130. Jahrgang (2013), Heft 2, S. 85 – 101

Austrian Journal of Forest Science
Centralblatt für das gesamte Forstwesen

The Impact of red heartwood on drying characteristics and mass transfer coefficients in beech wood

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Keywords: Air permeability, Beech, Defects, Diffusion coefficient, Drying, Red heartwood

Abstract

The effects of red heartwood on mass transfer coefficients and drying characteristics in beech wood (Fagus orientalis L.) were studied here. In this regard, some properties were measured within the dried boards containing red heartwood; then they were compared with those of the normal wood. The properties included longitudinal diffusion and specific air permeability coefficients, drying rate, radial and tangential shrinkage, crack occurrence, residual stresses (casehardening), and warp. Specimens were dried in a laboratory convective kiln under a constant temperature of 60 °C and a relative humidity (RH) of 40% until the final moisture content (MC) of 8%. For evaluation of the permeability and diffusion coefficients, other selected specimens were dried under milder condition. The results revealed that red heartwood decreased drying rate, but it increased the shrinkage, casehardening, and consequently drying defects. In this connection, the existence of tyloses in the vessel elements of red heartwood resulted in a considerably significant decrease in the longitudinal permeability; however, tyloses seemed to have no significant decreasing effect on the longitudinal diffusion coefficient.

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Introduction

Wood is frequently modified by engineering processes to give stiffness or homogeneous mechanical properties because few species offer radial and axial uniformity in their produced wood (Taghiyari 2011); the quality of wood can also be affected by rotation period, mono- or mixed-species cultivation, drying programs, nitrogen deposition in the soil, light and soil, as well as interaction between clone-type and site (Barna 2011; 2012; Lotfizadeh et al. 2012; Smidt et al. 2012). Furthermore, the majority of humans world-wide depend upon wood products harvested from forests; therefore, efficient use of wood is highly important. Although composite-boards offer the advantages of a homogeneous structure and the use of raw materials without restrictions as to the shape and size (Uetimane & Ali, 2011) and there are many studies on formaldehyde emission (Valenzuela et al., 2012) and improvement of resin (Stockel et al., 2012), however, solid woods are yet considered a main structural and artistic material. In this connection, the Eastern beech (*Fagus orientalis*) is one of the most important deciduous commercial tree species not only in Iranian forestry, but also in some other countries, for instance, Greece and Turkey. An undesirable phenomenon, called "red heartwood" or "false heartwood" frequently occurs in beech trees. There is no clear reason for its occurrence, but it can be related to fungal attacks, genetics, and environmental parameters such as soil pH. The mechanism of red heartwood formation is described in detail by Zycha (1948). According to a general theory, red heartwood is formed in old beech trees when air penetrates into the stem center (Wernsdörfer et al. 2005). Sorz and Heitz (2008), however, reported that there is not a significant difference in oxygen density between red and normal heartwood.

The presence of red heartwood in beech timbers reduces the quality, and thus the degree of wood utilization. Firstly, the use of beech timbers with red heartwood is limited from the aesthetical point of view. To solve this problem, the stabilization of red heartwood color by means of steaming or specific drying schedules has been recommended (Trenciansky and Hansmann 2007).

Secondly, tyloses and other substances found in red heartwood often influence the impregnation processes of beech timbers (Seeling 1998). Thus, numerous studies have been focused on controlling the occurrence of red heartwood in standing beech trees by silvicultural means (Knoke 2003). Pohler et al. (2006) found that there were no significant differences in the mechanical, technological, and bond ability properties between beech with and without red heartwood.

In spite of several researches conducted to characterize the anatomical, physical, mechanical, and chemical features of beech wood (Nasroun and AL-Shahrani 1998, Sadatnejad et al. 2008, Guler et al. 2002 and 2004, Albert et al. 2003, Papadopoulos 2008), investigations of the characteristics of beech red heartwood are still rare. Many authors have contributed to characterize the drying behavior of beech wood (Bajraktari 2010, Milic and Kolin 2008, Dedic 2000). Apart from the physical discrepancies of red heartwood in comparison to beech normal wood, it was reported to have inevitable different drying characteristics (Marinescu et al. 2010). The drying rate has a close relationship with the two parameters of permeability coefficient (Cia 2006) and diffusion coefficient (Brodie 2008). In fact, these two factors play a pivotal role in the drying behavior of wood within the free water and bound water domains (Tarmian and Perre 2009, Tarmian et al. 2012). So far, little or no clear study was carried out focusing on the drying properties of red heartwood, and its effect on mass transfer coefficient. The present research was therefore conducted to find out the effects of red heartwood on the permeability and diffusion coefficients of beech wood (*Fagus orientalis*), and consequently the drying behavior of beech wood; the results would help managers to have better wood-drying schedules for kilns.

Materials and methods

Specimen preparation

Three oriental beech trees (*Fagus orientalis*) from each of the two sample plots were cut to be used in the present study. Three short logs containing severe red heartwood were selected from the freshly-cut trees. The ends of the logs were immediately coated by liquid paraffin to prevent severe moisture loss. The logs were cut by a band saw to the flat-sawn boards, so as to obtain test samples containing either only normal wood, or red heart.

Specimens with dimensions of $25 \times 40 \times 200$ mm^3 (radial, tangential, and longitudinal, respectively) were used to evaluate the drying characteristics of both red heartwood and normal (without red heartwood) wood specimens, and also the same sample sizes to determine the permeability and diffusion coefficients. As regards the drying characteristics measurements, thirty test samples were cut from each log, out of which: fifteen blocks containing only normal wood, and fifteen others containing only red heartwood. Likewise, fourteen blocks were used with the same proportions for drying of other group of specimens, before cutting samples for the permeability and diffusion measurements. The specific gravity and the average initial moisture content (MC) of both normal wood and red heartwood were also assessed.

Drying procedure

Before drying, all specimens were end coated with epoxy resin to avoid longitudinal moisture reduction and were dried at a temperature of 60 °C and a RH of 40% in a laboratory conventional kiln until the final moisture content (MC) of 8%. Air movement speed was also about 1 $m.s^{-1}$.

For evaluation of the permeability and diffusion coefficients, other selected specimens were dried under milder condition at 50 °C and a RH of 63% until the final MC of 7%. In fact, milder circumstances were applied to reduce the drying rate. This precaution limits the sample from cracking due to related residual stresses which could lead to measurement errors.

Drying rate and drying defects

Drying rate was determined by weighing the specimens during drying. Radial and tangential shrinkage were also evaluated (according to Simpson 1991). After drying, the severity of the drying defects (warp) were measured based on the DIN-EN 1310 standard (1997), and the residual stresses (casehardening) by means of a well-known method called prong test were assessed for both the red heartwood and normal wood specimens. Remaining stresses were calculated from Eqn. 1 (Fuller 1995).

$$PR = \frac{x - x'}{l^2} \quad (1)$$

PR is the prong response of test sample (mm^{-1}), x is the distance between the outer prong edges before cutting (mm), x' is the distance between the outer prong edges after cutting (mm), and l is the length of the sample's prong (mm).

Air permeability measurement

Cylindrical specimens of 18 mm in diameter were cut in the longitudinal direction. As regards, from the dried blocks sixty samples were obtained, out of which: thirty blocks containing only normal wood and the remained proportion containing only red heartwood. The side surfaces of the specimens were coated with epoxy resin to prevent any lateral fluid flow (Ghorbani et al. 2012). Longitudinal air permeability was measured by an apparatus with milli-second precision based on the microstructure porosity of wood (Taghiyari et al., 2010 & 2013; Taghiyari & Efhami 2011). Fig. 1 depicts a schematic of the experimental apparatus used for the air permeability measurement. Connection between the specimen and holder was made fully air-tight. Air permeability coefficient was calculated using Eqns. (2) and (3):

$$k_g = \frac{\alpha V_d C L (P_{atm} - \beta \bar{z})}{\beta t A \bar{z} (P_{atm} - \gamma \bar{z})} \quad (2)$$

where k_g is the superficial gas permeability coefficient (m^2/ Pa s), V_d is the volume of the apparatus between points 1 and 2 [$V_d = \pi r^2 \Delta z$] (m^3), C is determined by equation 3, L is the thickness of specimen (m), P_{atm} is the atmosphere pressure (m Hg), Z is the average height of the water over the surface of the reservoir during the period of measurement (m), t is falling time (s), A is the cross sectional area of the specimen (m^2), and values of α, β and γ are given in Siau (1995).

$$C = 1 + \frac{\beta V_r z}{V_d (P_{atm} - \beta \bar{z})} \quad (3)$$

where V_r is the total volume of the apparatus above point 1 [including the volume of the hoses] (m^3) and Δz is the change in height of the water (m).

The air permeability coefficient was converted to specific air permeability coefficient by Eqn. 4.

$$K = \eta . k_g \quad (4)$$

where K is specific permeability coefficient (m^2), and η is the air viscosity at 20 °C (1.81×10^{-5} Pa s).

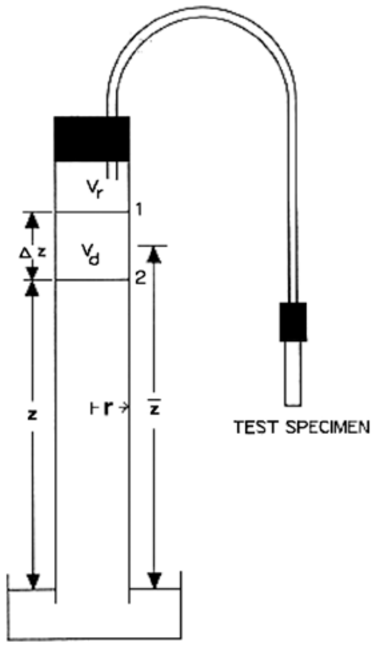

Fig. 1. Schematic view of the air permeability measurement apparatus (USPTO No. 8,079,249 B2) (Taghiyari, 2012 & 2013ab; Dashti et al., 2012a,b)

Diffusion coefficient measurement

After the air permeability measurement, each cylindrical specimen (18 mm in diameter) was cut into 5 mm-thick specimens. Then, the side surfaces of each sample were coated using an epoxy resin to avoid any water vapor leakage at the lateral surfaces of the sample during the measurements. The cup method was applied to measure the water vapor diffusivity. A schematic diagram of the experimental device (vapometer) is depicted in Fig. 2. The sample support comprises a glass pipe and a PVC pipe. A rubber tube was applied between the PVC pipe and the wood sample. Drilling a hole in the PVC tube, partial vacuum was applied for the rubber joint to temporarily stick to the internal part of the PVC tube to place the sample inside the cup without any damage to the rubber tube. The epoxy resin on the lateral face of the sample was used to strongly reduce the roughness of this face and allows an air-tightness assembly of the sample and the cup along the rubber tube. Before placing the sample in the vapometer, silicone-based grease (vacuum grease) was applied on the lateral surfaces of the specimen to avoid any flow in the microporosity layer formed between the sample and rubber surface. The saturated salt solution of sodium chloride (NaCl) was used to control the relative humidity inside the cup at about 75%. After preparation, the cups were placed inside a climatic chamber set at 60% RH. Water vapor diffuses from inside the cup with a higher RH_2 (75%) to outside with a lower RH_1 (60%). In fact, a low RH difference was applied to reduce the MC gradient inside the sample. This precaution limits the sample warp due to differential shrinkage which could lead to measurement errors. The cups were weighed every 12 h until a constant weight was reached.

The cup method is based on Fick's first law of diffusion under steady-state conditions. Under steady-state conditions, the water vapor flux in air can be written using Eqn. 5 (Agoua et al. 2001):

$$q = -\rho_g D_{eff} \nabla \left[\frac{\rho_v}{\rho_g} \right] = -\rho_g f D_v \nabla \left[\frac{\rho_v}{\rho_g} \right] \cong -f D_v \nabla(\rho_v) \tag{5}$$

where q is the water vapor flux through the wood sample ($kg.s^{-1}.m^{-2}$), ρ_g is the air density ($kg.m^{-3}$), ρ_v is the water vapor density ($kg.m^{-3}$), and $D_{eff} = fD_v$ where D_{eff} is the diffusion coefficient of wood ($m^2.s^{-1}$), D_v is the water vapor diffusion coefficient in air, and f is the dimensionless diffusivity. The dimensionless diffusivity (f) is a ratio of the water vapor diffusion coefficient in wood to the water vapor diffusion coefficient in air which is calculated from Eqn. 6. It is also worth mentioning that the resistance of water diffusion in the air layer between the water surface and the sample was omitted.

$$f = \frac{Q}{D_v A} \times \frac{L}{(RH_2 - RH_1) P_{vs}(T)} \times \frac{RT}{M_v} \tag{6}$$

where Q is the mass flux ($kg.s^{-1}$), A is the sample cross sectional area (m^2), M_V is the molar weight of the vapor ($kg.mole^{-1}$), RH_1 is the relative humidity inside the climatic chamber, RH_2 is the relative humidity inside the cup, R is the constant of perfect gas, L is the sample thickness (m), P_{vs} is the pressure of saturated water vapor at a temperature of $T(K)$, and D_v is the water vapor diffusion coefficient in air.

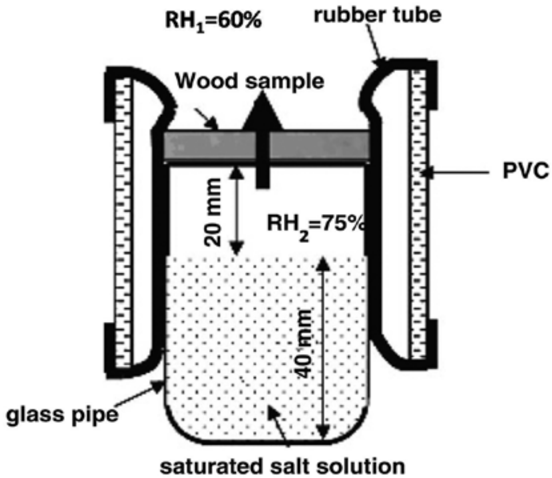

Fig. 2. Schematic of the experimental device (vapometer) used for measuring the diffusion coefficient (Tarmian et al. 2012)

Results

Fig. 3 shows the average changes in MC for both red heartwood and normal wood during the drying process. Results showed that drying rates for the wood containing red heartwood and normal wood were 0.53 and 0.67 %/h, respectively. The moisture flux in the red heartwood and in the domain of free water was noticeably less than that of normal wood (Fig. 4). Furthermore, moisture flux ratios were tapered off in lower than this domain (lower than FSP) in both types of woods. Table 1 shows the qualitative characteristics of dried samples, i.e. casehardening, shrinkage, cup, twist, and drying rate, between red heartwood and normal wood. In contrast to the normal wood, all red heartwood samples showed severe residual drying stress (casehardening). The amount of casehardening in heartwood and normal wood were 0.18 and 0.39 mm^{-1}, respectively. Two types of warp (cup and twist) occurred in the dried samples. The average amount of cup for heartwood and normal wood were also 1.32 and 1.84 mm, respectively; these values for the twist were 0.06 and 0.89 mm, respectively. Both radial and tangential shrinkage values were higher in case of the red heartwood, being in accordance with the research done by Marinescu et al. (2010). The mean values of air permeability for the specimens recorded for the normal wood and red heartwood are presented in Table 2. The red heartwood formation resulted in a major reduction in the longitudinal permeability of the wood. The specific gravity of normal wood and red heartwood were 0.560

(0.052) and 0.642 (0.041), respectively. Furthermore, the average initial MC of normal wood was significantly higher than red heartwood, 70 and 60% respectively.

Discussion

Drying rate

Similar to our drying rate results, Marinescu et al. (2010) also revealed that the drying rate in the normal wood is higher than red heartwood. The presence of red heartwood containing tyloses in beech wood reduced the drying rate of the wood when compared with that of normal wood. In the red heartwood and particularly in the free water domain, moisture is evaporated at a lower pace (Fig. 3).

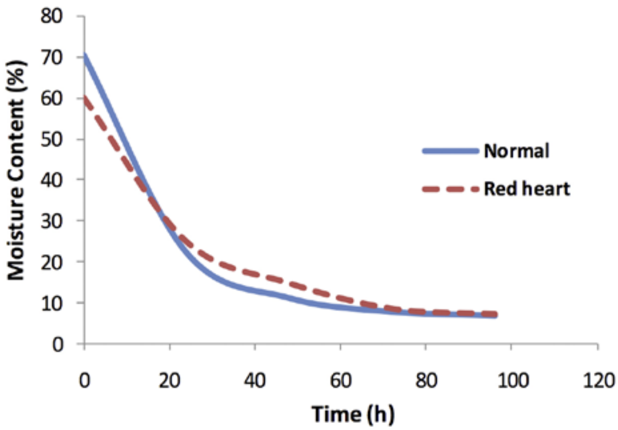

Fig. 3. The changes in MC of red heartwood and normal wood of beech with time during drying

The presence of tyloses in red heartwood vessels reduces the moisture flux (especially in the free water domain) due to obstruction of these elements, which are considered as free water conduction paths. The vessels' diameter is known to affect the drying rate. Findings of Gholamiyan and Tarmian (2010) indicate that there is no significant difference between the vessel diameter properties of red heartwood and normal wood. Thus, the presence of tyloses in the vessel structure plays a pivotal role in the reduction of drying rate and is in accordance with the results obtained by Keey et al. (2002). Furthermore, the average specific gravity of the red heartwood is a little high, which can to some extend affect the drying rate.

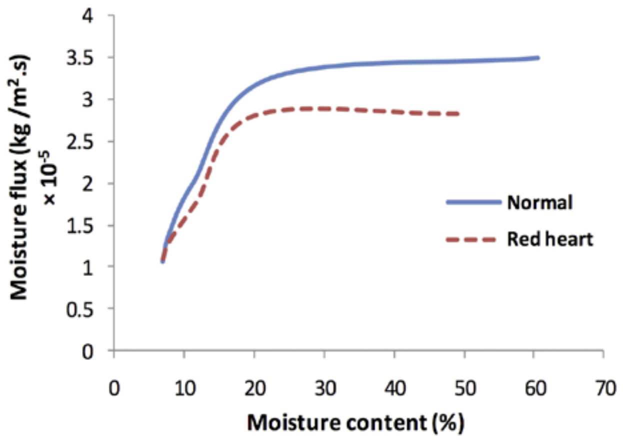

Fig. 4. The changes in moisture flux ratio of red heartwood and normal wood during drying

Drying defects

Cupping defect is caused by greater shrinkage parallel to the growth rings than shrinkage perpendicular to the growth rings. In general, a greater difference between tangential and radial shrinkage will result in a greater degree of cupping (Simpson 1991). Overall, the degree of warp was negligible in the normal wood; however, the significant amount of warp that occurred in the red heartwood was probably due to the severe drying stresses experienced by this kind of wood. In fact, the presence of tyloses within the vessel elements blocked free water conduction paths, reducing the water flux pace and eventually developing a MC gradient, and consequently increasing the residual stresses in the dried red heartwood samples.

In comparison with the shrinkage results in the present study, Bajraktari (2010) reported the overall shrinkage of normal beech wood to be 10.5%, while that of the red heartwood was 12.2%. It is hypothesized that some of the shrinkage that occurred in samples containing red heartwood was the result of the sample being close to the pith (that is, being in the juvenile wood of the stem).

Table 1. Qualitative Characteristics of Dried Samples

Sample type	Casehardening (mm^{-1})	Tangential shrinkage (%)	Radial shrinkage (%)	Cup (mm)	Twist (mm)	Drying rate (%/h)
Normal wood	0.18 (0.05)*	9.07 (0.78)	5.30 (0.56)	1.32 (0.11)	0.06 (0.03)	0.67 (0.04)
Red heartwood	0.39 (0.03)	9.91 (1.00)	6.07 (1.23)	1.84 (0.43)	0.89 (0.44)	0.53 (0.02)

*: standard deviation

Air permeability

Air permeability in wood significantly correlated with the pace of water flow in the domain of free water. Permeability in solid wood is considered a function of accessibility to the lumen and cell wall cavities (Taghiyari 2013a); therefore, even micro-cracks and fissures in the cell wall results in a significant increase in the specific air permeability (Taghiyari et al. 2012). Blockage of these vessel elements results in a drastic reduction in air permeability. The SEM observations indicate that in contrast to the normal wood vessels, a large number of these elements are blocked by tyloses in the red heartwood (Fig. 5). Since there is no significant difference in the diameter and proportion of vessels between red heartwood and normal wood (Gholamiyan and Tarmian 2010), the presence of tyloses inside the vessel lumens may be the main reason for the decreased air permeability along the longitudinal direction of the red heartwood. Keeping in mind that the specific gravity of these two types of wood is different, but some research shows that this factor has not pronounced effect on the permeability coefficient (Bao et al. 1999, Rayirath and Avramidis 2008). Tarmian and Perre (2009) conducted a research on the air permeability in longitudinal and radial directions of tension wood of *Fagus sylvatica*. They mentioned that the calculated average normal/tension wood longitudinal permeability ratio is 6:1, 3.5:1, and 2.5:1, respectively, for 15, 25, and 35 mm thick samples. Perre and Karimi (2002) performed a research to visualize, measure and understand the pathway of liquid and gas at both macroscopic and microscopic levels on specimens of beech (*Fagus sylvatica* and *Fagus orientalis*). The permeability to air and to water was measured. They mentioned that the permeability decreases significantly when the sample distance increases. Moreover, the value extrapolated for a zero-length sample is similar to the value predicted from the vessel diameters. Their observation stands for both sapwood and heartwood, in spite of the great permeability difference noticed between these zones. At the microscopic level, the percentage of active vessels decreases with the increase of sample total length and the increase of the distance from the injection point.

Table 2. Permeability and Diffusion Coefficients of Normal Wood and Red Heartwood along the Longitudinal Direction.

Sample type	Specific permeability coefficient (μm^2 10^{-14})	Diffusion coefficient ($D\times10^{-11}$ m^2 s^{-1})	Specific gravity
Normal wood	20.65 (9.61)*	8.16 (1.06)	0.560 (0.052)
Red heartwood	6.85 (1.41)	8.08 (1.04)	0.642 (0.041)

*: standard deviation

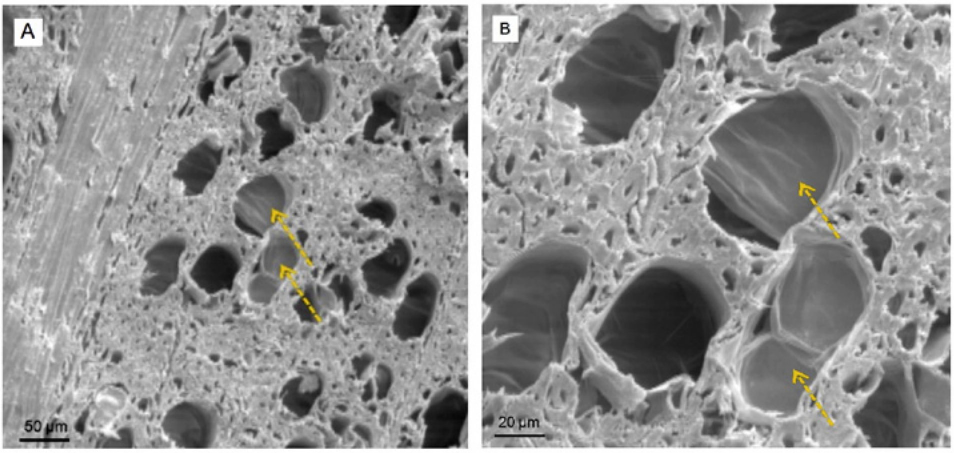

Fig. 5. SEM photographs of the cross sections of beech red heartwood (A and B; arrows show vessel elements filled with tyloses)

Diffusion coefficient

In general, moisture diffusion in wood is defined as a molecular mass flow under a concentration gradient. The driving force in bound water diffusion is the chemical potential (Walker 1993). Two types of diffusion take place in wood: gas diffusion which is, in fact, water vapor diffusion through air in cell cavities; and bound water diffusion which happens through the wood cell wall. Moisture diffusion is therefore not affected by the presence of tyloses in the vessels. In this regard, the lack of significant difference in diffusion coefficient confirmed that moisture contents within the range of bound water in both red heartwood and sound wood were equal.

Conclusions

The influence of red heartwood on beech wood drying characteristics and mass transfer coefficients was studied as to the scientific and commercial importance of this phenomenon and its profound effects on the different properties of dried woods. The main conclusions can be categorized as follows:

1. Tyloses did not have significant effect on the diffusion coefficient. It is therefore be concluded that moisture flux within the bound water range is rather a function of the cell wall structure. In contrast, tyloses reduced the specific air permeability coefficient and consequently reduced the drying rate above the FSP.
2. Due to the presence of tyloses and consequently the higher MC gradient, mild schedules are suggested for drying beech lumbers that contain red heartwood in order to prevent severe drying defects.
3. The higher occurrence of warp in the dried specimens that contained red heartwood may have been resulted from the greater amount of shrinkage in this kind of wood.

Acknowledgements

The authors would like to warmly thank Professor Michael Milota (Department of Wood Science and Engineering, Oregon State University) for his encouragement, advice, and technical information. Furthermore, we appreciate the kind cooperation of Mr. Mohsen Lotfalizadeh Mehrabadi in the design and building of the Gas Permeability Apparatus. We are grateful to Engines. Habib Nouri and Farzad Arbabi (SRTTU) for their sincere help in preparation of specimens.

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