Effects of Pretreatment with Saturated Wet Air and Steaming on the High-Frequency Vacuum Drying Characteristics of Wood

Haojie Chai,[a] Cong Xu,[a] Jie Li,[a] Fanxu Kong,[b] and Yingchun Cai [a,]*

The pretreatment of Mongolian pine (*Pinus sylvestris* var. *mongholica* Litv.) was conducted with saturated wet air (80 °C) and atmospheric saturated steam (100 °C) before high-frequency vacuum drying. Effects of the pretreatment on moisture content (MC), drying rate, drying crack, and drying shrinkage strain were investigated. The results showed that through pretreatment, the initial MC of the test material decreased by 2.6% to 6%, and the MC distribution was uniform. The maximum difference of the untreated wood MC distribution after drying was 2%, while that within the pretreated wood was less than 1%. The drying rate also increased, as the drying rates of the untreated and pretreated wood were 0.268%/h, 0.333%/h, and 0.398%/h, respectively. The drying shrinkage strain of the sample was reduced. The drying shrinkage strain of untreated wood was between 0.044 and 0.063, while the drying shrinkage strain of pretreatment wood was between 0.013 and 0.049. The crack of the test material was also reduced, and the drying quality was improved. The pretreatment reduced the high-frequency vacuum drying stress of wood and improved the drying speed and quality.

Keywords: Pretreatment; High-frequency vacuum; Moisture content; Drying quality

Contact information: a: Ministry of Education, Key Laboratory of Bio-Based Materials Science and Technology, College of Material Science and Engineering, Northeast Forestry University, Harbin, China 150040; b: Treessun Flooring Corporation, Huzhou, China 313009;
** Corresponding author: caiyingchunnefu@163.com*

INTRODUCTION

Boxed-heart square timber is prone to surface and radial cracks, and it readily forms defects during the drying process (Gao 2008). Pretreatment before drying is an effective means to accelerate the drying rate, reduce energy consumption, relieve the drying stress, and improve dimensional stability during the wood drying process. Saturated wet air and steaming treatment is a common physical pretreatment method. Its primary features are simple operation, low production cost, environmental protection, and no pollution, which effectively reduce the drying stress and drying defects (Fu *et al.* 2014).

Under the conditions of high relative humidity, the wood structure is softened by heating (not higher than 100 °C). As such, the internal energy of the water molecules inside the wood is increased, its activity is enhanced, the connection force between the structural components of the wood is reduced, and the flow of molecular chains inside the wood is increased. Simultaneously, it reduces the resistance of wood deformation, so that the moisture content (MC) gradient stress and drying shrinkage anisotropy stress are alleviated to reduce the risk of drying defects (Miao and Zhang 2009; Dashti *et al.* 2012; Ratnasingam *et al.* 2014). Harris *et al.* (1989) found that a 4 h steaming pretreatment improves the drying rate in the early drying stages. The increase in the drying rate was not because steaming changed the internal structure of wood, but because most of the heat energy was stored inside the wood. Alexiou *et al.* (1990) suggested that the steaming process can increase the drying rate because of the discharge of wood internal extracts, leading to the opening of the passage of water molecules into and out of the cell walls. Bekhta and Niemz (2003) studied the dimensional stability and mechanical properties of steaming spruce; the steaming treatment darkens wood, improves dimensional stability, and reduces mechanical strength. In a study of the dimensional stability of compressed wood by a pre-steaming treatment, Wong *et al.* (2008) stated that the steaming treatment softened the lignin and hemicellulose in the cell wall, increased the wood elasticity, and reduced the damage of the cell wall during compression. Thereby, dimensional stability of the compressed wood was increased.

In summary, the saturated wet air and steaming pretreatment has several advantages in reducing the drying stress, improving drying speed and quality, *etc.*, which are widely used in conventional drying. However, there has been limited research on wood high frequency drying characteristics after pretreatment. In this study, 120 mm Mongolian pine was pretreated before drying and treated with saturated wet air at 80 °C and atmospheric saturated steam at 100 °C for 8 h. The treated and untreated wood were subjected to high-frequency vacuum drying using the same drying schedule. The effects of the pretreatment on the initial MC, MC distribution, drying rate, drying crack, and drying shrinkage strain were discussed. Thereby, obtaining a suitable pretreatment process, improving the drying quality, reducing the drying time, and providing a powerful guarantee for realizing the rapid and high-quality drying of wood were achieved.

EXPERIMENTAL

Materials

Square-edged Mongolian pine timber with pith of was used as the research object. Several test materials with the same material and no cracking, decaying, and deformation were selected and processed into 120 × 120 × 500 mm sizes. The test materials were treated with saturated wet air at 80 ℃ and atmospheric saturated steam at 100 ℃ for 8 h. After the pretreatment was completed, the untreated and treated wood were subjected to high-frequency vacuum drying as per the same drying schedule. High frequency heating vacuum drying conditions were employed as follows: the ambient pressure was set to 8 kPa, and the control of the high-frequency output time was set to continuous oscillations lasting for 7 min and then stopping for 2 min. To reduce drying defects, a low temperature (55 ℃) was employed. When the wood MC reached 11%, the drying was finished, and the drying characteristics of the untreated and treated wood were compared.

Methods

MC detection

The test piece specification was 15 × 120 × 120 mm. As per the scribing and numbering shown in Fig. 1, the sample was decomposed into 25 samples along the scribe line. The initial MC and MC of each piece of wood were measured by the absolute drying weighing method. The MC distribution test piece was taken out before and after pretreatment to analyze the MC distribution. When the MC was dried to 29% and 11%, a 15 mm thick (fiber direction) layered MC test piece was taken at one end.

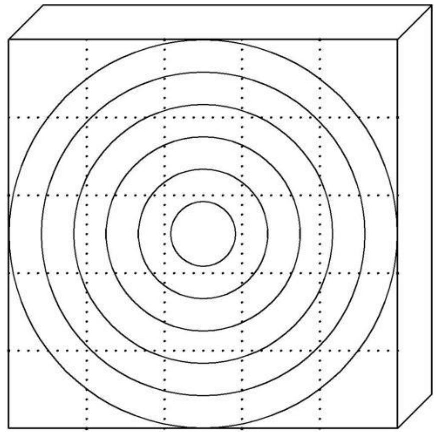

Fig. 1. The MC distribution test piece

Drying quality detection

Concerning the longitudinal cracking degree, the check length was checked and measured along the wood length and compared with the wood length. It was expressed as a percentage and calculated according to Eq. 1. The surface check length, width, and degree of internal checking were observed and measured. The cracks of widths less than 2 mm or lengths of less than 10 mm were neglected. The cracks were calculated by the whole crack when the cracks were less than 3 mm apart, and the internal crack was calculated regardless of the size. The longitudinal cracking degrees (%) was calculated as follows,

$$LS = l / L \times 100\% \qquad (1)$$

where l is the longitudinal cracking length (mm), and L is the wood length (mm).

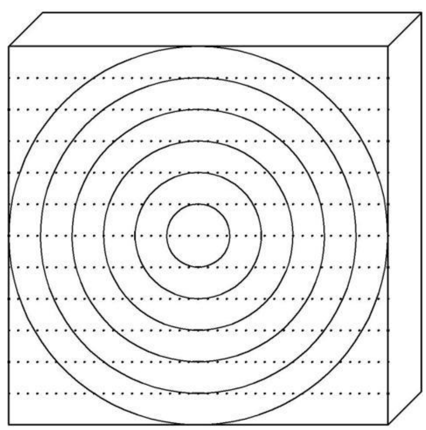

Fig. 2. The drying shrinkage strain test piece

Drying shrinkage strain detection

The manner of assessing drying shrinkage is shown in Fig. 2. A line was drawn on the strain test piece, and two reference points were determined for measuring the length of each specimen. Then photos were taken with a digital camera. At the same time, the sample was split along the line, and a picture was taken again. The picture was then input into the computer, and the distance was calculated between the two datum points of each specimen with the graph analysis software (ImageJ) (Fu *et al*. 2014). After measuring the above length, the dry shrinkage strains was calculated according to the Eq. 2,

$$\varepsilon_p = \frac{L_0 - L_1}{L_0} \qquad (2)$$

where L_0 is the distance between two measuring points of strain test piece before drying, L_1 is the distance between two measuring points of strain test piece when drying to the target moisture content, and L_2 is the real-time distance between two measuring points of strain test piece after splitting the strain test piece along the line.

RESULTS AND DISCUSSION

Effect of Pretreatment on the Initial MC

Changes in MC distribution before and after pretreatment

The MC distribution of the test materials before and after pretreatment is shown in Fig. 3. Before pretreatment, the MC distribution of the wood was high outside and low inside, the core layer MC was 30%, the surface layer MC was 133%, and the MC distribution was extremely uneven. After pretreatment, the core layer MC was 35 to 50%, the surface layer MC was 55 to 93%, and the uniformity of MC distribution was greatly improved, which was beneficial to reduce the drying stress caused by the MC gradient during the drying process.

Changes in MC before and after pretreatment

The changes in the weight of the wood before and after pretreatment are presented in Table 1. Under the two treatment methods, the initial weight of the test materials decreased to varying degrees. After the 80 ℃ saturated wet air treatment, the initial MC of the test material was decreased by 2.6%. After the 100 ℃ atmospheric saturated steam pretreatment, the initial MC of test material decreased by 6%. The results showed that the treatment temperature had a clear effect on the initial MC. A higher pretreatment temperature resulted in a greater decrease in the initial MC.

Table 1. Changes in the Wood Weight Before and After Pretreatment

Treatment Methods	Weight Before Treatment (g)	Weight After Treatment (g)	MC Before Treatment (%)	MC After Treatment (%)	MC Change (%)
80 °C saturated wet air	3297	3240	52%	49.4%	2.6%
100 °C atmospheric saturated steam	2700	2594	52%	46%	6%

Effect of the Pretreatment on MC Distribution

The MC distribution of the treated and untreated material when the sample was dried to target MC (a: 29%; b: 11%) is shown in Fig. 4. Compared with the untreated material, the MC distribution uniformity of the treated material was improved.

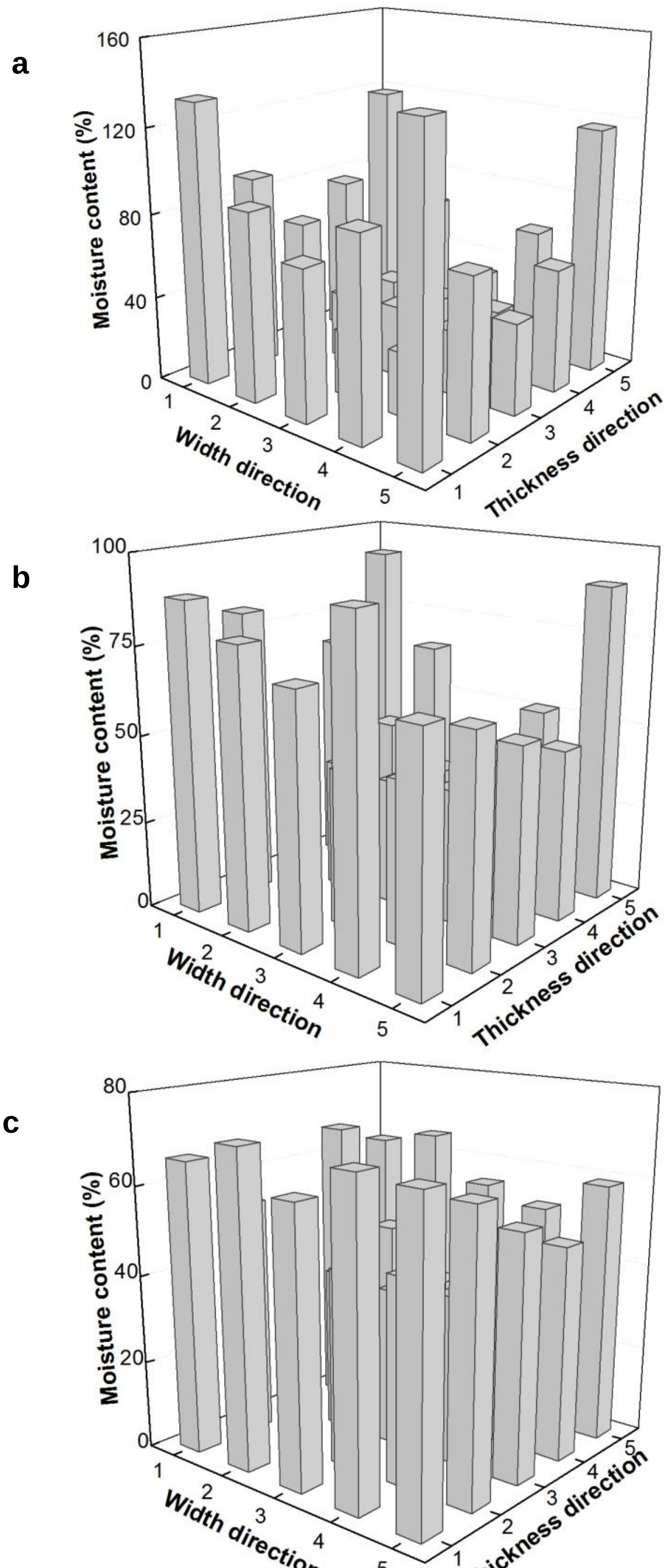

Fig. 3. MC distribution diagrams of the test material before drying (a: untreated wood; b: 80 °C saturated wet air treatment; c: 100 °C atmospheric saturated steam treatment)

When the average MC was 29%, the maximum MC difference was 12% for the untreated material, while those for the treated materials were 7% (80 ℃ saturated wet air) and 5% (100 ℃ atmospheric saturated steam), respectively. When dried to an average MC of 11%, the maximum difference in MC of the untreated material was reduced to 2%, while these values for both sets of pretreatment materials were smaller and the maximum difference was less than 1%. The above results demonstrate that a saturated wet air pretreatment and a steaming pretreatment can both reduce the MC gradient during the drying process of wood and make the MC distribution more uniform.

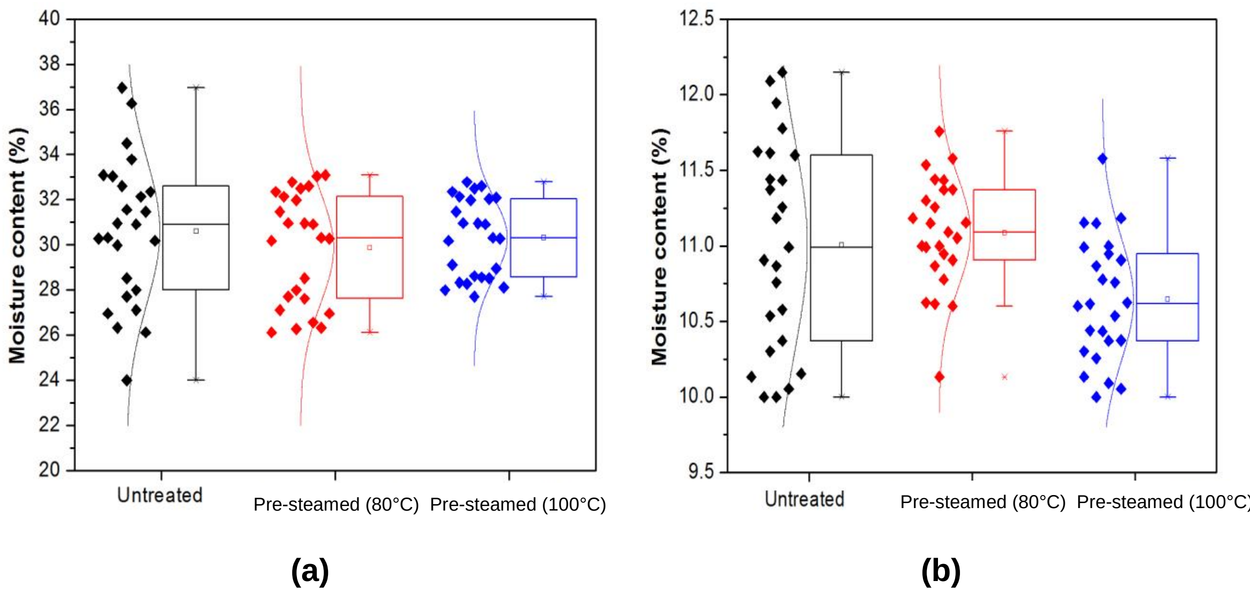

Fig. 4. Box plot of MC distribution of the untreated and treated wood when drying to different MC; (a) average MC of 29%; (b) average MC of 11%

Effect of the Pretreatment on the Drying Rate

The curve of the MC change during the drying process of the treated and untreated wood is presented in Fig. 5. When dried to the target MC of 11%, the required times for untreated material, 80 ℃ saturated wet air, and 100 ℃ atmospheric saturated steam treatment materials were 153 h, 123 h, and 103 h, respectively. The drying time was within the range of 0 to 72 h. Also, the drying rates of the two treatment materials were higher than that of the untreated material. A higher pretreatment temperature resulted in a faster drying rate. In the subsequent drying stages, the drying rates of each group were roughly the same.

The pretreatment changed the wood permeability and accelerated the outward diffusion of moisture inside the wood. Thereby, the pretreatment accelerated the drying rate. The average drying rate decreased in the following order: the 100 ℃ atmospheric saturated steam treated group, the 80 ℃ saturated wet air treated group, and the untreated group. Their corresponding average drying rates were 0.268%/h, 0.333%/h, and 0.398%/h, respectively. Therefore, the saturated wet air and steaming pretreatment before drying had a certain positive effect on increasing the drying rate and shortening the drying cycle.

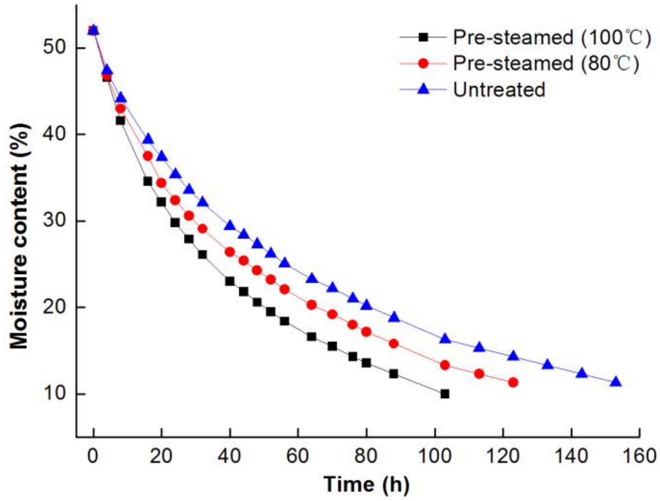

Fig. 5. MC changing curve during the drying process of the treated and untreated wood

Effect of the Pretreatment on Drying Quality

As shown in Table 2, drying cracks of the saturated wet air treated materials, steaming treated materials, and the untreated material were calculated. When cracks occurred, the MC of the untreated and pretreated wood were 35%, 31%, and 32%, respectively. The saturated wet air and steaming treatment delayed the generation of cracks to a certain extent. The pretreatment made the moisture inside the wood diffuse quickly. Also, the MC distribution was more uniform, and it was not easy to produce drying cracks. As per the analysis of several drying quality indicators, such as the crack number, maximum crack length and width, longitudinal cracking degree, and shrinkage rate, the pretreated materials were clearly superior to the untreated ones. The 80 ℃ saturated wet air treated material was slightly better than the 100 ℃ saturated steaming treated material.

The results showed that the saturated wet air and steaming pretreatment could effectively reduce the occurrence of drying defects in the wood drying process. This was because the MC gradients tended to cause interactions between the layers of the wood to generate inconsistencies in the drying shrinkage. The pretreatment reduced the MC gradient inside the wood, and the interaction between the core and surface layer was weakened. This reduced the generation of tensile stress on the wood surface (Song and Fu 2018). The drying quality of the 80 ℃ saturated wet air treatment wood was the best because the drying speed was relatively slow and the shrinkage of wood surface layer was weakened.

Table 2. Crack Statistics of the Treated and Untreated Wood

Treatment Methods	Moisture Content at the Time of Crack (%)	Number of Cracks	Maximum Crack Length (mm)	Maximum Crack Width (mm)	Longitudinal Cracking Degree (%)
Untreated	35	10	26.9	3.9	42.8
80 °C saturated wet air	32	5	15.5	1.9	22.8
100 °C atmospheric saturated steam	31	7	20.5	2.3	24.6

Effect of the Pretreatment on the Drying Shrinkage Strain

As shown in Fig. 6, the drying shrinkage strain of different parts of wood was different. This was because the tangential and radial shrinkage coefficients were different, and the radial drying shrinkage suppressed the tangential direction. Moreover, the MC of each layer in thickness tended to be uneven, and the inner and outer layer of wood were unevenly shrunk (Chen and Liu 2007). In addition, the high MC portion had an inhibitory effect on the low MC portion (Fu *et al.* 2016). At the same time, the material distribution of the boxed-heart timber was not uniform, the materiality of different positions was different, and the drying shrinkage properties were clearly different.

The actual shrinkage strain after wood drying was clearly improved after pretreatment. The shrinkage strain of the untreated material was between 0.044 and 0.063. The shrinkage strain of the pretreated material was between 0.013 and 0.049. This was because the pretreatment softened the wood structure, the inner energy of water molecule inside wood increased, and the activity was enhanced. Then, the connection force between the wood structural components was reduced, the fluidity of the internal molecular chains inside the wood was increased, and the resistance of wood deformation was reduced. Thereby, the MC gradient stress and drying shrinkage anisotropy stress were alleviated, and the drying shrinkage strain was reduced.

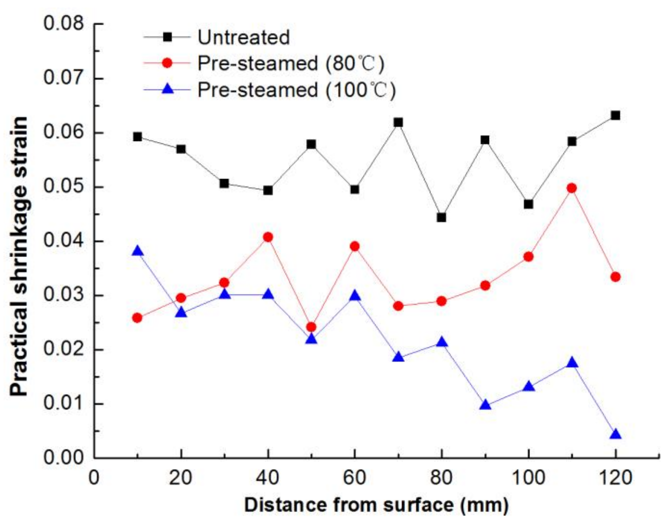

Fig. 6. The drying shrinkage strain distribution of untreated and pre-steamed wood

CONCLUSIONS

1. Steaming pretreatment reduced the MC distribution difference of wood between the surface and core layer. It also alleviated the effect of MC gradient and drying shrinkage anisotropy on the drying defects.
2. The steaming pretreatment shortened the drying cycle and the steaming pretreatment before the high frequency vacuum drying made the final MC distribution more uniform, reduced the occurrence of drying shrinkage strain, reduced the surface cracks, and enhanced the drying quality.

ACKNOWLEDGMENTS

This work was financially supported by the Fundamental Research Funds for the Central Universities of China (Grant No. 2572018AB07) and the National Natural Science Foundation of China (Grant No. 31670562).

REFERENCES CITED

Alexiou, P. N., Wilkins, A. P., and Hartley, J. (1990). "Effect of pre-steaming on drying rate, wood anatomy and shrinkage of regrowth *Eucalyptus pilularis* Sm.," *Wood Science and Technology* 24(1), 103-110. DOI: 10.1007/BF00225310

Bekhta, P., and Niemz, P. (2003). "Effect of high temperature on the change in color, dimensional stability and mechanical properties of spruce wood," *Holzforschung* 57, 539-546. DOI: 10.1515/HF.2003.080

Chen, W. L., and Liu, Y. X. (2007). *High-Temperature and High-Pressure Steam Drying Process Principle for Wood*, Science Press, Beijing, China.

Dashti, H., Tarmian, A., Faezipour, M., Hedjazi, S., and Shahverdi, M. (2012). Effect of pre-steaming on mass transfer properties of fir wood (*Abies alba* L.); A gymnosperm species with torus margo pit membrane," *BioResources* 7(2), 1907-1918. DOI: 10.15376/biores.7.2.1907-1918

Fu, Z., Zhao, J., and Cai, Y. (2014). "Investigation of tangential strain caused by shrinkage anisotropy using image analytical method," *Engineering Sciences* 16(4), 25-29. DOI: 10.3969/j.issn.1009-1742.2014.04.005

Fu, Z., Zhao, J., Huan, S., Sun, X., and Cai, Y. (2014). "The variation of tangential rheological properties caused by shrinkage anisotropy and moisture content gradient in white birch disks," *Holzforschung* 69(5), 573-579. DOI: 10.1515/hf-2014-0089

Fu, Z., Zhao, J., Yang, Y., and Cai, Y. (2016). "Variation of drying strains between tangential and radial directions in Asian white birch," *Forests* 7(3):59, 1-8. DOI: 10.3390/f7030059

Gao, J. M. (2008). *Wood Drying*, Science Press, Beijing, China.

Harris, R. A., Schroeder, J. G., and Addis, S. C. (1989). "Steaming of red oak prior to kiln-drying: Effects on moisture movement," *Forest Products Journal* 39(11/12), 70-72. DOI: 10.1515/hfsg.1989.43.6.411

Miao, P., and Zhang, W. (2009). "Effect of steaming treatment on transverse permeability of wood," *Journal of Nanjing Forestry University* 33(2), 99-102. DOI: 10.3969/j.issn.1000-2006.2009.02.024

Ratnasingam, J., Grohmann, R., and Scholz, F. (2014). "Effects of pre-steaming on the drying quality of Rubberwood," *European Journal of Wood and Wood Products* 72(1), 135-137. DOI: 10.1007/s00107-013-0747-7

Song, T., and Fu, Z. (2018). "Effect of radio-frequency convection drying on wood temperature gradients and drying quality," *Journal of Northeast Forestry University* 46(8), 74-79. DOI: 10.13759/j.cnki.dlxb.2018.08.014

Wong, T. S., Paridah, M. T., Zaidon, A., Edi, S. B., and Azmi, I. (2008). "Effects of presteaming and compressing pressure on the dimensional stability of densified wood," in: *Proceedings of National Conference on Forest Product*, Kuala Lumpur, pp. 183-189.

Article submitted: June 19, 2019; Peer review completed: September 19, 2019; Revised version received: October 6, 2019; Accepted: October 16, 2019; Published: October 21, 2019.
DOI: 10.15376/biores.14.4.9601-9610