Thermal Conductivity Temperature Dependence of Heat-treated Wood at Different Moisture Content Levels

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Effects of temperature dependence and relative humidity were studied relative to the thermal conductivity of heat-treated pine and heat-treated beech, which are frequently used for building construction. Pine and beech wood were exposed to heat treatment at 180, 200, and 220 °C in nitrogen gas for 2 h. As a result, the thermal conductivity values of the heat-treated wood decreased as the temperature of the heat treatment process increased and relative humidity increased. However, thermal conductivity of wood became more stable after heat treatment under relative humidity changes. The thermal conductivity values increased with rising mean plate temperatures, while the temperature dependence of the heat-treated wood was not affected by the relative humidity changes. Consequently, heat-treated wood, with variable humidity without excessive heat changes, can be preferred for the construction of buildings.

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INTRODUCTION

Heat treatment modification of wood is usually carried out at temperatures between 160 and 240 °C, and various external variables (temperature, duration, type, and composition of the surrounding atmosphere) influence the chemical changes that occur all over the treatment process. Heat treatment provides certain advantages in terms of reducing wood hygroscopicity, enhancing wood dimensional stability, and boosting biological durability (Rowell et al. 2009; Sandberg et al. 2013; Nasir et al. 2018; Kamperidou 2019; Fu et al. 2019).

Nowadays, due to these great features, heat-treated wood is extensively preferred in non-structural modern building construction, including exterior cladding, terraces, windows, flooring, stair treads, kitchen floors, bathrooms, and saunas (Gündüz et al. 2008; Sandberg and Kutnar 2016; Herrera et al. 2018). The most attractive property of heat-treated wood is its low hygroscopicity, which broadens its applications, particularly in the building industry. Decorative color options are another advantage for consumers, as the natural color of the wood is dark after heat treatment (Esteves et al. 2007; Aydemir and Gündüz 2009; Esteves and Pereira 2009). The dimensional stability of wood is affected by hygroscopicity, which also reduces the risk of fungal and insect attacks (Kandem et al. 2002; Yıldız et al. 2006; Köcaefe et al. 2008; Kamperidou 2019). As a result, the longevity of a wooden structure is directly correlated with the hygroscopicity of wood. Heat-treated wood with low hygroscopicity can be used more efficiently throughout its life in buildings without experiencing any dimensional movement problems due to possible changes in the
humidity in the environment (Priadi and Hiziroğlu 2013). In addition, hygroscopic hysteresis of wood increases with heat treatment (Fu et al. 2019). The mass loss of wood during heat treatment is one of the most crucial features in thermal modification, and it is commonly used as an indicator of heat treatment intensity (Hill 2006; Candelier et al. 2016). The thermal treatment reduces the wood’s volume and mass, but since the latter is more intense, the density also decreases (Pásztory et al. 2017). However, some major drawbacks of heat treatment include weakening the wood’s overall strength and stiffness and making it more brittle (Czajkowski et al. 2020).

Nowadays, thermal insulation is becoming more important in the construction of new buildings, as energy becomes more precious and demand rises (Coman et al. 2017). Thermal efficacy is primarily determined by a material’s k-value, which is defined as the heat transfer rate through a unit thickness of the material per unit area per unit temperature difference (Sahin Kol and Sefil 2011). A material’s k-value is influenced by density, porosity, moisture content, and mean temperature difference. The thermal load, and thus the energy consumption, of a building can be considerably decreased by using materials with low thermal conductivity (k-value) (Budaiwi and Abdou 2013; Cavus et al. 2019). As the usage of heat-treated wood in buildings has grown in popularity, so has research into its thermal qualities. Numerous studies have been carried out to assess the heat treatment on the thermal conductivity (k-value) of wood (Sahin Kol and Sefil 2011; Korkut et al. 2013; Olarescu et al. 2015; Aytin et al. 2016; Sahin Kol and Aysal Keskin 2016; Pasztory et al. 2017; Pelit et al. 2017; Czajkowski et al. 2020). It has been hypothesized that the structural and chemical change brought about by heat treatment could potentially impact its k-value. The k-value is reduced after heat treatment, but how much was found to depend on thermal treatment duration and temperature (Kol and Sefil 2011; Olarescu et al. 2015; Pásztory et al. 2017; Pasztory et al. 2018; Srivaro et al. 2019; Czajkowski et al. 2020; Čabalová et al. 2022).

Several studies have examined the impact of operation temperature on the thermal performance of insulating materials and heat-treated wood (Abdou and Budaiwi 2005; Srivaro et al. 2019; Olarescu et al. 2015, Pasztory et al. 2018). Their results demonstrated a linear relationship between mean temperature and increased thermal conductivity values. In addition, Berardi and Naldi (2017) noticed that the thermal response of materials treated to different temperatures significantly depends on the type of material. In materials with lower density, the variations become more clear.

In addition to operating temperatures, another important factor that has a big impact on the k-value of a material is its moisture content, which is affected by the humidity level of the surroundings. A material’s k-value increases as its moisture content rises. This means that moisture diminishes the thermal performance of materials. The moisture content of materials used for walls and roofs is typically distinct in buildings. The amount of moisture in the insulating material is significantly influenced by the indoor environment, ambient air humidity, and moisture characteristics of the wall or roof system (Abdou and Budaiwi 2005).

The goal of this study was to evaluate the effect of changing operating temperature on the thermal conductivity variation of heat-treated wood depend on relative humidity and as a result, to estimate the relative sensitivity of k-value of heat-treated wood typically used in building constructions. Published k-values of heat-treated wood were evaluated at standard temperature and humidity conditions. However, depending on the prevailing climatic conditions, materials employed in building construction can be subjected to large changes in ambient temperature and relative humidity. Consequently, their real thermal
behavior may be very different from the expected under standard conditions. Thus, a more realistic evaluation of the thermal insulation performance of heat-treated wood in different climates will result in a more accurate assessment of thermal performance and a more accurate estimate of energy-efficient design (Abdou and Budaiwi 2005).

**EXPERIMENTAL**

**Materials**

The samples with the dimensions of 25 mm × 100 mm × 100 mm (R, T, L) were prepared from the sapwood region of kiln-dried lumbers [made of one beech (Fagus orientalis L.) and one pine (Pinus sylvestris L.) stems from the region of Yenice Balkisik and Bolu Mengen, Turkey respectively]. In this stage, samples that were reasonably straight-grained and free from any visual anomalies were chosen for the study to acquire the best results and optimize the variability in the data. In the beginning, there were a total of sixty flawless samples that were split into four groups, with each group having fifteen samples. The first group was used as a reference and did not undergo heat treatment. The remaining three groups were subjected to a heat treatment under nitrogen gas at the temperatures 180, 200, and 220 °C, respectively. Before the heat treatment, all samples (control samples included) were dried at 103 °C to reach constant weight to prevent the splitting of samples during heat treatment. Immediately after oven drying, reaching 0% equilibrium moisture content of wood, the samples were kept in a desiccator to prevent them from getting moisture until further processing. Prior to heat treatment, oven-dry samples were weighed, and the mass before heat treatment was determined.

**Methods**

*Heat treatment*

The heat treatment was performed in a vacuum oven with a sensitivity of ± 1 °C under nitrogen atmosphere. The whole process of heat treatment is made up of the following steps. Initially, the air inside the oven was vacuumed to reduce the ambient pressure to 100 to 150 mbar. The contact of the system with oxygen was prevented, and the ambient pressure was decreased to -900 mbar through a vacuum with a vacuum pump. The oven was filled with nitrogen gas until the pressure gauge again reached to 0 levels and set to target temperature (180, 200, and 220 °C). The temperature was increased by 1.5 °C min 1 from ambient (20 °C) to the target temperatures and maintained the target temperature for 2 h. Then the heating system was set to 103 ± 2 °C, and the temperature was decreased by 1 °C min 1 to 103 °C. When the oven temperature had cooled to 103 °C, the samples were removed from the oven and kept in a desiccator to prevent them from getting moisture during further cooling. Then the samples were re-weighed, and the post-heat masses were determined.

*Climatization*

After heat treatment, heat-treated pine (HTP) and heat-treated beech (HTB) samples were divided into three subgroups (each includes five test repetitions) to ascertain the thermal conductivity at various levels of relative humidity. The reason for choosing these climatization conditions is because they are similar to the usage areas of heat-treated wood, such as outdoor flooring, balcony flooring, and saunas. The relative humidity is 36% in indoor environments such as indoor flooring, 70% and 80% in outdoor flooring, balcony
flooring, and roofing, and 80% in saunas. Prior to thermal conductivity measurement, the specimens were conditioned at 20 to 22 °C and 36, 70, and 80% relative humidity (RH) until a constant weight was reached. At the end of the climatization, the dimensions of wood samples and weights were measured sensitively, and the samples’ density (δ) and equilibrium moisture content (ω) at different relative humidity were estimated according to Eqs. 1 and 2.

\[
\delta = \frac{M}{V} \tag{1}
\]

In Eq. 1, \(\delta\) is the density (g/cm\(^3\)), \(M\) is the moist weight (g), and \(V\) is the moist volume (cm\(^3\)).

\[
\omega = \left[\frac{(M_r - M_0)}{M_0}\right] \times 100 \tag{2}
\]

In Eq. 2, \(\omega\) is the moisture content (%), \(M_r\) is the moist weight (g), and \(M_0\) is the oven dry weight (g).

**Determination of thermal conductivity**

The single-specimen guarded hot plate apparatus Taurus TLP 300 DTX meter (Taurus Instruments GmbH, Weimar, Germany) was used to measure thermal conductivity (\(k\)-value) in accordance with ISO 8302 (ISO standard 1991) (Fig. 1). The measurement is done in a circle with a 100 mm diameter in the middle of the sample, and the sample is typically 500 mm × 500 mm × sample thickness (L, T, and R). The outside sections provide protection against the effects of the environment. Standard conditions (500 mm\(^2\)) were simulated by placing samples with identical 100 mm x 100 mm x 25 mm (L, T, R) dimensions in the center of a plate and covering the plate’s brims with wood plates of the same fiber orientation and thickness (Niemz et al. 2010; Sonderegger et al. 2011). Cold and hot plate temperatures were 5 °C/15 °C, 15 °C/25 °C, and 25 °C/35 °C. So, the \(k\)-value was recorded at temperatures 10, 20, and 30 °C. The change in temperature between the hot and cold plates was 10 °C. The total time it takes to measure each sample is 390 minutes, and the result was the average of 13 measurements.

![Half-diagram of the single-specimen guarded heated plate apparatus](image)

**Fig. 1.** Half-diagram of the single-specimen guarded heated plate apparatus
Fourier transform infrared (ATR-FTIR) analysis

After heat treatment, absorption spectra were analyzed to evaluate changes in the functional groups of wood cell wall components. Heat-treated and un-treated samples were ground and then measured. The spectra of each sample were obtained at a wavelength of 700 to 4000 cm\(^{-1}\) with a resolution of 4 cm\(^{-1}\).

RESULTS AND DISCUSSION

Figures 2 and 3 show the \(k\)-values un- and heat-treated pine and beech samples as a function of relative humidity (RH) at 10, 20, and 30 °C mean plate temperatures.

![Graphs showing thermal conductivity of untreated and HTP specimens at different temperatures and RH](image)

**Fig. 2.** Thermal conductivity of untreated and HTP specimens at mean plate temperatures of 10 °C, 20 °C, and 30 °C as a function of relative humidity.
After applying heat treatment to pine (Fig. 2) and beech (Fig. 3), it was observed that their $k$-values decreased. The $k$-values of the samples decreased as the heat treatment temperature increased. A modest decrease in $k$-values was observed at 180 °C, but the variation quadrupled when the heat treatment temperature reached 220 °C.

There was a linear correlation between the $k$-value and RH in all samples, at the 95% confidence level. As RH increased, the $k$-value of samples linearly increased. The increasing trend of the $k$-value as a RH function appeared identical for untreated and 180 °C-heated samples. Considered with RH, the $k$-values of untreated and 180 °C heat-treated samples increased considerably from 36% to 70%. But the gap between 70% and 80% wasn’t very big. The increase in $k$-value with increasing RH was more linear in samples...
treated to higher temperatures. The samples heat-treated at 220 °C had a much higher coefficient of determination \( (R^2 = 0.84 \text{ to } 0.96) \) of the \( k \)-value with RH than the others. The first could say that there had been an improvement in the \( k \)-value’s consistency with regard to the EMC of heat-treated wood when exposed to high temperatures.

Wood responds to changes in its moisture environment by absorbing and releasing water molecules. This happens when wood is exposed to environments with considerable variations in relative humidity (RH). EMC of wood results from the adsorption and desorption of water molecules over time in a steady environment of temperature and RH. Therefore, the potential of wood to adapt to its surroundings can be altered by modifying the EMC. Water absorption is always associated with an increase in thermal conductivity, since the thermal conductivity of water is approximately 20 times larger than that of stationary air. As a result, it is critical to investigate the effect of moisture on thermal performance, particularly in building insulating materials. According to the study’s findings, heat treatment, reduced the EMC of wood (Table 1). As the heat treatment temperature was increased, the wood density somewhat decreased and the EMC decreased dramatically. As can be seen from the data in Table 1, the variation in EMC as a function of heat treatment temperature was significantly larger than the variation in density. It can therefore be concluded that the decrease in EMC may have a greater impact on the reduction in \( k \)-value caused by heat treatment. Pine and beech exhibited chemical alterations that impacted the physical qualities such as density and hygroscopicity during the heat treatment. As can be seen in Figs. 4 and 5, considerable variations were noticed, mostly around 220 °C. The decrease in wood porosity and MC was attributed to the deformation of cell wall components and changes in their chemical composition produced by a rise in heat treatment temperature.

**Table 1. Moisture Content and Density Values of UT and HT Samples at Different Relative Humidity**

<table>
<thead>
<tr>
<th>Heat Treatment Temperature (°C)</th>
<th>Relative Humidity at 20 °C (%)</th>
<th>Moisture Content (%)</th>
<th>Density (g/cm³)</th>
<th>Moisture Content (%)</th>
<th>Density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Untreated</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>36</td>
<td>36</td>
<td>7</td>
<td>0.597</td>
<td>7</td>
<td>0.648</td>
</tr>
<tr>
<td>70</td>
<td>12.8</td>
<td>0.602</td>
<td>12.7</td>
<td>0.653</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>16.2</td>
<td>0.605</td>
<td>16.1</td>
<td>0.662</td>
<td></td>
</tr>
<tr>
<td>180</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>36</td>
<td>4.1</td>
<td>0.522</td>
<td>3.7</td>
<td>0.638</td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>7.4</td>
<td>0.593</td>
<td>7.6</td>
<td>0.662</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>10.4</td>
<td>0.588</td>
<td>10.9</td>
<td>0.66</td>
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<tr>
<td>200</td>
<td></td>
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</tr>
<tr>
<td>36</td>
<td>3.8</td>
<td>0.552</td>
<td>3.4</td>
<td>0.623</td>
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<tr>
<td>70</td>
<td>7.5</td>
<td>0.589</td>
<td>7</td>
<td>0.613</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>10</td>
<td>0.574</td>
<td>10</td>
<td>0.65</td>
<td></td>
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<tr>
<td>220</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>36</td>
<td>3.6</td>
<td>0.563</td>
<td>3.3</td>
<td>0.622</td>
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<tr>
<td>70</td>
<td>6.6</td>
<td>0.564</td>
<td>6.9</td>
<td>0.607</td>
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<tr>
<td>80</td>
<td>8.7</td>
<td>0.56</td>
<td>8.5</td>
<td>0.593</td>
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</tr>
</tbody>
</table>
It is known that the absorption bands of functional groups of wood are between 1800 and 800 cm\(^{-1}\). These bands are caused by stretching and bending vibrations in the molecules, which give rise to absorbances in the so-called fingerprint zone. The bands between 3550 and 2900 cm\(^{-1}\) correspond to OH and C-H stretching. It is also significant for the primary components of wood (Kubovský et al. 2020). The band at 1030 cm\(^{-1}\) corresponds to C-O-C stretching of primary alcohols in cellulose and hemicelluloses (Esteves et al. 2013; Xing and Li 2014; Kubovský et al. 2020). It can be seen in Figs. 4 to 5 that this band declined with increasing heat treatment temperature. This shows that the hemicellulose and cellulose structure had slowly changed. At 2940 cm\(^{-1}\) (asymmetric CH\(_2\) stretching) and 2880 cm\(^{-1}\) (symmetric CH\(_2\) stretching) (Esteves et al. 2013; Xing and Li 2014; Kubovský et al. 2020), only minor alterations with a slight decrease in band
intensities were observed. This verifies the thermal decomposition of lignin and alterations at the level of cellulose crystallinity. The band at 3335 cm⁻¹ represents the OH stretching vibration in hemicelluloses and lignin (Esteves et al. 2013; Xing and Li 2014; Kubovský et al. 2020). In the analysis, there was a significant drop in this band. As shown in Figs. 5 and 6, the intensity of this peak decreased as the heat treatment temperature increased, and the wood became less hydrophilic (Huang et al. 2012).

It should be observed that for all RH settings, the k-values of HTP and HTB were lower than those of untreated ones. The heat treatment mainly affected the most hydrophilic compounds (Figs. 4 to 5). Depolymerization of carbohydrates, particularly hemicelluloses, results in a decrease in the overall number of hydroxyl groups. The hydroxyl groups have a direct impact on the absorption of water. Heat treatment can raise the relative percentage of crystalline cellulose, which is known for its low accessibility of hydroxyl groups to water molecules (Figs. 4 to 5) and can have a major impact on moisture absorption and polarity of wood. As a consequence, the treated wood has a lower water affinity (Herrera et al. 2014). This indicates that water uptake and absorption in wood slow down, so the amount of water in the wood decreases (Hill 2006; Gu and Hunt 2007; Sahin Kol 2009; Sahin Kol and Sefil 2011). The k-value of water is much higher than wood, so the k-value tends to increase as EMC increases or decreases as EMC decreases. The findings were consistent with prior research that had used heat treatment on other types of wood (Sahin Kol and Sefil 2011; Korkut et al. 2013; Sahin Kol and Aysal Keskin 2016; Pasztory et al. 2017, 2020; Pelit et al. 2017).

Heat treatment results in the depolymerization of some hemicellulose, cellulose and lignin molecules in the wood tissue, reducing the amount of wood material (Cheng et al. 2016). Thus, heat treatment reduces the number of solid substances within the wood, enlarges the pores, and increases the amount of through-pore porosity (Jang and Kang 2019; Jang et al. 2020; Čabalová et al. 2021; Mawardi et al. 2022). That is, heat-treated wood has a larger pore capacity and significantly more air content, resulting in a bigger effect of operating temperature on k-values. The k-value decreases with decreasing density (Sonderegger et al. 2011).

In addition, when the temperature of the heat treatment was increased, the k-values of HTP and HTB both fell, but at different rates, and the rate of decrease was greater in beech. At 80% relative humidity, the rate of change in unheated samples of HTP at 180, 200, and 220 °C was 0.6%, 2.7%, and 8.7%, while it was 3.7%, 12%, and 14% in HTB. Because the heat treatment temperature causes different chemical changes in softwood (pine) and hardwood (beech), the change rate of mass loss varies, and thus, the variation of pore size, and porosity, are different (Jang and Kang 2019). Previous studies have shown that hardwoods have less thermal stability than conifers (softwoods) because of differences in their chemical structures. Softwood and hardwood have different kinds and amounts of hemicellulose, and the xylans in hardwood are more likely to break down when heated than the mannans in softwood (Hill 2006; Sahin Kol and Sefil 2011; Pásztory et al. 2017).

Figures 6 and 7 display the influence of thermal conductivity on mean plate temperature for UT and HT samples under three distinct relative humidity conditions. All samples showed a linear relationship between the k-value and mean plate temperature at the 95% confidence level. For all heat treatment temperatures, the rate of change of k-value as a function of plate temperature was the same for HTP and HTB as it was for the untreated ones. The highest k-values were obtained in the samples where the average plate temperature was 30 °C, and the lowest k-values were obtained in the samples where the average plate temperature was 10 °C. A similar trend was also obtained in some studies in
the literature (Olarescu et al. 2015; Pasztory et al. 2018; Srivarapu et al. 2019). According to the findings of this investigation, the thermal conductivity of heat-treated wood increases linearly with temperature.

![Graph showing thermal conductivity of untreated and HTP specimens at three different moisture conditions of 36%, 70%, and 80% as a function of mean plate temperature.]

**Fig. 6.** Thermal conductivity of untreated and HTP specimens at three different moisture conditions of 36%, 70%, and 80% as a function of mean plate temperature.
This research showed that higher-temperature-treated wood outperformed lower-temperature-treated wood in terms of thermal performance. The Wood Handbook states that for use as a thermal insulator for buildings, the $k$-value of material must be between
0.1 and 0.14 W/mK (Ross 2010). Even when subjected to the high levels of relative humidity (80%) and temperature difference (30 °C) seen in the study, $k$-value of HTP and HTB did not go above these ranges. Although HTP and HTB still were within this spectrum, where strength requirement is desired, low-temperature HTP is preferable. As a consequence of this, HTP and HTB can be employed as structural thermal insulation. When more insulation is needed, it was also shown that pine is superior to beech. Low-temperature heat-treated beech is preferable for applications where superior thermal insulation properties and satisfactory mechanical strength are required.

**CONCLUSIONS**

1. The thermal conductivity of heat-treated wood increased with the relative humidity. However, this difference was insignificant at small relative humidity changes. Accordingly, it can be said that the thermal conductivity of wood becomes more stable after heat treatment under relative humidity change. This indicates that heat treatment could improve the energy performance of wood subjected to prevailing climatic conditions.

2. Contrastingly, the thermal conductivity of heat-treated samples dependence on changes in temperature was similar to that of untreated specimens, showing a relatively high increase of thermal conductivity with an increase in the mean plate temperature. The thermal conductivity of wood was still sensitive to temperature after heat treatment, and the temperature dependence of the heat-treated wood was not affected by the relative humidity change.

3. Heat-treated pine exhibited a lower conductivity than heat-treated beech. According to heat treatment temperature, average plate temperature, and relative humidity, both variations were quite similar and can be considered insulating materials. However, pine can be preferred where higher insulation is desired.

**ACKNOWLEDGMENTS**

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