Mass Transfer Through Microwave-Treated Fir Wood (Abies alba L.): A Gymnosperm Species with Torus Margo Pit Membrane

Hadi Dashti, Asghar Tarmian, Mehdi Faezipour, Sahab Hedjazi, and Mahdi Shahverdi
Department of Wood and Paper Science & Technology, Faculty of Natural Resources, University of Tehran, Karaj, Iran

In this research, the effect of microwave pretreatment on mass transfer coefficients of Abies alba L. was investigated. For this purpose, wood specimens with dimensions of 340 x 100 x 50 mm and average moisture content of 50% were exposed to a microwave with 2450 MHz frequency for time durations of 7 and 10 minutes. After drying, the air permeability and water vapor diffusion coefficients were measured through the longitudinal and radial directions of the specimens and results were analyzed using chemical composition measurement, FT-IR (Fourier Transform Infrared) test, and SEM (Scanning Electron Microscope) studies. The FT-IR study of pretreated samples showed no specific change, although SEM photographs proved the hydrolyzation of bordered pits as a result of microwave heating. Results revealed that microwave pretreatment had no effect on the longitudinal permeability and diffusion coefficients. In contrast, the radial mass transfer rates were improved due to the microwave pretreatment. Although the microwave pretreatment had no noticeable influence on the chemical compositions of the treated specimens, the torus of some bordered pits was hydrolyzed due to microwave radiation.

Keywords Abies alba; Diffusion; Drying; FT-IR; Microwave; Permeability; SEM

INTRODUCTION

Mass transfer properties of wood, including air permeability and water vapor diffusivity, play an important role in some industrial applications. The water vapor diffusion coefficient of wood is influential in many industrial operations, such as drying, bending, peeling, and coating, as well as in the service time of wooden structures (i.e., flooring, roof structure, wooden packaging, and furniture). Permeability is also well known to be a crucial parameter in many processes, such as impregnation and preservation of wood. Fir wood (Abies alba L.) as a gymnosperm species with torus-margo pit membrane is characterized by its low permeability, mainly due to pit aspiration during drying. Thus it is difficult to expect consistent penetration of preservatives in dried woods. It is well known that the water vapor diffusivity in wood is strongly influenced by the wood density; i.e., more cell-wall substance traversed per unit distance offers more resistance to water diffusion. Indeed, the water vapor diffusivity through Abies alba L. wood is relatively fast due to its low specific gravity. This is undesirable for some wood applications, such as packaging. Thus, special efforts have been devoted to modifying the mass transfer properties of wood.[1–3] The mass transfer properties of wood can be modified by some pretreatments, such as steaming and microwave radiation. Several researchers have pointed out that microwaves can destroy the porous structure of wood and thus improve fluid flow.[4–6] Intensive microwave (MW) power applied to green wood generates steam pressure within the wood lumens by fast free water evaporation. Under high internal pressure, the pit membranes in cell walls, tyloses in vessels, and weak ray cells are ruptured to form pathways for easy transportation of liquids and vapors.[7] An increase in the intensity of the MW energy increases the internal pressure, resulting in the formation of narrow voids in the radial and longitudinal planes.[8] Torgovnikov and Vinden[9] showed that controlled use of microwave powerful energy for drying newly cut hardwood timbers can directly affect both permeability and density due to early rupturing of ray cells. Brodie[10] applied MW pretreatment to two species of popular and eucalyptus and then dried them in a solar dryer. They showed that, due to produced microscopic cracks and thus increased permeability and diffusion, drying rates increased. Hong-Hai et al.[11] examined the effect of microwave treatment on larch wood. There was an increased permeability without any significant reduction of MOE and MOR. Furthermore, radial parenchyma and some pit membranes were ruptured and tiny cracks also emerged through the cell walls as consequences of applying the treatment. Cai and Oliveira[12] found that the impacts of
microwave and radio-frequency pretreatments on the gas permeability of subalpine fir wood were not significant. However, they indicated that the findings cannot be generalized because they may depend on the power intensity applied. Fei et al.\cite{13} and Zhao et al.\cite{5} showed that MW pretreatment improves the moisture diffusion coefficient and reduces wood drying time in eucalyptus. However, Li et al.\cite{2} found that although MW pretreatment damaged the structure of the pit membrane in Masson pine wood, it did not effectively improve the diffusion coefficient.

The present research aims to evaluate the effect of microwave treatment on the mass transfer properties of *Abies alba* L (a gymnosperm species with torus-margo pit membranes). Chemical analysis, FT-IR (Fourier Transform Infrared) spectroscopy, and SEM (scanning electron microscope) experiments were also conducted to closely analyze the effect of microwave treatment on the wood porous structure.

**MATERIAL AND METHODS**

**Sampling and Microwave Pretreatment Procedure**

Fir wood (*Abies alba* L.) flat-sawed boards with green dimensions of 340 × 100 × 50 mm and initial moisture content of 45–50% were selected for the study. Six samples were considered for each set of experiments.

A microwave oven with frequency of 2.45 GHz was used for the pretreatment. Three different treatment conditions were applied, which have been provided in Table 1. To prevent the occurrence of severe checking of wood samples, every 30 to 60 seconds of microwave application the heating was stopped for 60 to 120 seconds, so that the heat could be distributed and the temperature reach equilibrium throughout the wood specimens.

**Drying Method**

The microwave-treated and the control samples were end-coated using oil paint to avoid moisture flow through the end sections. Subsequently, they were conventionally dried inside a 0.2 m³ laboratory kiln at constant temperature of 60°C and RH of 50% to the final MC of 10%. Furthermore, 2.5 × 2.5 cm² stickers from the same species were used in this study. Air movement speed was also about 1 m·s⁻¹, provided by an internal fan, and air was horizontally circulated in the kiln. The drying process was also terminated without any conditioning treatment.

**Air Permeability Measurement**

For air permeability measurement, cylindrical specimens with 18 mm in diameter and 10 mm in thickness were taken from the dried boards in radial and longitudinal directions. Then, the lateral surfaces of specimens were coated using epoxy resin to prevent any lateral flow. Figure 1 depicts a schematic of the experimental apparatus used for the air permeability measurement. The falling-water volume-displacement method was used to calculate specific gas permeability values based on the microstructure porosity of wood.\cite{14–16} The specific permeability (*K*) was calculated using Siau’s equations\cite{14}:

\[
K = \eta \cdot k_s
\]

where *K* is the specific permeability (m²·m⁻¹), *η* is the viscosity of air (*η* = 1.81 × 10⁻⁵ Pa s), and *k_s* is the superficial permeability that can be determined as follows:

\[
k_s = \frac{\pi V_d C L (P_{atm} - \beta \gamma z)}{6 t A \gamma z (P_{atm} - \gamma z)^{1.5}}
\]

**TABLE 1**

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Microwave total time (min)</th>
<th>Microwaving period (s)</th>
<th>Rest time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>MW1</td>
<td>7</td>
<td>30</td>
<td>120</td>
</tr>
<tr>
<td>MW2</td>
<td>7</td>
<td>60</td>
<td>120</td>
</tr>
<tr>
<td>MW3</td>
<td>10</td>
<td>60</td>
<td>60</td>
</tr>
</tbody>
</table>

*FIG. 1. Schematic view of the air permeability measurement apparatus.*\cite{14}
where \( k_w \) is the superficial gas permeability coefficient (m\(^2\)/Pa s), \( V_d \) is the volume of apparatus between points 1 and 2 (m\(^3\)), \( P_{\text{atm}} \) is the atmospheric pressure (m Hg), \( L \) is the length of wood specimen (m), \( z \) is the average height of water over surface of reservoir during period of measurement (m), \( A \) is the cross-sectional area of wood specimen (m\(^2\)), \( \beta \) is the molar weight of vapor (kg mole\(^{-1}\)), \( RH_1 \) is the relative humidity inside the climatic chamber, \( R \) is the constant of perfect gas, \( L \) is the sample thickness (m), \( P_{\text{vs}} \) is the pressure of saturated water vapor in temperature of \( T \) (K) and \( D_v \) is the binary diffusion coefficient of water vapor in air.

The dimensionless diffusivity (f) is calculated according to the above formula: where \( Q \) is the measured mass flux (kg \cdot s\(^{-1}\)), \( A \) is the cross-section of sample (m\(^2\)), \( M_v \) is the molar mass of water (kg mole\(^{-1}\)), \( P_{\text{vs}}(T) \) is the pressure of saturated water vapor in the temperature of \( T \) (K) and \( D_v \) is the binary diffusion coefficient of water vapor in air.

\[
C = 1 + \frac{\beta V_r z}{V_d (P_{\text{atm}} - \beta z)}
\]

Anatomical and Chemical Analysis

To closely analyze the effect of microwave treatment on the wood porous structure, scanning electron microscope (SEM) studies were conducted. Chemical composition analysis of the treated and control specimens were also carried out. Lignin and holocellulose contents of each specimen were analyzed according to TAPPI T 204 cm-97 and TAPPI T 249 cm-75 standards, respectively. Furthermore, acetone-soluble and water-soluble extractive contents were determined based on TAPPI standard methods, TAPPI T 207 cm-99 and TAPPI T 222 cm-98, respectively. An FT-IR test was also applied for all treatments. For these tests, KBr powder was mixed with the flour of wood samples using a weight ratio of 100:1. From this mixture, small tablets of about 13 mm diameter and 1 mm thickness were prepared using a Beckmann pellet apparatus under high pressure and vacuum. The IR spectra of every sample were analyzed with a Perkin Elmer Spectrum One FTIR spectrometer. Average curves from eight repeated scans were obtained between wave numbers of 4000 and 600 cm\(^{-1}\). This corresponds to the functional group (4000–1300 cm\(^{-1}\)) and the fingerprint (1300–900 cm\(^{-1}\)) regions. Precision of the spectrometer was 4 cm\(^{-1}\).

Statistical Analysis

Statistical analysis was conducted using SPSS software program, version 13. One-way ANOVA was performed to conclude significant difference at a 95% confidence level. Grouping was then made between treatments using the Duncan’s multiple range test.

RESULTS AND DISCUSSION

Effect of Microwave Treatment on Air Permeability

Results showed that the longitudinal permeability of Abies alba L. was not affected by the microwave treatment (Fig. 2). In contrast, the radial permeability slightly increased due to the microwave radiation (Fig. 3). As regards the longitudinal permeability coefficient of microwave-treated and non-treated samples, there was no significant correlation, although this trend was inverse in the transverse direction and they were placed into two different groups statically. The radial permeability of the wood specimens improved by 75, 102, and 71% due to...
the microwave treatments at MW1, MW2, and MW3 compared to the control. However, no significant improvement was observed by increasing microwave radiation time from 7 to 10 minutes. The positive impact of microwave treatment on the radial permeability can be explained by some difference in the pit structure between microwave-treated and untreated wood samples (see SEM images in Fig. 4). The torus of some bordered pits was hydrolyzed due to microwave radiation (Fig. 4b). In contrast, most of the bordered pits were in aspirated conditions in the control samples (Fig. 4a), hindering the fluid (air) flow through the pits. In addition, the increasing effect of microwave radiation on the radial permeability may be attributed to the rupture occurrence in the ray parenchyma cells. Torgovnikov and Vinden[17] mentioned that when microwave energy is applied to wood, steam is generated within the wood cells and thus, under high internal steam pressure, the pit membranes on the cell walls and the weak ray cells rupture to form pathways for easy fluid transfer.

Our results are in agreement with some previous studies reporting the positive effect of microwave radiation on wood permeability.[9,10,17] Vinden and Torgovnikov[9] also mentioned that the permeability of some wood species in the radial direction can be increased by a factor of 170–1,200 times due to microwave radiation. As previously reported by Tarmian and Perre,[18] the radial permeability of softwoods is significantly controlled by ray parenchyma rather than by bordered pits. Therefore, it can be concluded that the improving effect of microwave treatment on the radial permeability of *Abies alba* L. is mainly due to the rupture in the ray cells rather than the bordered pit modification. The microwave treatment had no noticeable effect on the wood chemical composition (Table 2). Results of FT-IR also revealed no specific degradation in the treated specimens (Fig. 5). Hence, changes in the permeability coefficient could not be related to the chemical modification.

**Effect of Microwave Treatment on Water Vapor Diffusivity**

MW treatment had no effect on the longitudinal water vapor diffusion coefficient (Fig. 6). In contrast to the longitudinal water vapor diffusivity, the radial water vapor diffusivity increased as a result of microwave radiation (Fig. 7). From the statistical point of view, a significant difference was observed among microwave-treated and control samples regarding the transverse permeability coefficient. On the other hand, there was no meaningful difference when the longitudinal permeability was considered. On average, the radial diffusivity of the specimens microwave radiated at MW3 condition was 3.5 times higher than that of the control specimen. Since no changes occurred in the chemical composition of *Abies alba* L. due to the microwave radiation, the increasing effect of the microwave treatment on the radial diffusivity cannot be related to the chemical modification of the microwave-exposed specimens. Thus, the increased radial diffusion coefficient can be attributed to the porous structure.
modification as mentioned in the previous section (see Fig. 4). In agreement with our results, Fei et al.\textsuperscript{[13]} and Zhao et al.\textsuperscript{[5]} reported that microwave radiation can improve the moisture diffusion coefficient, whereas Li et al.\textsuperscript{[2]} found that the microwave pretreatment was able to damage the structure of the pit membrane in Masson pine wood but could not effectively improve the diffusion coefficient.

**TABLE 2**

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Acetone-soluble extractives (%)</th>
<th>Water-soluble extractives (%)</th>
<th>Holocellulose (%)</th>
<th>Lignin (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>6.58</td>
<td>5.23</td>
<td>65.33</td>
<td>32.88</td>
</tr>
<tr>
<td>MW1</td>
<td>6.88</td>
<td>5.14</td>
<td>65.21</td>
<td>30.64</td>
</tr>
<tr>
<td>MW2</td>
<td>6.37</td>
<td>5.46</td>
<td>66.49</td>
<td>31.09</td>
</tr>
<tr>
<td>MW3</td>
<td>6.22</td>
<td>5.30</td>
<td>66.56</td>
<td>30.29</td>
</tr>
</tbody>
</table>

**FIG. 5.** FT-IR spectroscopy analysis of fir wood specimens: microwave-treated (MW3) and control samples.

**FIG. 7.** The average radial water vapor diffusion coefficient of microwave-treated and control \textit{Abies alba} L. specimens.

**CONCLUSIONS**

This research was conducted to study the effect of microwave radiation on the mass transfer properties (i.e., air permeability and water vapor diffusivity) of fir wood (\textit{Abies alba} L.), a gymnosperm species with torus margo pit membrane. Overall, the microwave pre-treatment had no effect on the mass transfer coefficients through the longitudinal direction. However, both radial permeability and diffusion coefficients improved due to the microwave radiation. The chemical composition measurement as well as FT-IR tests proved that there were no wood chemical changes due to microwave radiation; thus, the radial mass transfer improvement cannot be related to the chemical modification. In contrast, based on the SEM observations, the tracheid bordered pits were significantly affected by the microwave treatment. The torus of bordered pits was hydrolyzed due to the microwave radiation. Hence, the wood porous structure modification due to the microwave radiation can be considered as an effective factor for the mass transfer improvements in \textit{Abies alba} L. Since ray parenchyma cells play an important role in the radial mass transfer through the wood, the mass transfer improvements of fir wood as a result of microwave radiation can also be related to the ray cells’ rupture. A study on the effect of such microwave radiation on the mass transfer properties...
of softwood species without torus margo pit membranes was recommended for further research.

REFERENCES