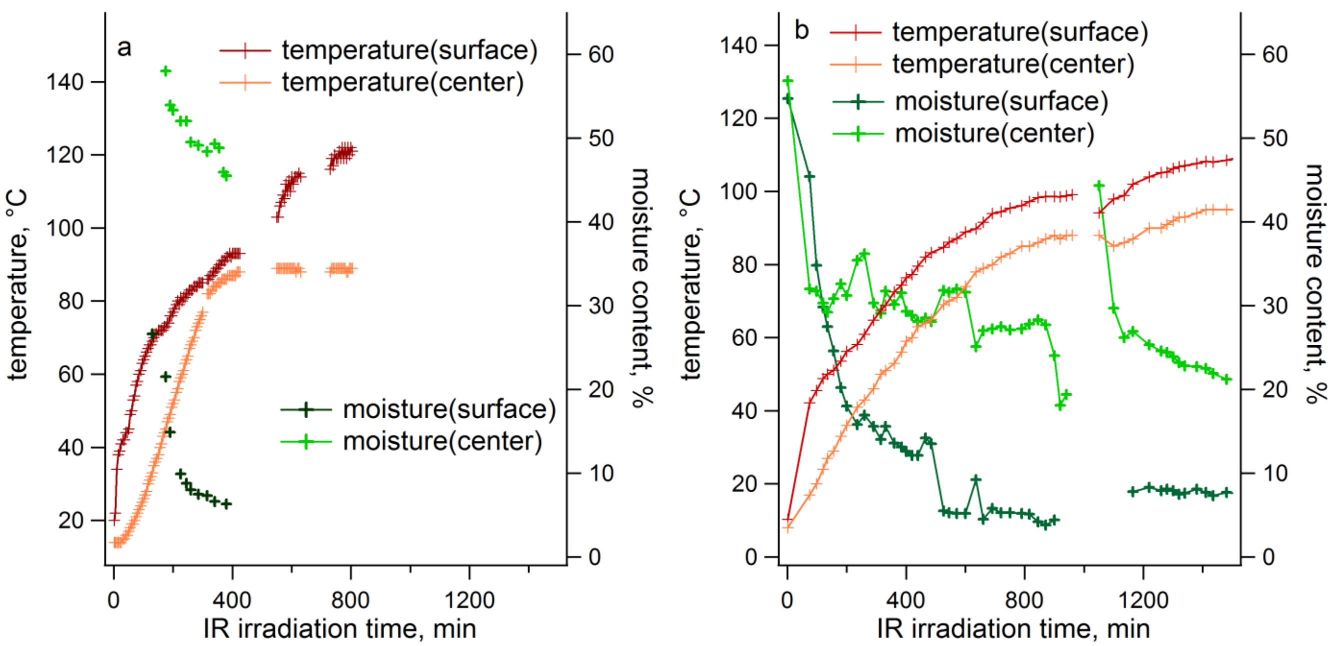

Fig. 3. The moisture and temperature profiles of green timbers measured in the surface and the core as a function of IR exposition time. Maximum emitter temperature: **(a)** 165 ºC; **(b)** 140 ºC

The core temperature increased linearly up to a point where the temperature reached a plateau. This stagnation point was reached after 5 hours (300 min.) of irradiation; afterwards, no further increase was observed with the core temperature measurement. The average moisture content of the sample after 800 min. of IR exposure decreased to below the fiber saturation point (FSP) of 25%.

The moisture content of the surface had already reached the air-dried state (12 to 15%) within 3 hours. However, the moisture flux increased much more slowly in the core (*i.e*. at 10 cm), although it could also be observed from the beginning without ambiguity. Moisture data acquisition ceased after 400 min. because of loss of contact between the sensors caused by wood warping.

Figure 3b shows temperature and moisture profiles for measurements using a lower IR emitter temperature. As observed earlier at a higher emitter temperature, the moisture content started to decrease for both the surface and the core from the beginning of the treatment.

Again, the surface reached the air-dried state after 5 hours of irradiation, while the core moisture content showed a slower, although constant decrease. During this phase, the contact between the sensors and the wood lasted for approximately 15 hours. At this point, the timber was removed from the furnace and the sensor screws were tightened in order to restore the contact necessary for detection. After returning the sample into the furnace, the measured moisture content was significantly higher than before, and it started to decrease instantly. Such a change would not be observed in the case of the surface moisture content. After resuming, the detection could go on till the 25 hour (cumulative time) of the treatment. The core temperature did not reach 100 ºC throughout the irradiation process.

DISCUSSION

The characteristic stagnation of the core temperature to below 90 ºC was judged to be the most uncommon phenomenon experienced during the IR treatments. However, such temperature profiles have been already discussed by Keylwerth (1952). In that work, convective drying process of spruce boards of 24 mm thickness was monitored by measuring the temperature and moisture content for both the surface and the core. The same stagnation of the core temperature was detected. Keylwerth explained this stagnation by the lag of heat supply to the core due to intensive evaporation of water starting from the periphery of the sample. First, the wood absorbs heat for evaporating the water at the surface region, resulting in a delay of heat supply into the core; *i.e.* the moisture of wood starts to evaporate at the periphery, while the absorbed heat is transformed into latent heat and the core temperature stagnates. At the end of the stagnation of the core, the temperature increase coincides with the decrease of the moisture content to below the FSP at the surface, and later at the core. The mechanism of the moisture change was not detailed by Keylwerth.

Relying on the results by Keylwerth (1952), the starting point of the moisture change in the core coincides quite well with the core temperature reaching T_{st} (the dew point). In our experiment (Fig. 3), however, the starting point of the moisture decrease did not coincide with the surface or the core with respect to reaching the stagnation of temperature at T_{st}. Instead, it began much earlier when the IR irradiation was initiated. Moreover, the surface temperature did not necessarily reach the boiling point of water while the stagnation process was starting at the core.

The distinct geometry of the samples and the different heat transfer mode played an important role in the detection of temperature and moisture data differently from what has been reported in the literature. Considering that the drying process had begun in the core before the core was significantly heated up, we conclude that heat transfer is not the only factor that induces moisture flux. Other driving forces, such as the concentration difference resulting from the rapid retraction of water from the periphery, have a significant role in the drying process as well.

Based on our observations (T_{st} in Fig. 1 and 3), we assume that the drastic change of the temperature gradient between the core and surface temperatures corresponds to a phase change inside the sample under continuous heat supply by the IR irradiation. At the applied temperature, however, the only possible phase change that can occur is the transformation of liquid water to vapor.

The evaporation of water can occur at each temperature range of the IR treatment; therefore, no drastic change in the core temperature gradient is expected as a result. The abrupt limit of the core temperature must be an indication of the phase change due to the boiling of water at the core.

The phase change started at a temperature below 100 ºC, which requires a local pressure below the nominal atmospheric pressure (*i.e.* vacuum effect). Moreover, the lower pressure cannot cause water boiling at the surface region; consequently, the boiling must have started at the sample's core and not at the periphery. Other authors also mentioned lower pressure effects using atmospheric pressure conditions in the surrounding during thermal treatments (Perré and Turner 2002; Oloyede and Groombridge 2000; Pang *et al.* 1995). This phenomenon is explained by the evacuation of water from the pores by capillarity action. In our experiments, however, the driving force caused by capillarity action was not sufficient to produce the necessary vacuum pressures for boiling at T_{st}. While looking for other influencing factors, we considered the possibility of the occurrence of osmosis due to the nature of the wood moisture as a dilute solution. In this context, wood moisture is composed not only of water but also of dissolved nutrients and minerals.

After the tree is felled, a solute concentration difference arises in the wood between its dry periphery and its wet core. The low water concentration at the periphery draws water from the central cells through the cell walls forced by the concentration difference. Considering the solid framework of the cells as semipermeable walls, the occurrence of osmosis is predicted (Cserta *et al.* 2011). As the moisture evacuates due to osmosis from the central region symmetrically in both directions, the empty lumens cannot be filled again; therefore, the local pressure decreases. The vacuum produced may decrease the temperature at which water boiling occurs. We hypothesize that this causes core temperature stagnation. The evaporation of the internal moisture is fostered by a vacuum resulting in the disappearance of the liquid phase water and, consequently, the end of osmosis.

CONCLUSIONS

In the present work, experiments were performed in which Norway spruce samples of approximately 50 mm and 200 mm thickness were exposed to IR radiation. Temperature and moisture profiles were recorded at the surface and at the core of the samples under controlled conditions. Based on the results, the following mechanism of wood drying is proposed:

A characteristic stagnation of the core temperature occurred simultaneously with a continuous decrease of the moisture content. Considering that the moisture movement in the wood is governed by osmotic effects, this temperature stagnation was explained by a lower localized pressure at the core, which reduced the boiling point temperature of water. As the moisture evacuates due to osmosis from the central region symmetrically in both directions, the empty lumens cannot be filled again; therefore, the local pressure decreases, resulting in a partial vacuum. This vacuum might assist internal water evaporation, resulting in the disappearance of the liquid water, and consequently, the end of osmosis.

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REFERENCES CITED

Björk, H., and Rasmuson, A. (1995). "Moisture equilibrium of wood and bark chips in superheated steam," *Fuel* 74(12), 1887-1890.

Bucki, M., and Perré, P. (2003). "Radio frequency/vacuum drying of wood: A comprehensive 2-D computational model on the board's scale," Proceedings of the *8th International IUFRO Wood Drying Conference*, Brasov, Romania, August 24-29, pp 33-38.

Cserta, E., Hegedűs, G., and Németh, R. (2011). "Drying process in Norway spruce wood exposed to infrared radiation," *BioResources* 6(4), 4181-4189.

Erriguible, A., Bernada, P., Couture, F., and Roques, M. A. (2007). "Simulation of vacuum drying by coupling models," *Chem. Eng. Proc.* 46(12), 1274-1285.

Fyhr, C., and Rasmuson, A. (1997). "Some aspects of the modelling of wood chips drying in superheated steam," *Int. J. Heat Mass Transfer* 40(12), 2825-2842.

Keylwerth, R. (1952). "Der Verlauf der Holztemperatur während der Furnier- und Schnittholztrocknung (The variation of the temperature of wood during the drying of veneers and sawn wood)," *Holz Roh Werkst*. 10(3), 87-91.

Oloyede, A., and Groombridge, P. (2000). "The influence of microwave heating on the mechanical properties of wood," *J. Mat. Proc. Technol*. 100(1-3), 67-73.

Pang, S. (2002). "Investigation of effects of wood variability and rheological properties on lumber drying: application of mathematical models," *Chem. Eng. J.* 86(1-2), 103-110.

Pang, S., Keey, R. B., and Langrish, T. A. G. (1995). "Modelling the temperature profiles within board during the high temperature drying of *Pinus radiata* timber the influence of airflow reversals," *Int. J. Heat Mass Transfer* 38(2), 189-205.

Perré, P., and Turner, I. (2002). "A heterogeneous wood drying computational model that accounts for material property variation across growth rings," *Chem. Eng. J*. 86(1-2), 117-131.

Poncsak, S., Kocaefe, D., Younsi, R., Kocaefe, Y., and Gastonguay, L. (2009). "Thermal treatment of electrical poles," *Wood Sci. Technol*. 43(5-6), 471-486.

Ray, C. D., Gattani, N., Castillo, E., and Blankenhorn, P. (2005). "Time series techniques for dynamic, real time control of wood drying processes," *Forest Prod. J*. 55(10), 64-71.

Stahl, M., Granström, K., Berghel, J., and Renström, R. (2004). "Industrial processes for biomass drying and their effects on the quality properties of wood pellets," *Biomass Bioenergy* 27(6), 621-628.

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