# WOOD RESEARCH 56 (4): 2011 441-454

# OSMOTIC MOISTURE TRANSFER IN WOOD EXPOSED TO INFRARED RADIATION

Erzsébet Cserta, Róbert Németh University of West Hungary, Faculty of Wood Sciences Sopron, Hungary

> Gergely Hegedűs Kentech Ltd. Budapest, Hungary

(Received March 2011)

# ABSTRACT

The drying process of wood exposed to infrared radiation is discussed in this paper. A test pilot-plant was developed using infrared heat radiators. Thick, rectangular Norway spruce (*Picea abies* [L.] Karst.) timbers of 200±10mm were irradiated in a closed system. The mechanism of the drying process was discussed based on measured moisture distributions. The change of the moisture profiles was followed up in different stages of the infrared irradiation process. Furthermore, the change of the moisture content was measured continuously in time at certain distances from the sample surface.

Due to the infrared radiation, thermal energy is continuously absorbed by the liquid or gaseous moisture phase of the timber. An evaporation front is expected to be formed at the beginning of the infrared process in the surface region. As the evaporation front progresses into the core, a concentration difference is formed among the wood cells producing osmosis through the cell wall. The most intensive moisture gradient in the wood was formed parallel to the heating surfaces without any accordance with the position of the growth rings. The moisture transfer rate was maintained at an approximately uniform value through the whole cross-section of the wood.

KEYWORDS: Infrared treatment, wood drying, osmosis.

# **INTRODUCTION**

In the woodworking practice, the main aims of the thermal processing of wood are to increase the dimensional stability and the durability of wood for further use while reducing its moisture content. Obviously, the different kinds of drying techniques strongly influence the final quality properties of wood and predict the possible use of the material (Ståhl et al. 2004, Pang

2002, Lestander et al. 2009, Zhang and Cai 2008, Di Blasi 1998). To find the optimal drying parameters, the comprehensive understanding of the drying mechanism of wood is essential.

Moisture in wood can exist as vapor in the pores, capillary or free (liquid) water in the pores, hygroscopic or bound water in the solid structure (Siau 1984), and constitutive water in the chemical composition within cell walls (Di Blasi et al. 2003). Furthermore the liquid water can be distinguished as liquid water in vessel elements, liquid water in fiber and parenchyma elements, and bound or cell wall water (Almeida et al. 2007). When all available sites are covered with water but the cell lumens are free of liquid water the medium is at the fiber saturation point (FSP) (Siau 1984, Almeida et al. 2007).

Moisture moves within the wood as 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, Younsi et al. 2007, Bekhta et al. 2006). However, wide range of the assumptions is known about the moisture movement during drying, not all of them can be preciously supported by experimental research.

The mechanism of wood drying was noted as a diffusion problem and the movement caused by capillary effects in early drying theories (Krischer 1956). The existence of capillary pressure is usually evidenced by considering wood as an assembly of capillaries and making a balance of forces acting on a liquid which has risen or fallen in a capillary tube (Siau 1984, Di Blasi 1998, Andersson et al. 2006, Surasani et al. 2008). Furthermore, chemical potential of water is to consider as driving force of water movement. At the beginning of the drying process, free water is moved to the wood surface by capillary forces where it is evaporated into the atmosphere (Andersson et al. 2006). This process goes on until the local saturation falls to zero. At this point, no more free water locally exists in the wood but the solid structure is still saturated with bound water (Goyeneche et al. 2002) (FSP). Due to the evaporation process, the surface temperature is decreased, and heat must be transferred from the environment in order to maintain the drying of the wood (Andersson et al. 2006, Nyström and Dahlquist 2004).

The moisture profiles in wood depend slightly on the distribution of temperature and concentration of the surrounding fluid field (Perré and Turner 2002, Timoumi et al. 2004). The schematic of the moisture gradient curves across the thickness of a convective dried board is demonstrated in Fig. 1.

Principally, the sharp moisture gradient close to the surface shows that the migration of capillary water is significant in the neighbourhood of the exposed surface. As the drying time passes, the moisture profile becomes parabolic (Younsi et al. 2006) until the moisture gradient between the core and the surface disappears. At the end of the drying process, the wood reaches an equilibrium state with its environment (Andersson et al. 2006), while the moisture content profile becomes almost flat (Remond et al. 2007).

The final moisture content inside the wood depends on temperature and humidity level of the environment (Andersson et al. 2006). Therefore, drying is influenced by heat and mass transfer between the surroundings and wood, as well as by the complex moisture transport processes which take place in the wood (Bekhta et al. 2006, Cai and Oliveira 2010). The common wood drying technologies are based on the convective heat transfer method. However, radiative pre-treatments using microwave (Oloyede and Groombridge 2000), infrared (Chua et al. 2004) and radio-frequency (Bucki and Perré 2003) radiation techniques can have an impact on the drying rate of wood due to the modification of the moisture distribution, and the wood permeability.



Fig. 1: The moisture gradient curves across the thickness of a board at successive stages of the convective drying from the freshly cut state to equilibrium at 10 % moisture content.

In our experiments, a novel high temperature drying process was developed. Infrared emitters were used to supply thermal energy to the samples. The change and shape of the moisture distribution of *Picea abies* timber was monitored. The shape of the moisture distribution was followed up at different stages of the infrared exposing time in the whole cross-section, while the change of the moisture content was measured continuously in time in certain distances from the timber surface. The sharpest moisture gradient was formed parallel to the heating surfaces without any accordance with the position of the growth rings. An evaporation front was formed at the beginning of the infrared process in the surface region mainly due to the intensive infrared heat absorption of the moisture content. As the evaporation "front" progresses into the core, a concentration difference is formed inside the wood producing osmosis. This osmosis may be taken into account as main driving force of the liquid moisture movement. The osmotic movement of water is predicted until liquid water exists in the wood. By the infrared radiation, the moisture transfer rate is successfully maintained at an approximately uniform value throughout the cross-section of the wood.

## MATERIAL AND METHODS

### **Experimental setup**

A temperature-controlled experimental furnace was developed using infrared (IR) heat radiators. The heating block was made up of 2x6 infrared emitters at two vertical sides of the furnace (Fig. 2). Infrared frequency-layers were used around the heating wires, which transmitted only the selected wavelengths from the infrared spectrum. The temperature of the heating wire was measured and controlled by a digital temperature controller (Dixell s.r.l). It involves an on-off control. Simultaneously, the surface temperature of the heating blocks was measured at the outer side of the transmitting layer. The samples were placed as close as possible to the infrared emitters diminishing the distance between the sample and infrared emitters to less than 50 mm at both sides. The pressure inside the furnace was atmospheric. The moisture content of the samples was measured by Elbez WHT 860 electric resistance type digital moisture meter (Elbez, Cz). The

analysis was carried out using Statistica 8 (StatSoft, Inc., Tulsa, OK, USA) and Microsoft Excel 2002 (Microsoft Co., Redmond, WA, USA) packages.

## Sample preparation

The measurements were made by Norway spruce (*Picea abies* [L.] Karst) wood. The main influencing factor in the selection of this wood type was its abundant use in the timber industry. To measure the moisture distribution, thick, rectangular timbers of 200±10 mm thickness (width) were dried. The timbers were exposed to symmetric boundary conditions heating at two sides by the parallel infrared heating panels. The position and the orientation of the timbers between the infrared emitters are presented in Fig. 2.



Fig 2: Schematic of the furnace area with the location and the orientation of the drying timber.

The results of a green (freshly cut) Norway spruce timber of 200x200x500 mm exposed to infrared radiation during 45 hours is presented. The term green refers to the freshly cut state of the sample without prior air drying. The initial moisture content of the sample was  $50\pm20$  %. During the infrared irradiation process, the timber was not moved. Loss in mass was allowed only from the flat surface by sealing the butt-edges of the timber with a high temperature resistant waterproof polymer (silicone).

50 mm thick slices were cut from the timber perpendicular to the heated surface at different stages of the drying time. The cuts were done after 15, 25, 35, and 45 hours of infrared irradiation time. No relevant informations were obtained from the cut slice after 15 hours, since negligible difference can be found between the moisture distributions after 15 and 25 hours. Therefore, the results of 15 hours irradiation are not shown here. The three examined slices are indicated by numerals in the schematic of Fig. 2. The cut ends of the timber were covered with silicon again after every cut. The actual moisture distribution in the slices was measured along concentric meshes immediately after the cut. The origin of the mesh concurred with the location of the pith.

Internal moisture content was determined at six different points along the direction of the internal flux of water (from the center to the timber surface). The fixed moisture sensors were built in the timber to control the moisture change of the sample during the infrared irradiation process permanently. The moisture sensors were placed in holes by isolating silicon. The locations of the moisture detectors were next to the surface, and in 20, 40, 60, 80 mm distance from the

surface and in the core (100 mm) slanted at a 45° angle. The built-in moisture sensors were coupled by cables to the digital moisture meter device outside the furnace.

The moisture profiles were approached by distance wighted fitting to smooth the data and guide the eye.

# RESULTS

In our experiments, a high temperature drying process of wood was developed. To the thermal treatment, only infrared emitters were used to supply thermal energy to the sample. The aim was to monitor the effect of the absorbed infrared thermal radiation on the drying mechanism of wood. In contrast to the generally examined lumbers of approximately 20-50 mm thickness (Rozas et al. 2009, Hakkou et al. 2005, Awoyemi and Jones 2011, Ohmae and Nakano 2009, Pang 2002, Gonzalez-Peña and Hale 2010), we have exposed thick, rectangular timbers of 200±10 mm thickness (width) to infrared irradiation. As a matter of fact, the drying experiments in pilot plants are not conventionally made on timbers, especially, because of the long drying time. However, detailed investigations of the moisture movement can be done exactly on thick samples.

## Evolution of the moisture profiles

One aspect in the monitoring of infrared drying process can be the moisture transport mechanisms occurring within the material exposed to infrared irradiation. The moisture distribution was determined in the whole cross-section of the timber at certain stages of the infrared exposing time. To present the 2D moisture profiles, the results measured at the bottom, the center, and the top of the timber are used. The moisture distribution is demonstrated in 3D projections as well, since not only the moisture content level but also the variation of the moisture content is of great importance for the performance of timber structures and engineering wood products (Häglund 2007). The moisture distribution of three cut slices (Fig. 2) were detected right after the cut process to receive the actual and local moisture distribution of the cross section of the timber exposed to infrared radiation. Furthermore, it was important to monitor the effect of the structural variation (i.e., growth rings, location of the pith) on the moisture movement. The results of the cut slice of 25 hour infrared irradiation are presented in Fig. 3.

Principally, the similar parabolic moisture profile (Fig. 1) was formed as it had been affirmed during convective heat treatments (Younsi et al. 2007). This parabolic profile is resulted in the fast moisture migration in the surface region enforced by the intensive infrared heat absorption. Obviously, an intensive evaporation process starts to occur when the surface temperature approximates the boiling point of water. This front is considered as the region where the most intensive evaporation occurs. As the surface region dries out, the evaporation process is dislocated towards to the still wet core confirming the progress of the evaporation front into the core. The zone, where the highest value of the moisture gradient is formed in the wood, refers to the actual location of the evaporation front. These shapes of the moisture profiles and progress of the evaporation front is indicated depending on the sample thickness (width) in Fig. 3.

As time passes, the moisture gradient should become steeper close to the surface according to the literature (Younsi et al. 2007, Younsi et al. 2006). We have controlled the change of the moisture profile by measuring the moisture distribution of the second presented slice (Fig. 4). This slice was cut after exposing the timber to infrared irradiation during for 35 hours. Interestingly, the received moisture profiles of the timber are not severely parabolic already. The sharpest moisture gradient (i.e., evaporation front) was dislocated with around 20-40 mm

closer to the core. Inflection points can be detected connecting to the observed dislocation of the evaporation fronts at both sides of the timber. The progress of the evaporation front towards the core is confirmed. The transferred location of the evaporation front is explained by the radiative character of the heat transfer into the wood. Assumingly, the infrared radiation is hardly absorbed by the solid framework of the wood because the infrared radiation has negligible degradative effect on the wood polymers (Evans et al. 2008). More likely, the water is heated intensively by the infrared radiation while the wood solid framework only absorbs a small part of the applied infrared heat radiation.



Fig. 3: The 3D a) and the 2D b) moisture profiles in the cross-section of the P. abies timber after 25 hours infrared irradiation.



Fig. 4: The 3D a) and the 2D b) moisture profiles in the cross-section of the P. abies timber after 35 hours infrared irradiation.

The advancing of the inflection points of the moisture profile is verified by the results of the third analyzed slice irradiated during 45 hours (Fig. 5).

In the conventional drying processes, the differences in the temperatures and the average moisture contents along the boards become insignificant (Pang et al. 1995) and the moisture profile becomes flat at the end of the thermal treatment (Remond et al. 2007, Younsi et al. 2007) (Fig. 1). In contrast, the moisture profile of the wood exposed to infrared irradiation reserved its inflection point with a significant moisture gradient between the surface and the core still after 45 hours infrared exposing time (Fig. 5). The sharpest moisture gradient was rather close to the core than to the surface region.



Fig. 5: The 3D a) and the 2D b) moisture profiles in the cross-section of the P. abies timber after 45 hours infrared irradiation.

## Change of the drying rate

The moisture change was followed up continuously as well by fixed moisture sensors built in the timber in different distances from the surface during the infrared exposing time. In this way, the drying rate can be monitored simultaneously with the infrared irradiating process. The large thickness was expected to affect the drying rate because the thicker boards need longer time to dry than the thinner ones.

In Fig. 6, the moisture values are indicated by the distance of the measuring points from the surface, respectively. Since the structure of the wood changes during the irradiation process, it can happen, that the direct contact breaks between the moisture sensors and the inhomogeneous solid matter of the wood. This direct contact resumes if the moisture sensor is tightened, or if there is a change in the structure of the wood which results in getting good thermal contact between the sensor and the wood matter again. The imprecise measurement values caused by the lack

of contact were not taken into account. Also, the measured moisture values below the relevant measuring limit of the device (7 %) are neglected. For these reasons, the detected moisture values after cutting the  $2^{nd}$  examined slice are not considered to be relevant, and are not presented in Fig. 6.



Fig. 6: The change of the moisture content of the P. abies timber depending on the time exposed to infrared irradiation. The moisture content is measured in the specified distance from the surface.

Obviously, the moisture exits the surface region fast. The average moisture content decreases below 15 % both in the surface and in 20 mm from the surface after around 10 hours. As the drying time passes, the moisture values decrease continuously, but abrupt jumps can be detected in the moisture profiles of the 40-100 mm region after every cut or tightening. This phenomenon is due to a condensation process of water vapor in the wood which occurred when the timber was outside the furnace at room temperature while the slices were cutting or the sensores were tightening. Since the moisture sensors are mostly sensible to the liquid water the measured moisture value is higher after returning the sample to the furnace than it was before breaking temporally the infrared thermal process. It is due to the result of the condensation of vapor in wood.

The evacuation of the moisture from the surface region (20 mm) must be almost complete after 7 hours because no condensed liquid phase was detected after the temporal breaks of the infrared irradiation process (connecting to the tightening and cutting processes). Except the principal warming-up interval and the condensation processes, the moisture loss rate of the 40-100 mm regions can be approached almost linear. It can happen, since the drying rate is strongly determined by the heat transfer rate. By the infrared radiation, thermal energy is continuously supplied to the liquid or gaseous moisture of wood. The moisture transfer rate is maintained at an approximately uniform value through the whole cross-section of the wood. An average 40±10 % moisture loss was detected after the infrared irradiation process.

# DISCUSSION

By means of the 3D results (Fig. 3a, 4a, and 5a), the effect of the anatomical structure of P. *abies* is discussed on the moisture distribution, since it is assumed to be in direct connection

with the final product quality due to the stress formation inside the wood (Almeida et al. 2007). The strong density variation across the growth rings is expected to determine the moisture field during drying. Authors (Perré and Turner 2002, Pang 2002) state that the moisture profile through the sample should follow the annual ring contour. On the contrary, no connection can be seen between the shape of the moisture distribution and the location of the growth rings during drying the timber by infrared irradiation. The most intensive moisture gradient was formed parallel to the infrared emitters without any accordance with the orientation of the growth rings. However, the maximal value of the moisture content was realized around the pith instead of the center line of the timber. This can be attributed to the strong structural difference of the wood cells between the pith and any other part of the timber. Despite of the density change according to the growth rings, the moisture movement and the location of the evaporation front was determined more likely by the distance from the infrared heat radiators. Obviously, the density variation within the spruce timber shows negligible effect on the moisture permeability of the wood cell structure on macroscopic level (expect the pith).

The difference of the evolution of the moisture distribution profiles between samples dried convectively (Pang et al. 1995) and these ones exposed to infrared radiation supports the assumption that the moisture transfer mechanism during infrared irradiation also differs from the convective treatments (Cai and Oliveira 2010, Fyhr and Rasmuson 1997) occurring during conventional high temperature drying processes.

The advancement of the sharp gradient of the moisture profiles of the infrared irradiation process refers to the progress of an evaporation plane (front). Such front is mentioned already in the literature (Surasani et al. 2008, Pang et al. 1995) connecting to convective drying as well. In these earlier hypotheses, the wood can be divided into dry and wet zones according to the location of the evaporation front (i.e., drying front) advancing in the drying time. The moisture content before to the evaporation interface in the dry zone is composed mostly of vapor. Above the front, a wet zone is produced where the moisture is assumed to exist as liquid water and water vapor. Pang et al. (1995) assume that the evaporate plane begins to recede from the start of drying due to the initially aspirated state of the pits in green P. radiata heartwood samples. It can occur because the rate of heat transfer into the sample diminishes due to the evaporation of moisture at the surface, therefore, the mass-transfer rate falls (Pang et al. 1995). The drastic drop of the evaporation rate is postulated by Surasani et al. (2008) as well in their simulation results when the surface starts to dry out after all macro-throats are emptied.

In contrast, no drastic fall of the gradient of the moisture profiles of *Picea abies* timber can be observed simultaneously with the surface desiccation in our measurements, and the progress of the evaporation front into the core seems to be quasi uniform (Fig. 6). Also the significant moisture gradient is preserved until the end of the infrared treatment (Figs. 3, 4, and 5), while the evaporation front behaves as it were a moving membrane separating the liquid moisture and the vapor from each other.

To approach the cell wall system as a membrane seems to have special sense in case if the moisture content of the wood is considered as an aqueous solution. It can be done, since the wood structure is considered to be able to store nutritious substances, and transfers minerals and water, which have been previously absorbed by the root system (Andersson et al. 2006). Consequently, a salt concentration difference must exist in the wood between its dry and wet regions. The cells in the inner, wet region of the sample have smaller salt concentration than the outer, dryer cells forming a dilute solution inside the wood. Since, in a living tree, the pits on wood cell walls are for transportation of liquid nutrition (sap), and in wood drying they allow liquid water to flow between adjacent lumens (Pang 2002) the approach of the cell walls as semi-permeable membranes

#### Vol. 56 (4): 2011

is supported. The important role of the permeability of the pit membranes is postulated in the literature (Zhang and Cai 2008) already. The level of the permeability of the cell wall membranes can depend on several factors. According to Pang (2002), the permeability difference in radial and tangential directions of wood is in relationship with the location of the bordered pits on the radial-longitudinal faces of the wood cells. Almeida et al. (2007) discussed the influence of the portion of the axial parenchyma on the water permeability of wood. Furthermore, the effect of the heat treatment (Awoyemi and Jones 2011) and thermal irradiation (Evans et al. 2008) on the permeability of the wood polymers to heat is declared based in the literature as well (Maunu 2002, Del Menezzi et al. 2008, Mitsui et al. 2004, Mitsui and Tsuchikawa 2005, Mitsui et al. 2008, Schimleck et al. 2005, Brito et al. 2008, Hakkou et al. 2005, Awoyemi and Jones 2011).

Based on the infrared measurements, we assume that the concentration difference between the two sides of the cell walls results in starting an osmotic movement of water from the inner dilute cells towards the outer regions with higher dissolved solute concentration through the semipermeable pit membranes. The occurrence of the osmosis is verified already between the cell walls in the surface and a concentrated solution under polymer molecules (eg., PEG – polyethylene glycol) bulking process by Jeremic et al. (2007). Contrarily, no earlier assumptions were found explaining the moisture movement in wood by osmosis during thermal treatment, without applying any artificial bulking of concentrated solution.

Considering the osmosis as a driving force of the moisture movement during the drying process, the importance of the local liquid moisture content is evident. Already, an enforcing effect of the existing average liquid moisture content was noticed on the internal effective mass transfer coefficient by Rozas et al. (2009) in their numerical study. Moreover, the fact that the surface of the absolutely dry wood samples cannot be bulked with liquid solution, even at very low molecular weights (Jeremic et al. 2007) can be explained by the missing liquid moisture content, since the necessary surrounding of the osmosis is not ensured. Also, the hypothesis of the osmotic moisture movement seems to be supported by those NMR observations (Almeida et al. 2007) that the region exists in drying wood where loss of bound water takes place in the presence of free (liquid) water ensuring the wet surrounding necessary to occur osmosis.

Referring to the relative small size of water molecules compared to the solute compounds of the moisture in wood, the osmotic movement of water is predicted through the cell walls driven by the concentration difference produced due to osmosis in a complex process of heat and mass transfer.

## CONCLUSION

In the present paper, the dynamics of the moisture movement is discussed in wood exposed to infrared irradiation. The change of the moisture distribution was followed up in different stages of the infrared irradiation process. A test pilot-plant was developed, where thick, rectangular *P. abies* timbers of 200±10 mm were exposed to infrared radiation. The mechanism of the moisture movement was discussed by analyzing the measured moisture profiles.

The most intensive moisture gradient was formed parallel to the heating surfaces without any accordance with the position of the growth rings. An evaporation front was formed at the beginning in the surface region due to the high infrared heat absorption of the moisture content. (The heat supply necessary to the progress of the evaporating front into the core, transferred by the infrared radiation, is absorbed mostly by the moisture of wood.) As the evaporation front progresses into the core, a concentration difference is formed between the wood cells producing osmosis through the pits of the cell walls. The osmosis may be taken into account as a driving force of the liquid moisture movement. The osmotic movement of water is predicted until liquid water exists in the wood. By the infrared radiation, the moisture transfer rate is successfully maintained at an approximately uniform value throughout the cross-section of the wood.

## ACKNOWLEDGMENT

The authors are grateful to Kentech Ltd. for making available the infrared pilot plant and all the technical backgrounds for the infrared heat treatment. We also would like to thank the SEDO Group and Askada Ltd. for their scientific advice and financial support concerning the infrared drying experiments. Furthermore, the authors acknowledge the support of S. Gergely PhD. for his forward-looking advices. The research work was co-financed by European Union and by the European Social Fund. (TÁMOP 4.2.1. B-09/1/KONV-2010-0006 Intellectual, organizational and R+D infrastructural development on University of West Hungary.

# REFERENCES

- Almeida, G., Gagne, S., Hernandez, R.E., 2007: A NMR study of water distribution in hardwoods at several equilibrium moisture contents. Wood Science and Technology 41(4): 293-307.
- Andersson, M., Persson, L., Sjöholm, M., Svanberg, S., 2006: Spectroscopic studies of wood drying-processes. Optics Express 14(8): 3641-3653.
- 3. Awoyemi, L., Jones, I.P., 2011: Anatomical explanations for the changes in properties of western red cedar (*Thuja plicata*) wood during heat treatment. Wood Science and Technology 45(2): 261-267.
- 4. Bekhta, P., Ozarkiv, I., Alavi, S., Hiziroglu, S., 2006: A theoretical expression for drying time of thin lumber. Bioresource Technology 97(13): 1572-1577.
- Brito, J.O., Silva, F.G., Leão, M.M., Almeida, G., 2008: Chemical composition changes in eucalyptus and pinus woods submitted to heat treatment. Bioresource Technology 99(18): 8545-8548.
- Bucki, M., Perré, P., 2003: Radio frequency vacuum drying of wood a comprehensive 2D computational model on the boards scale. 8<sup>th</sup> International IUFRO Wood Drying Conference, 24-29. August 2003, Brasov, Romania.
- Cai, L., Oliveira, L.C., 2010: Experimental evaluation and modeling of high temperature drying of sub-alpine fir. Wood Science and Technology 44(2): 243-252.
- Chua, K.J., Chou, S.K., Mujumdar, A.S., Ho, J.C., Hon, C.K., 2004: Radiant convective drying of osmotic treated agro products effect on drying kinetics and product quality. Food Control 15(2): 145-158.
- Del Menezzi, C.H.S., de Souza, R.Q., Thompson, R.M., Teixeira, D.E., Okino, E.Y.A., da Costa, A.F., 2008: Properties after weathering and decay resistance of a thermally modified wood structural board. International Biodeterioration and Biodegradation 62(4): 448-454.
- 10. Di Blasi, C., 1998: Multi-phase moisture transfer in the high-temperature drying of wood particles. Chemical Engineering Science 53(2): 353-366.
- 11. Di Blasi, C., Branca, C., Sparano, S., La Mantia, B., 2003: Drying characteristics of wood cylinders for conditions pertinent to fixed-bed countercurrent gasification. Biomass and Bioenergy 25(1): 45-58.

- Evans, P.D., Urban, K., Chowdhury, M.J.A., 2008: Surface checking of wood is increased by photodegradation caused by ultraviolet and visible light. Wood Science and Technology 42(3): 251-265.
- 13. Fyhr, C., Rasmuson, A., 1997: Some aspects of the modelling of wood chips drying in superheated steam. International Journal of Heat Mass Transfer 40(12): 2825-2842.
- Gonzalez-Peña, M.M., Hale, M.D.C., 2010: Rapid assessment of physical properties and chemical composition of thermally modified wood by mid-infrared spectroscopy. Wood Science and Technology 45(1): 83-102.
- 15. Goyeneche, M., Bruneau, D.M., Lasseux, D., Desbat, B., Nadeau, J.P., 2002: On a porescale film flow approach to describe moisture transfer in a hygroscopic porous medium. Chemical Engineering Journal 86(1-2): 165-172.
- Hakkou, M., Petrissans, M., Zoulalian, A., Gerardin, P., 2005: Investigation of wood wettability changes during heat treatment on the basis of chemical analysis. Polymer degradation and stability 89(1): 1-5.
- 17. Häglund, M., 2007: Moisture content penetration in wood elements under varying boundary conditions. Wood Science and Technology 41(6): 477-490.
- Jeremic, D., Cooper, P., Heyd, D., 2007: PEG bulking of wood cell walls as affected by moisture content and nature of solvent. Wood Science and Technology 41(7): 597-606.
- 19. Krischer, O., 1956: Trocknungstechnik. Springer-Verlag. Berlin-Göttingen-Heidelberg.
- Lestander, T.A., Johnsson, B., Grothage, M., 2009: NIR techniques create added values for the pellet and biofuel industry. Bioresource Technology 100(4): 1589-1594.
- Maunu, S.L., 2002: NMR studies of wood and wood products. Progress in Nuclear Magnetic Resonance Spectroscopy 40(2): 151-174.
- 22. Mitsui, K., Tsuchikawa, S., 2005: Low atmospheric temperature dependence on photodegradation of wood. Journal of Photochemistry and Photobiology B: Biology 81(2): 84-88.
- Mitsui, K., Murata, A., Tsuchikawa, S., Kohara, M., 2004: Wood photography using light irradiation and heat treatment. Color Research and Application 29(4): 312-316.
- Mitsui, K., Inagaki, T., Tsuchikawa, S., 2008: Monitoring of hydroxyl groups in wood during heat treatment using NIR spectroscopy. Biomacromolecules 9(1): 286-288.
- Nawshadul, M.H., 2002: Modelling of solar kilns and the development of an optimised schedule for drying hardwood timber. Ph.D. thesis, The University of Sydney Department of Chemical Engineering.
- 26. Nyström, J., Dahlquist, E., 2004: Methods for determination of moisture content in woodchips for power plants-a review. Fuel 83(7-8): 773-779.
- Ohmae, Y., Nakano, T., 2009: Water absorption properties of bamboo in the longitudinal direction. Wood Science and Technology 43(5): 415-422.
- Oloyede, A., Groombridge, P., 2000: The influence of microwave heating on the mechanical properties of wood. Journal of Materials Processing Technology 100(1): 67-73.
- Pang, S., 2002: Investigation of effects of wood variability and rheological properties on lumber drying application of mathematical models. Chemical Engineering Journal 86(1-2): 103-110.
- Pang, S., Keey, R.B., 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. International Journal of Heat and Mass Transfer 38(2): 189-205.

- Perré, P., Turner, I., 2002: A heterogeneous wood drying computational model that accounts for material property variation across growth rings. Chemical Engineering Journal 86(1-2): 117-131.
- 32. Remond, R., Passard, J., Perré, P., 2007: The effect of temperature and moisture content on the mechanical behaviour of wood, a comprehensive model applied to drying and bending. European Journal of Mechanics 26(3): 558-572.
- Rozas, C., Tomaselli, I., Zanoelo, E.F., 2009: Internal mass transfer coefficient during drying of softwood (*Pinus Elliottii* Engelm.) boards. Wood Science and Technology 43(5-6): 361-373.
- 34. Schimleck, L.R., Jones, P.D., Peter, G.F., Daniels, R.F., Clark, A., 2005: Success in using near infrared spectroscopy to estimate wood properties of *Pinus taeda* radial strips not due to autocorrelation. Journal of Near Infrared Spectroscopy 13(1): 47-52.
- 35. Siau, J.F., 1984: Transport processes in wood. Springer-Verlag, Berling-New York, 245 pp.
- Ståhl, M., Granström, K., Berghel, J., Renström, R., 2004: Industrial processes for biomass drying and their effects on the quality properties of wood pellets. Biomass and Bioenergy 27(6): 621-628.
- Surasani, V.K., Metzger, T., Tsotsas, E., 2008: Consideration of heat transfer in pore network modelling of convective drying. International Journal of Heat and Mass Transfer 51(9-10): 2506-2518.
- 38. Timoumi, S., Mihoubi, D., Zagrouba, F., 2004: Simulation model for a solar drying process. Desalination 168: 111-115.
- 39. Younsi, R., Kocaefe, D., Kocaefe, Y., 2006: Three-dimensional simulation of heat and moisture transfer in wood. Applied Thermal Engineering 26(11-12): 1274-1285.
- 40. Younsi, R., Kocaefe, D., Poncsak, S., Kocaefe, Y., 2007: Computational modelling of heat and mass transfer during the high-temperature heat treatment of wood. Applied Thermal Engineering 27(8-9): 1424-1431.
- 41. Zhang, Y., Cai, L., 2008: Impact of heating speed on permeability of sub-alpine fir. Wood Science and Technology 42(3): 241-250.

Erzsébet Cserta, Róbert Németh University of West Hungary Faculty of Wood Sciences Bajcsy-Zs. u. 4, H-9400 Sopron, Hungary Corresponding author: nemethr@fmk.nyme.hu

> Gergely Hegedűs Kentech Ltd. Sárgarózsa 22 H-1163 Budapest Hungary