Drying Stress Relaxation of Wood Subjected to Microwave Radiation

Qin He and Ximing Wang*

An effective and rapid drying stress relieving technique was developed using microwave conditioning. The process was analyzed by measuring the stress factor and moisture content gradient through the thickness of the board. The experiments showed that the drying quality of *E. urophylla x E. tereticornis* was improved after microwave conditioning during the wood drying process. The drying stress relaxation increased with the duration of the microwave radiation. Stress and moisture content gradient through the thickness of the board were compared and are discussed in this report.

Keywords: Wood drying; Microwave conditioning; Moisture content gradient; Stress relaxation

*Contact information: College of Material Science and Art Design, Inner Mongolia Agriculture University, China; *Corresponding author: W_ximing@263.net*

INTRODUCTION

The drying rate of wood accelerates with increases in the moisture content gradient and temperature of the wood. However, the generation of defects related to inner check, surface check, and collapse also increases due to high drying stress (Kollmann 1956). Scheduled steam conditioning during the drying process can be used to moderate the drying rate, thus achieving good drying quality due to reduced drying stress and a decreased frequency of checks (Zhu 1998). Steam conditioning treatment at different drying stages has several different functions. In the beginning, stream conditioning helps increase temperature and evenly heats the wood, thereby helping operators to achieve targets of drying rate and product quality (Alexiou *et al.* 1990). During the middle stage of drying, when the moisture content of wood is reduced to below the fiber saturation point, wood stress begins to change. Steam conditioning treatment can cause adsorption on wood's surface, decreasing the moisture content gradient of wood, relieving inner drying stress, and finally preventing wood from cracking (Chen and Workman 1980). At later stages, in order to eliminate residual stresses and equalize the moisture content gradient between its boards, wood should be steam conditioned. Conventional steam conditioning methods can be time- and energy-consuming (Zhu 1998). If treatments are improper, then wood can be discolored and many defects can be generated (Ellwood and Erickson 1962).

Theoretically, there are three methods to relieve the drying stress of wood. The first method is to increase the surface moisture content (MC) of the wood; the second is to decrease the internal MC of the wood; and the third is to increase the MC of external wood and to decrease MC of internal wood at the same time. The steam conditioning treatment falls into the first category. Pre-steaming increase the surface MC, so it can reduce the moisture gradients from centre to surface (Alexiou *et al.* 1990; Keey *et al.* 2012). The second method is not practical because surface MC changes as the internal

MC of wood is reduced. The third method is more feasible. This method quickly decreases the moisture content gradient of wood by increasing the external MC and decreasing the internal MC of wood simultaneously. This is possible because during microwave heating, the temperature in a higher MC zone is correspondingly higher than that of a lower MC zone, which drives internal water to the wood surface. The effect of microwave treatment is to modify moisture diffusivity (Yang 2005).

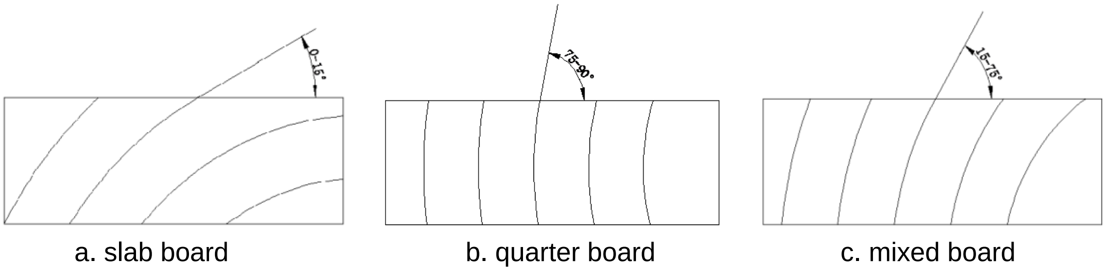
Microwave conditioning is a good example of the third method. In microwave heating, energy is directly transferred into wood, absorbed by the material, and transformed into heat. By contrast, in conventional drying methods, heat penetrates the material through its surface and diffuses internally. Microwave technology has already been widely applied throughout wood industry for over half century. Examples include the technique of wood bending after microwave heating, lumber drying *via* microwave heating, and pressing systems that use microwave heating (Antti 1992; Antti and Perre 1999; Montoro and Manrique 1999; Wang and Xue 2002; Tu 2007; Prasad and Pandey 2012). And some research has focused on wood structure and water transfer in wood under the microwave heating (Daian 2011; Gasparik 2013; Grinchik *et al.* 2015).

During the microwave heating process, the temperature and moisture fields change simultaneously. The amount of microwave energy absorbed by a material increases with its moisture content, and the temperature in a higher MC zone is correspondingly higher than that of a lower MC zone, which drives internal water the wood surface. Thus the moisture content gradient within lumber is reduced. Based on this principle, this research concentrated on microwave treatments to evaluate lumber stress relaxation at different drying phases.

EXPERIMENTAL

Materials

Twelve 8-year-old *E. urophylla* x *E. tereticornis* trees regrown from the East-Gate Forest Station in Nanning, Guangxi province, China were selected for this study. The trees had a breast-height diameter of 28.8 cm and a height of 27.4 m on average. From each tree eight boards of 800 mm were sawn in the slab, quarter, or mixed boards into 100mm (width) x 25 mm (thickness) sizes. All boards were sorted according to their end-grain angles on cross section, as shown in Fig. 1: Slab board: $0^\circ \leqslant \beta \leqslant 15^\circ$; quarter board: $90^\circ \geqslant \beta \geqslant 75^\circ$; and mixed boards: $15^\circ < \beta < 75^\circ$. From both ends of each board, 100-mm lengths were cut and three parts (specimens) of equal lengths were kiln-dried.



a. slab board b. quarter board c. mixed board

Fig. 1. Illustration of a cross section of a sample

Methods

The boards were kiln-dried following the schedule shown in Table 1. During the drying process, boards were treated with microwave heat during four different drying stages: over 40% MC, 30 to 40% MC, 20 to 30% MC, and 10 to 20% MC. The treatment times for each drying stage were 120, 150, and 180 s, respectively. The power of the microwave processor was set at 1500 W with a frequency of 2450 MHz. After microwave treatments, the MC, MC gradient, and stress of every specimen were determined. Diagrammatic representation of test samples are show in Fig. 2. The moisture content of all oven-drying boards was estimated by an MC meter during drying process and the final absolute MC were measured by the oven-drying method using the specimen cut from the boards. Drying stress of the board was determined by the fork tooth method. A 10 mm width specimen was cut from the treated board, then the specimen was oven dried at 103 °C for 2 h and cooled, following determination the S and L, the specimen cut into the fork tooth shape (Fig. 3). The S_1 value was determined after the fork tooth was fixed. Drying stress (δ) was calculated according to the formula (GB),

$$\delta(\%) = (S_1 - S)/2L \times 100\% \qquad (1)$$

In this formula, S and S_1 are the fork tooth width before and after being fixed (mm), and the L is the length of the fork tooth (mm).

Table 1. Drying Schedule

Moisture content (%)	Temp. of dry bulb (°C)	Temp. difference between wet and dry bulbs (°C)	Relative humidity (%)
Above 45	65	3	86
40 to 45	65	4	82
35 to 40	70	6	75
30 to 35	70	8	71
25 to 30	75	11	60
20 to 25	80	16	48
15 to 20	85	22	33
Below 15	90	30	28

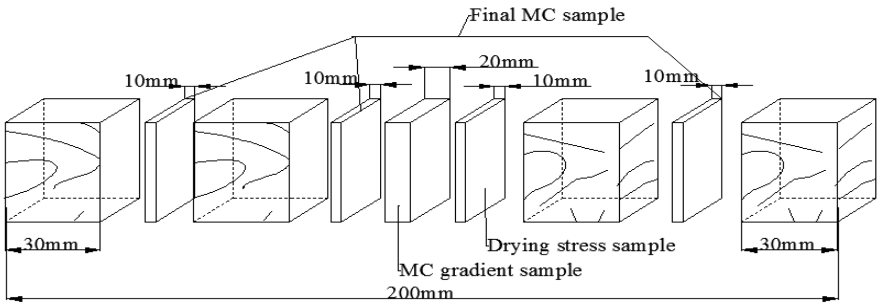


Fig. 2. Representation of test samples

The MC gradient was determined by the following method (Fig. 4). The MC of No. 2 slice was the internal layer MC, the average MC of No.1 and No.3 slices were external layer MC. Deviation MC (W_h) was calculated according to the formula,

$$W_h(\%)=W_i- W_e \qquad (2)$$

In this formula W_i is internal layer MC, and W_e is the external layer MC.

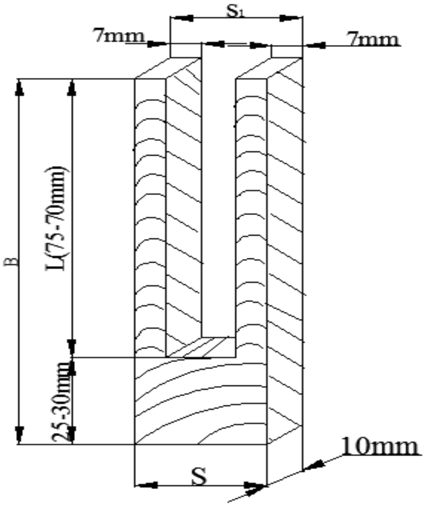


Fig. 3. Illustration of sample used for stress determination

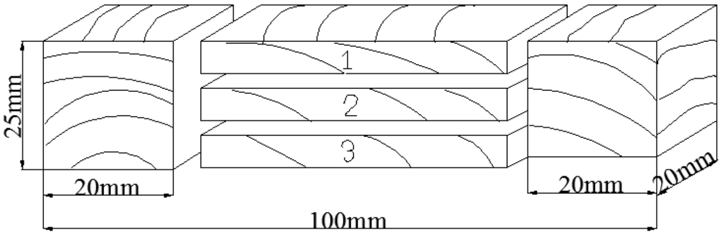


Fig. 4. Illustration of sample used for MC gradient

RESULTS AND DISCUSSION

Microwaves are electromagnetic waves with a wavelength of 1 mm to 1 m and frequencies of 3 to 40 MHz. In a microwave’s electromagnetic field, water molecules of wood are reoriented, causing movement and friction and thus producing heat within the wood. The internal temperature of wood subsequently increases. Water, a strong polarity medium, absorbs more microwave energy than wood itself. Therefore, areas of greater moisture content have higher temperatures. In this way, the MC within wood is forced toward equilibrium automatically when subjected to microwave heating.

Effect of Treating Time on Stress

The experimental results of MC and stress relaxation experiments are summarized in Table 2.

Table 2. MC and Stress Values under Different Microwave Treatments

Sample	Untreated sample					Treated (120 s)					Treated (150 s)					Treated (180 s)				
	MC /%	Ext. Layer MC /%	Int. Layer MC /%	Devia -tion MC /%	stress /%	MC /%	Ext. Layer MC /%	Int. Layer MC /%	Devia -tion MC /%	stress /%	MC /%	Ext. Layer MC /%	Int. Layer MC /%	Devia -tion MC /%	stress /%	MC /%	Ext. Layer MC /%	Int. Layer MC /%	Devia -tion MC /%	stress /%
Mixed B	49.9	33.8	64.3	30.5	18.2	41.3	32.2	58.4	20.2	12.3	40.1	30.9	46.8	15.9	6.4	37.6	29.2	41.6	12.4	4.2
	34.8	19.8	47.8	28.0	19.0	21.1	17.3	38.8	21.5	14.1	25.1	16.7	31.2	14.5	7.1	22.6	16.4	25.9	9.5	3.4
	22.9	10.9	33.9	23.0	16.2	21.5	9.3	25.6	16.3	12.2	15.1	8.9	19.8	11.1	6.9	13.1	8.7	16.0	7.3	3.2
	16.1	8.3	22.2	13.9	13.4	12.6	6.5	16.8	10.3	7.8	7.8	5.6	9.0	3.4	3.8	4.8	3.2	4.8	1.6	2.1
Slab B	46.2	31.6	58.1	26.5	18.1	42.6	30.1	51.4	21.3	13.9	37.2	29.5	42.8	13.3	7.3	34.6	29.2	38.5	9.7	3.3
	31.8	18.6	41.8	23.2	18.3	24.9	16.8	35.8	19.0	15.2	23.6	16.8	29.1	12.7	6.8	20.1	16.2	22.9	6.7	2.9
	23.3	9.8	32.9	23.1	19.1	16.8	9.2	22.3	13.1	12.5	14.5	8.5	18.8	10.3	7.1	12.2	8.5	15.5	7.0	3.0
	16.2	8.0	22.1	14.1	16.2	13.7	7.5	17.7	10.2	12.3	8.9	7.5	9.0	1.5	1.0	8.6	8.2	8.8	0.6	0.8
Quarter B	49.8	33.1	63.1	30.0	17.3	46.2	33.2	56.4	22.8	13.1	39.1	31.6	44.8	13.2	7.9	36.6	29.8	40.6	10.8	3.8
	34.6	19.2	47.3	28.1	19.1	35.6	18.3	37.9	19.6	16.8	25.1	18.2	31.4	13.2	7.0	21.1	15.5	25.6	10.1	4.2
	22.9	10.6	33.5	23.1	19.0	19.5	9.8	25.7	15.9	16.3	14.9	9.3	18.8	9.5	6.7	12.4	8.9	15.1	6.2	3.0
	16.9	8.5	22.9	14.4	15.4	13.4	8.5	16.9	8.4	10.6	8.9	7.6	9.6	2.0	4.1	7.8	7.2	8.1	0.9	0.8

Figures 3 to 6 illustrate the MC gradient of mixed boards in different drying stages. It appears that the drying stress was relieved by microwave conditioning in a short time as the stress index decreased with increasing microwave treatment duration. For example, in the mixed board treated at the 49.9% MC level, the stress index was reduced from 18.2% to 12.3% (after 120 s of treatment), 6.4% (after 150 s of treatment), and finally, 4.2% (after 180 s of treatment). Its MC gradient decreased from 30.5% to 20.2% (after 120 s of treatment), 15.9% (after 150 s of treatment), and 12.4% (after 180 s of treatment). The mixed boards, slabs, and quarters had the same tendencies.

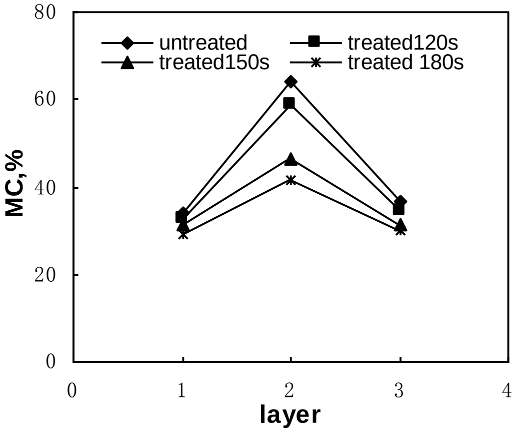


Fig. 5. The change of MC in different layers (AMC=49.9%)

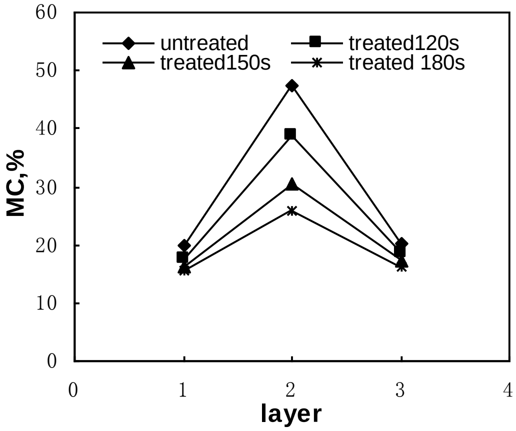


Fig. 6. The change of MC in different layers (AMC=34.8%)

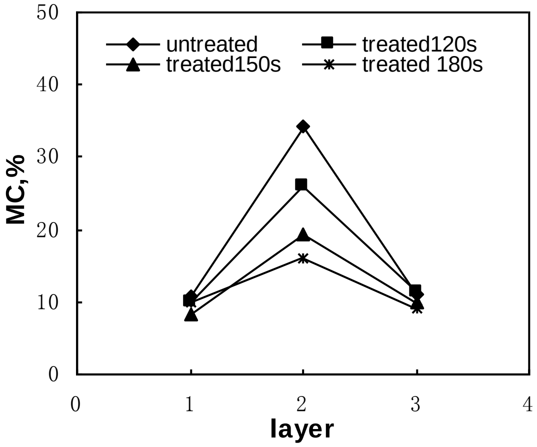


Fig. 7. The change of MC in different layers (AMC=22.9%)

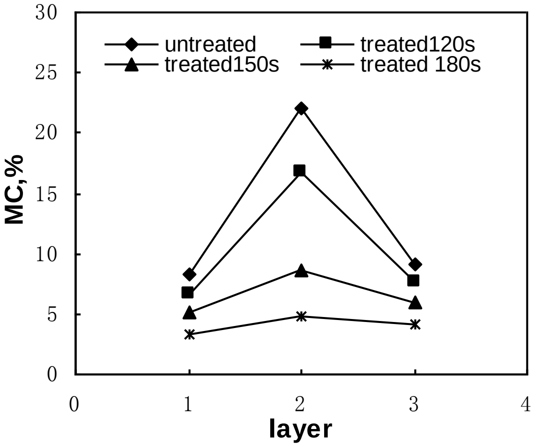


Fig. 8. The change of MC in different layers (AMC=16.1%)

Effect of Grain on Treatments

A calculation was conducted to identify the influence of wood grain on microwave conditioning treatments of slabs, quarters, and mixed boards in the 180 s microwave treatment condition. Deviation MC percentage [(deviation MC of 180 s microwave – deviation MC of untreated)/ deviation MC of untreated] and stress index percentage (stress index of 180s microwave sample–stress index of untreated) / stress index of untreated) were measured and are summarized in Table 3. Generally speaking, boards with lower MC levels received more effective relaxation than those with higher MC level. Wood grain also affected treatment efficiency especially the slab board.

Table 3. Drying Stress Results

Sample	MC (%)	Deviation MC percentage (%)	Stress index percentage (%)
Mixed B	49.9	0.59	0.77
	34.8	0.66	0.82
	22.9	0.68	0.80
	16.1	0.88	0.84
Slab B	46.2	0.63	0.82
	31.8	0.71	0.84
	23.3	0.70	0.84
	16.2	0.96	0.95
Quarter B	49.8	0.64	0.78
	34.6	0.64	0.78
	22.9	0.73	0.84
	16.9	0.94	0.95

Comparisons with Steam Conditioning

It has previously been reported that drying stress can be relieved by steam conditioning after 5-h treatments on 25 mm-thick *E. urophylla* x boards (Jiang and Wang 2003). Wang (1990) measured the drying stress index changes of elm 25 mm-thick boards dried at high temperatures for three hours to 32% MC, showing that the drying stress index was reduced from 15.8% to 6.9%. Comparatively, in slab boards treated with microwave conditioning at 46.2% MC, stress index was reduced from 18.1% to 13.9% (after 120 s of treatment), 7.3% (after 150 s of treatment), and finally, 3.3% (after 180 s of treatment). Its MC gradient was reduced from 26.5% to 21.3% (after 120 s of treatment), 13.3% (after 150 s of treatment), and finally, 9.7% (after 180 s of treatment). The data demonstrate that microwave conditioning can quickly and effectively decrease the stress generated during drying compared to conventional steaming conditions under similar processing parameters.

Equilibrium Action of MW Treatment on Water of Wood and Drying Stress

During conventional drying, heat is transferred from the surface of wood to its interior and it is difficult to form a temperature gradient of high inner and low outer temperatures. Typically, the surface of the wood begins to dry before it has been heated fully. Even during free water evaporation, the rate of evaporation from the surface is faster than the water transfer speed inside the wood. At the stage of bound water evaporation, this speed difference becomes larger and larger with decreasing moisture content. This moisture content gradient (higher inner and lower outer temperatures) is the main driver of water transfer inside wood. When the moisture content of the surface layer is lowered to the fiber saturation point, the surface layer begins to shrink. However, at this moment the interior moisture content is still above the fiber saturation point, and it therefore is not likely to shrink; inner shrinkage and outer shrinkage are not consistent, and thus, the surface layer is restricted by the interior layer and forms drying stresses inside the wood. As the moisture content gradient increases, so does the drying stress. Another reason is that discrepancies between the radial and tangential shrinkage of wood also raise stress and strain. When the inner stress of wood exceeds a certain limit, it can be destroyed. Because the maximum tensile strength perpendicular to the grain of the wood is far smaller than the maximum compression strength in this direction, it is possible that cracks are formed on the surface of the wood during the incipient drying phase, and interior cracks are formed during the later stage of drying. Therefore, when the moisture content gradient and drying stress inside the wood reach a certain degree (drying stress was smaller than the maximum tensile strength perpendicular to the grain of the wood), some measures to decrease the moisture content gradient and drying stress must be carried out to prevent cracking. In the case of wood treated by microwave, heat is uniform in every part of the wood. The high-frequency electric field causes rapid evaporation of water in the cells, forming pressurized steam. This steam diffuses out and impacts the cell wall, breaking through weak points such as the pit membrane. At the same time, the inner vapor tension drives interior water to the surface layer and causes the moisture content gradient between the inner and outer layers to decrease, thereby reducing cracking and improving drying quality. However, long microwave heat treatment would result in interior cracking, so this option should be explored and researched further before use.

Reasons for Reduced Drying Stress during MW Treatment

Effect of moisture content on heat produced in microwave field

High-frequency microwaves are an energy form but are not themselves heat. Their energy is dielectric. Mechanisms of energy translation include ion conduction, dipole turning, interface polarization, magnetism stagnancy, piezoelectricity, electrostriction, nucleus-magnetism sympathetic vibration, iron-magnetism sympathetic vibration, and so on. Thus, ion conduction and dipole turning are two main mechanisms of dielectric heat translation.

(1) Ion conduction

Charged particles are accelerated when under an electric field and are moved along the direction opposite their polarity. This directional excursion manifests itself as conducting electric current macroscopically. These ions collide with other particles surrounding them as they move, meanwhile passing kinetic energy to these collided particles and making them move intensively. If the material is located in a high frequency electric field, particles in the materiel would be subject to repeated changes in direction. The resulting intensive collisions then produce heat, converting electric energy to heat energy. The power per unit volume expended in this way is given by (Pan 1998):

$$P_{\mathrm{v}}=\sigma\cdot|\mathrm{E}|^2 \tag{3}$$

In this formula, P_{v} is power of unit volume (W/m^3), E is electrical field strength vector (V/m), and σ is conductance (S/m). Conductance of wood is dependent on density, temperature, and moisture content of wood. When the moisture content of wood is 0 to 30%, the specific conductance of wood could rise one hundred thousand times with the increase of moisture content; when moisture content of wood is beyond 30%, specific conductance did not exceed four times with the increase of moisture content (Chen 1985). And conductivity of wood rose with increase of moisture content. Therefore, when wood is subjected to a high frequency electric field, heat produced in high-moisture content area is far greater than that produced in low-moisture content areas. Specific heat, temperature conduction, and heat conduction modulus of wood rose with the increase of moisture content.

(2) Dipole turning

Dielectric contributions are of two kinds, non-polar molecule dielectric and polar molecule dielectric contributions. When there is no external electric field, a non-polar molecule provides positive-negative superposition. By contrast, in the case of polar molecules there is no superposition. However, because of the rule of less movement of interior molecules, this kind of dielectric is still a non-electriferous state.

There were many nonpolar molecules and polar molecules in wood. Under the action of an external electric field, positive and negative charges of dielectric comprising nonpolar molecules give rise to relative displacement and form a dipole along the action direction of an external electric field. So there emerged positive and negative bound charges on the dielectric surface, meaning that there was polarization of the dielectric. Under the action of external electric field, each of the polar hydroxyl groups in wood all get put into motion, making the dipole turn and chose the direction of the external electric field, resulting in a turning of polarization (Yin 2003). With an increase of external electric field strength, displacement polarization of nonpolar molecule and turning polarization of polar molecule is strengthened. If these molecules are placed in a changing external electric field, nonpolar molecules and polar molecule are all polarized repeatedly, with the change of electric field, resulting in continual rearrangement of dipoles. Thus, because of intrinsic movement of molecules due to their content of heat, and reciprocity between adjacent molecules, regular movement of molecules with turning of external electric field was interfered and counteracted. This is the origin of a frictional effect, leading part of the energy to be translated into thermal energy, resulting in the heating of the wood. The power expended is given by (Jones 1992):

$$P_{\mathrm{v}}=2\pi f\varepsilon_0\varepsilon''_{\mathrm{r}}\cdot|E|^2 \qquad (4)$$

In this formula, ε_0 is permittivity in vacuum, $\varepsilon_0=8.85\times10^{-12}$ F/m; $\varepsilon''_{\mathrm{r}}$ is relative loss factor, $\varepsilon''_{\mathrm{r}}=\varepsilon''/\varepsilon_0$, and ε'' is loss factor (F/m). Permittivity of wood varied with tree species, moisture content, frequency of electric field, and direction of electric field to wood fiber. The permittivity of wood also rose with increase of moisture content.

Theoretical calculations showed that heat produced in high-moisture content areas was higher than that produced in low-moisture content areas. Generally, the moisture content of wood interior was high, so heat produced inside the wood was greater. A gradient of temperature gradient was established from higher values in the interior toward lower values on the outer portions of the wood. Its direction was the same as the moisture content gradient. Interior water of wood was boiled away early and transferred fast to the wood surface under the combined action of the temperature gradient and the moisture content gradient; thus the moisture content of wood surface was raised, resulting in a decrease in the contrast of moisture content in different sections of the wood. These effects were consistent with an objective to achieve a better equilibration of moisture in the wood in the course of hot-humid treatment.

Transfer force variation of interior water of wood under MW action

The drying process of wood in a gas medium includes mainly two kinds of phenomena, namely water evaporation of wood surface and water transfer from the center part of the wood. The speed of water evaporation of wood surface is faster by 10 to 30 times than that of water transfer of center part of the wood. Even though at the stage of free water evaporation, it was difficult to ensure that speed of water evaporation of wood surface was accordant to that of water transfer of wood interior; at the stage of bound water drying, the speed difference of water transfer of these two processes was bigger. Therefore, the moisture content difference between the inner high value and outer low value was formed soon after drying, and drying stress formed subsequently. At the stage of free water evaporation, the transfer force of interior water of wood was hydrostatic pressure; at the stage of bound water evaporation, the transfer force was derived from temperature gradient and moisture content gradient. The quantity of water transfer was (Jones 1992):

$$I = -\alpha r_0(\partial w/\partial x - \delta \cdot \partial t/\partial x) \tag{5}$$

In this formula, I is water runoff, α is water conductive modulus, r_0 is wood density, δ is heat-humidity transfer modulus, and $\partial t/\partial x$ is the temperature gradient.

In the course of wood drying, in order to improve interior water transfer speed of wood, the temperature gradient and moisture content gradient inside wood should be increased, such that the direction of the temperature gradient is in accord with the direction of moisture content gradient. But generally, the temperature gradient was zero or the direction was opposite to that of the moisture content gradient. Therefore, it couldn’t play a leading role relative to the transfer of interior water from the wood; rather, the moisture content gradient was responsible for the transfer. When putting wood in a drying process involving a MW electrical field, heat produced in high-moisture content area is higher than that produced in low-moisture content areas, resulting in a temperature gradient of inner high and outer low, at this moment, direction of temperature gradient accorded to direction of moisture content gradient. Water of wood is then transferred fast to wood surface under the combined action of these two transfer motivations. The moisture content gradient was reduced, the moisture content deviation was decreased, and the moisture content stress was relieved also.

CONCLUSIONS

Microwave conditioning relieved the MC gradient and drying stress, and this was achieved much more quickly and effectively than conventional steam conditioning; microwave conditioning also prevented boards from cracking, shortened their drying time, and guaranteed better drying quality.

The drying stress was relieved by microwave conditioning in a short time, as the stress index decreased with increasing microwave treatment duration. Boards with lower MC levels received more effective than those with higher MC level. Wood grain also affected treatment efficiency especially the slab board.

When wood was subjected to a drying process involving a MW electrical field, temperature gradient was from an inner high and outer low value, and the direction of temperature gradient accorded to direction of moisture content gradient. Water of wood is then transferred fast to wood surface under the combined action of these two transfer motivations. The moisture content gradient was reduced, the moisture content deviation was decreased, and the moisture content stress was relieved also.

However the mechanical characteristic and viscoelastic of the microwave conditioning sample, the water transfer in wood under MW should be investigated in future work.

ACKNOWLEDGMENTS

This work was support by the project No. 2013DFA32000 from the International Science & Technology Cooperation Program of China.

.

REFERENCES CITED

Alexiou, P. N., and Marchant, J. F. (1990). "Effect of pre-steaming on moisture gradients, drying stresses and sets, and face checking in regrowth *Eucalyptus pilularis Sm.*," *Wood Sci. Technol* 24(2), 201-209. DOI:10.1007/BF00229056

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*," *Wood Sci. Technol.* 24(1), 103-110. DOI:10.1007/BF00225310

Antti, A. L. (1992). "Microwave drying of hardwood: Moisture measurements using CT-scanning," Proceeding of the 3rd International Conference on Wood Drying, August 18-21, Vienna, Austria.

Antti, A. L., and Perre, P. (1999). "A microwave applicator for on line wood drying: Temperature and moisture distribution in wood," *Wood Sci. Technol.* 33(2), 123-138. DOI:10.1007/s002260050104

Chen, J. Q. (1985). *Wood Science*, Chinese Forest Publication, Beijing, China.

Chen, P. Y. S., and Workman Jr., E. C. (1980). "Effect of steaming on some physical and chemical properties of black walnut heartwood," *Wood & Fiber Science* 11(4), 218-227.

Daian, G. (2011). *Delamination in Timber Induced by Microwave Energy*, Springer Netherlands, Netherlands, 159-172. DOI:10.1007/978-90-481-9550-3_8

Ellwood, E. T., and Erickson, R. W. (1962). "Effect of presteaming on seasoning stain and drying rate of redwood," *Forest Production Industry* 12(7), 328-332.

Gasparik, M. (2013). "Changes in temperature and moisture content in Beech wood plasticized by microwave heating," *BioResources* 8(3), 3372-3384.

Grinchik, N. N., Adamovich, A. L., and Kizina, O. A. (2015). "Modeling of heat and moisture transfer in wood in finish drying by the energy of a microwave field," *Journal of Engineering Physics and Thermophysics* 88(1), 35-41. DOI:10.1007/s10891-015-1165-y

Jiang, Z. H., and Wang, X. M. (2003). *Drying of Eucalyptus Plantation*, Chinese Forest Publication, Beijing, China.

Jones, P. L. (1992). "Electromagnetic wave energy in drying processes," in: *Drying 92*, Mujumdar, A. S. (ed.), Elsevier Sci. Publ., pp. 114-136.

Keey, R. B., Langrish, T. A. G., and Walker, J. C. F. (2012). *Kiln-Drying of Wood*, Springer, Berlin, Heidelberg, Berlin, Germany. DOI:10.1007/978-3-642-59653-7_11

Kollmann, W. G. (1956). *The Principles of Wood Science and Technology*, New York Publication, USA.

Montoro, T., and Manrique, E. (1999). “Measurement of the refracting index of wood for microwave radiation,” *Holz als Roh und Werkstoff* 57(4), 295-299. DOI: 10.1007/s001070050062

Pan, Y. K. (1998). *Modern Drying Technology,* Chemical Industry Press, Beijing, China.

Prasad, B. E., and Pandey, K. K. (2012). “Microwave drying of bamboo,” *European Journal of Wood and Wood Products*70(1-3), 353-355. DOI:10.1007/s00107-010-0496-9

Tu, D. Y. (2007), “Modeling and on-line measurement of drying stress of Pinus massoniana board,” *Drying Technology* 25(3), 441-448. DOI: 10.1080/07373930601183827

Wang, X. M. (1990). “Study on drying of elm in high temperature,” *Forest Production Industry* 17(4), 7-11.

Wang, X. M., and Xue Z. H. (2002). “Preliminary research on microwave modified wood,” *Wood industry* 16(6), 16-19.

Yang, M. (2005). “Study on releasing drying stress of wood by MW treatment,” Master’s Thesis, Inner Mongolia Agricultural University, Hohhot, China.

Yin, Z. W. (2003). *Dielectric Physics,* Science Publication, Beijing, China.

Zhu, Z. X. (1998). *Wood Drying*, Chinese Forest Publishing, Beijing, China.

Article submitted: August 14, 2014; Peer review completed: November 21, 2014; Revised version received and accepted: May 20, 2015; Published: June 1, 2015.
DOI: 10.15376/biores.10.3.4441-4452