University of West Hungary
Faculty of Wood Science
The József Cziráki Doctoral School of
Wood Sciences and Technologies

Drying Process of Wood Using Infrared Radiation

Ph.D. Theses

Erzsébet Cserta

advised by

Dr. habil Németh Róbert

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Abstract

The mechanism of wood drying using infrared (IR) heat transfer method was studied. The thermal treatment was executed in a purpose-made industrial pilot-plant. During experiments Norway spruce (*Picea abies* [L.] Karst) woods of $50\,mm$ and $200\,mm$ thickness were exposed to IR radiation, and temperature and moisture data were registered under controlled technological conditions to monitor the evacuation process of moisture.

By means of the results, 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. Therefore, we proposed that the moisture movement in wood is governed by osmotic effects.

Based on a characteristic stagnation of the core temperature simultaneously with the continuous decrease of the moisture content, a low pressure boiling of moisture was assumed in the core but not in the surface. As moisture evacuates due to osmosis from the central region, it cannot fill the abandoned lumens again; therefore, pressure decreases locally. The boiling of the internal moisture is fostered by vacuum resulting in the disappearance of the liquid phase water and, consequently, the end of osmosis.

Overview

In the woodworking practice, the main aim of the thermal processing of wood is to increase the dimensional stability and the durability of wood for further use while reducing its moisture content. The dried product has to meet quality requirements, therefore, the freshly cut wood destined for treatment must be prepared under controlled conditions. On the technical level, selection of a proper drying method is of utmost importance in order to produce high quality products. Obviously, the different kinds of drying techniques strongly influence the final properties of wood and determine the possible use 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 some physical phenomena (moisture diffusion; pressure) that directly influence mass transfer during drying.

This research work deals with the analysis of the drying mechanism of wood based on experimental results executed in a purpose-made pilot plant. We employed a radiative drying method using IR radiation as an alternative to the conventional convection based wood drying process. IR heaters were designed to transmit energy quickly and with high efficiency. The particular wavelength of the IR radiation had a critical effect on the effectiveness of the heating process. Our IR heaters emitted the heat with the optimum wavelength for the final product and in line with the process.

Objectives

The conventionally applied wood drying technologies are based on the knowledge of the drying mechanism of the wood tissue. Through the understanding and description of the macro- and microlevel heat and mass transport processes in the drying wood we can achieve the appropriate adjustments of the technological parameters and, thus, we can accurately influence the driving forces of the drying process. At microscopic level, the mechanisms cannot or can only partly be examined even with complex instruments. Therefore, when analysing the drying mechanism we rely on the results of macroscopic measurements. Based on the results of macroscopic measurements carried out on measuring equipment composed of simple elements, we gain insight into microscopic processes. This kind of mapping of the drying mechanism helps us in improving the quality of dried wood produced in the woodworking industry, and in increasing the efficiency of the drying technologies.

The transport processes occurring during the drying treatment represent a widely researched area in wood science. The effect of temperature and relative humidity on the EMC is known from the literature. Through variation of the method of heat transport, the dynamics of the heat flow and ,thus, the change of the moisture distribution can be influenced. In the Hungarian and also in the international literature, however, the moisture as a dilute solution and the concentration change of its solute content during the drying process, as well as, its influence on the moisture movement in wood is less of a central field of research. Note that this factor is not insignificant and it further complicates the already complex transport process models.

When examining the dynamics of concentration change the characteristics of the separating walls between the regions of different concentration have to be considered, as well. In the wood, it is the cell walls that function as the separating walls. For an exact understanding of the structure of these walls, no direct, nondestructive measurements are available, and the type and species specificity also impedes their precise presentation of general validity. Through the analysis of the processes at a higher, macroscopic level, however, we can gain insight into the properties of the cell walls, and also their role in the transport processes.

My research aims the description of the drying mechanism by means of examining the spatial and temporal change of the temperature and the MC of wood exposed to IR radiation. To achieve this I defined the following tasks:

1. The effect of the IR irradiation on the heat and mass transport processes in the wood.

   (a) Examination of the driving force of the drying mechanism in function of the exposition time due to the temperature change detected in the surface and the core region.

   (b) Tracking of the drying dynamics by means of the moisture measurements executed simultaneously with the temperature measurements.

2. Analysis of the moisture distribution across the whole cross-section of timbers. Characterization of the drying mechanism based on the 1D and 2D moisture distributions obtained after different exposition time intervals, as well as, validation of the assumption that the internal part of the wood can also be heated by IR radiation.

3. Examination of the effect of technological parameters on the drying dynamics and on the final product quality. (Parameter-study). To be examined:

   (a) The effect of the initial moisture content on the drying dynamics.

   (b) The effect of the change of IR radiation on the drying dynamics.

   (c) A statistical analysis of the results.

Materials and Methods

The focus of the present work was to study the effect of the IR irradiation on wood samples. Within this extended topic, the center of attention was the process of moisture transfer inside the wood. In order to modify the wood matter, a test facility was developed, where the wood samples were thermally treated at temperatures below $170\,^{\circ}C$ and under normal atmospheric pressure using infrared (IR) radiation at a selected frequency range.

The technology was developed considering that only the kind of radiation which is absorbed in a material transfers energy to the absorber. We studied only the spectral range which is transmitted through the lignocellulosic structure of the wood without significant attenuation while it is absorbed in the water content of the wood moisture. The spectral range which fulfills the above conditions is the near-infrared (NIR) radiation. Lignocellulosis do absorb to some extent in the NIR region are due to the overtone and combination of the fundamental molecular vibrations of –CH, –NH and –OH groups, but NIR absorption bands are typically 10-100 times weaker than their corresponding fundamental mid-IR absorption bands. At the same time, water has significant absorption peaks in the NIR spectral range, especially around $1900nm$.

As discussed above, the solid components of wood are more transparent than water in the NIR frequency range. If a wet sample is exposed to radiation in this range, effective energy transfer to the water can be achieved without discrete energy transfer to the solid structure of the wood. The incident radiation penetrates into the wood framework if it is not filled with moisture. In this way, thermal energy can be transferred directly to the wet part of the sample even if the good-conductive water has already been eliminated from the surface region limiting heat conduction. For this reason, the drastic decrease of the drying rate which is caused by the lack of continuous moisture in the surface region can be avoided.

The final results and efficiency of the unit depended on the design of the heating panels and on the selection of the appropriate material of the building blocks. The measurements were executed on Norway spruce (*Picea abies* [L.] Karst) wood from a 35-year-old standing. The thermal treatment process presented here can be used for all types of wood.

Conclusions and Theses

In this research, the drying process of wood exposed to IR radiation was examined by means of temperature and moisture measurements at macroscopic level. Based on the results and their interpretation, we claim the following:

1. We propose an entirely new mechanism to describe heat and mass transfer for the IR heating. We confirmed that the phase change of liquid water to gaseous phase under IR treatment is governed by osmosis due to the semipermeability of the wood structure to aqueous solutions.

    · Based on the temperature stagnation of the core, we assume that the drastic change of the gradient of the core temperature profile corresponds to a phase change inside the sample under continuous heat supply by IR irradiation. At the applied temperature, however, the only possible phase change that can occur is the transformation of liquid phase water to gaseous phase.

    · The abrupt stop of the core temperature must be an indication of the phase change due to boiling of water in the core. The boiling, thus, starts at a temperature below $100\,°C$ requiring a local pressure below the normal atmospheric level.

    · The drying process starts in the internal part of the sample at the beginning of the IR treatment. The reason why the boiling must have started in the deeper region and not in the periphery is that the initial moisture content in the periphery dries out fast, therefore, no significant subatmospheric pressure can be produced there. According to the simultaneous moisture and temperature measurements, the surface temperature did not necessarily reach the boiling point of water while the stagnation process was starting in the core. Therefore, no boiling could occur at the periphery at normal atmospheric pressure when the core stagnation has already appeared.

    · Considering the atmospheric pressure of the furnace, at least one barrier must exist which impedes the equalization of the difference between the atmospheric pressure of the furnace and the subatmospheric pressure generated in the wood. The cell wall can be considered as a barrier separating the cell volumes.

- As the IR irradiation induced drying occurs first at the periphery, the solute concentration of the moisture increases in that region resulting in a difference of concentration between the core and the periphery. Consequently, water is drawn from the central cells through the cell walls forced by concentration difference. If the cell wall allows only the passage of water but not that of solute molecules, the concentration difference produces osmotic pressure difference between the two sides of the cell wall. The subatmospheric pressure is likely to be the result of an osmotic evacuation of water from the core.
- Osmosis happens on the semipermeable cell wall. The concentration difference between its two sides results in an osmotic movement of water from the diluted core towards the periphery with higher dissolved salt concentration. As the moisture evacuates due to osmosis from the central region symmetrically in both directions, moisture cannot fill the abandoned lumens again; therefore, pressure decreases locally. The evaporation of the internal moisture fostered by subatmospheric pressure condition results in the disappearance of the liquid phase water and, consequently, the end of osmosis.

2. In contrast to the general opinion that the IR radiation is only capable of heating the wood superficially, the experiments have demonstrated that the internal part of a board can also be heated by it. The reason for this is that lignocelluloses do not or only partly absorb the radiation in the applied spectral range while water has local absorption maximum. The requirement that the lignocelluloses be transparent with respect to the applied IR radiation has to be fulfilled. At the same time, it is necessary that the water molecules have high absorptivity in the same spectral region to facilitate drying. Therefore, the continuous heat transfer to the moisture in the deeper regions is maintained even if the surface region of the drying samples becomes desiccated. It can be achieved in this way that heat is absorbed only in water, while the thermal insulation effect of the dried layers is avoided. Moreover, the frequent problem of overheating the surface can be prevented as well.

   · When comparing the moisture distributions of the slice cross-sections we observed that the air-dried region increased continuously from the periphery while there was a central part with relatively high moisture content even in the last slice. In order to explain the *non-parabolic* character of the moisture distributions, we have taken into consideration the different absorptivity of water and lignocelluloses. The radiation which is transmitted through the lignocelluloses is absorbed in the moisture in the lumens.

   · In regions where heat absorption is the most intensive, a relatively steep moisture content drop is formed between the dry and still wet regions. This moisture drop region moves toward the core with time. The dynamics of its movement can be seen from the moisture profiles obtained at different heights. The advancement of the moisture drop refers to the dynamics of the drying.

   · We did not observe drastic decrease of the drying rate simultaneously with the desiccation of our samples. The moisture profiles as functions of the exposition time mirror a continuous drying rate in the inner region. The achieved uniformity of the drying rate refers to the fact that heat is transferred in a radiative manner.

3. The initial moisture content of the samples and the IR irradiation intensity are two parameters which have significant effects on the dynamics of the drying with respect to the optimization of the drying technology.

    · Since osmosis can only occur between liquid phases, it requires the presence of the continuous phase of liquid water. Since there is variability in the curves with respect to the stagnation temperature below FSP, we conclude that the amount of liquid water necessary for osmosis must still be available locally in the core. By the decrease of the initial moisture content below FSP, it is the time interval of osmotic process that decreases. In this context, our results refer to the presence of free water in the wood tissue even below the FSP. Therefore, the liquid medium necessary for the osmotic mechanism is ensured.

    · It can be confirmed that the drying rate cannot be increased by raising the heating rate above a certain limit. There is a maximally achievable value above which the increase of pressure cannot enhance the flux of permeation. Although the increased heating intensity results in increasing internal pressure, the increase of the cell internal pressure and the increase of the moisture flux through the cell wall do not exhibit linear relationship. The increase of the internal pressure above the value of the maximal permeability leads to the explosion of the cell walls, which serve as semipermeable membranes.

    · In order to reduce the risk of crack formation, wood samples must be heated by IR radiation keeping the temperature difference between the wood surface and its core at an optimally low level. Therefore, the intensity of the IR emitters has to be adjusted in a way that the temperature through the whole cross section of the wood is maintained between optimal boundary conditions. Based on our experiments the optimum is around $20\,^{\circ}C$.

Summary

For the improvement of the efficiency of drying technologies, the profound understanding of the drying mechanism of wood is essential. In this work, we examined the dynamics of the moisture movement in the IR irradiated wood at macroscopic level through measurements of temperature and moisture. Our starting point was the temperature values detected in the core and the surface regions of the samples. We have concluded that the consequent stagnation of the core temperature occurring around $90\,°C$ refers to a phase change at this temperature in the core regions. We have proved through simultaneous temperature and moisture measurements that an osmotic moisture movement through the semipermeable cell wall plays a significant role in the formation of liquid phase water to gaseous phase.

The moisture distribution maps have also supported the theoretical assumption that the IR radiation is not only capable of heating the wood superficially, but the internal part of a board can also be heated by it. The reason for this is that lignocelluloses do not or only partly absorb the radiation in the applied spectral range while water has local absorption maximum in the same spectral region.

We have also examined the effect of certain experimental parameters on the results and, thus, on the drying mechanism. We have drawn the following important conclusions based on the temperature profiles of different arrangements: The amount of liquid water necessary for osmosis must still be available locally in the core below FSP. Furthermore, the radial cracks formed in the samples exposed to high intensity irradiation refer to the fact that the drying rate cannot be increased by raising the heating rate above a certain limit.

Publications in the research field

Articles:

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

Cserta, E., G. Hegedűs, and R. Németh (2011)"Osmotic moisture transfer in wood exposed to infrared radiation", Wood Research, 56(4),