Effects of Frequency and Processing Time on the Drying Course of Ultrasound-assisted Impregnated Wood

Zijian Zhao, Qing Ma, Zhengbin He, and Songlin Yi *

Impregnating wood, assisted with ultrasound technology, could improve the impregnation efficiency by improving the permeability of wood, thus affecting the subsequent drying process. Poplar lumber and phenolic resin were applied to investigate the influence of ultrasound-assisted impregnation on the wood drying process. The ultrasonic frequency and processing time were analyzed and correlated. The results indicated that the average drying rate of impregnated wood was generally faster in the earlier stage and slower in the later period than the blank group. At the earlier drying stage, the drying rate exhibited a decreasing tendency with increasing ultrasonic time, as the frequency remained constant. However, with an unaltered processing time, a contrary trend was detected as the frequency was increased. The ultrasonic frequency and time caused an complex effect on the average drying rate during the later drying course. These findings could be applied to the impregnated wood drying industry to strike a balance between ultrasound-assisted performance and the related drying effectiveness.

Keywords: Wood drying; Ultrasound; Impregnation; Frequency and time

*Contact information: Beijing Key Laboratory of Wood Science and Engineering, Beijing Forestry University, Beijing, P.O. Box 979, 100083, P.R. China; *Corresponding author: ysonglin@126.com*

INTRODUCTION

Impregnation with phenolic resins or other chemical additives is a method that is being used to improve wood's mechanical performance and resistance to decay. During impregnation, the chemical additives are forced into the wood with special technology, which generally includes three patterns: vacuum, atmospheric pressure, and high pressure impregnation (Luo 2000). Impregnation in a vacuum-press environment is extremely equipment-dependent, necessitating a stirred tank, liquid accumulator, impregnating pot, vacuum pump, pressure pump, and the necessary controlling system. Although this technology can achieve higher impregnating depth and weight gain, it demands large capital, high power, and complicated operation. Despite the weaker performance compared to the vacuum-press, impregnation at ordinary pressure needs only simple devices, limited investments, low energy, and can be conveniently handled (Li 2005). Consequently, it is of great significance to improve the impregnating performance at atmospheric pressure to improve energy savings and reduce emissions during wood manufacturing.

Ultrasound is a type of assisting method that has been used to promote the impregnation of wood at ordinary pressures (Li *et al.* 2006). When ultrasound waves propagate in liquid media, they cause a cavitation effect, with numerous cavitation bubbles. The bubbles rapidly collapse and produce a shock wave (Feng 2006; Duan *et al.* 2008; Legay *et al.* 2011), which enhances the removal of extractives strongly attached to the wood cell wall (He *et al.* 2012, 2013). Thus, the permeability and mass transfer of the wood is improved (Fuente-Blanco *et al.* 2006; Gallego-Juarez *et al.* 2007; Soria and Villamiel 2010) and the impregnation efficiency is consequently increased. In addition, based on the previous studies by the first author (Zhao *et al.* 2014) of this article, ultrasound-assisted impregnation is susceptible to the initial moisture content of wood. When the moisture content is nearer the level of green timber, the ultrasound can achieve a larger assistance, leading to higher weight gain of resin. However, drying is an important step following the impregnation.

Wood drying is an important step for all wood products during the manufacturing process, and it consumes roughly 40% to 70% of the total energy in the entire wood manufacturing process (Zhang and Liu 2006). However, studies concerning the dewatering of impregnated timber are limited, particularly studies related to ultrasound-assisted impregnated wood.

Fast-growing poplar is one of the widely used planted trees in China, and low-molecular weight phenolic resin is frequently applied in modified wood manufactures. (Wang *et al.* 2015). Based on this, this study attempts to determine the effects of frequency and processing time on the drying of ultrasound-assisted impregnated wood with the poplar and phenolic resin. This research could provide a theoretical basis for the production practice.

EXPERIMENTAL

Materials

Fast-growing poplar (with basic density of 0.38 g/cm^3, tree-age of 9 years, and diameter at breast height of 25.6 cm), obtained from Guangdong Landbond Furniture Co. Ltd in Guangdong Province, China, was selected. The selected poplar was preserved in water to prevent decay. The defect-free poplar sapwood blocks, with initial moisture contents of 160% to 180%, were machined to dimensions of 20 mm (L) ×20 mm (T) × 20 mm (R).

Low-molecular weight phenolic resin, provided by Beijing Dynea Chemical Industry Co. Ltd in Beijing Province, China, was used as impregnation resin. The phenolic resin (with a density of 1.196 g/mL and solids content of 50%) was diluted to an aqueous solution with 23% concentration.

Methods

The samples were divided into seven groups—A, B, C, D, E, F, and G—with 30 replicates per group. The subsequent processing conditions for these groups are shown in Table 1. The impregnation was carried out in an ultrasonic cleaning machine using a phenolic resin aqueous solution.

Table 1. Processing Conditions for Each Group

	A	B	C	D	E	F	G
Frequency	28 kHz	28 kHz	28 kHz	40 kHz	40 kHz	40 kHz	--
Processing time	20 min	40 min	60 min	20 min	40 min	60 min	--

After the impregnation, the impregnated specimens (including the control group) were dried for 10 h at room temperature and 9 h at a temperature of 70±2 °C; finally, the process was concluded at the temperature of 103±2 °C until no mass change was detected.

For the entire experimental process, the weight change of the samples was an essential factor. Therefore, the weight at each test process was recorded. Before impregnation, the initial weight for each sample was recorded. Following the 10-h air-seasoning the sample was weighed again. During the 9-h drying process at a temperature of 70±2 °C the weights of the samples were recorded every 3 h. Subsequently, the samples were dried to oven dry at a temperature of 103±2 °C and the oven dry weight was recorded. The moisture content throughout the whole process and the final weight gain rate of each sample were calculated based on the recorded data. The resultant for each group was the average of the 30 replicates.

The initial moisture content of group G was determined according to Eq. 1,

$$MC_0 = \sum_{i=1}^{30} \frac{m_{0Gi} - m_{5Gi}}{m_{5Gi}} \times 100\% \tag{1}$$

where MC_0 is the initial moisture content of group G, and m_{0gt} and m_{5gt} are the initial and oven-dry weights of every sample of group G, respectively. The MC_0 value was taken as the initial moisture for every block specimen.

Second, according to MC_0 and the initial weight of the specimens of groups A to F, the oven-dry weight of these specimens could be calculated using Eq. 2,

$$m_{od} = \frac{m_0}{1 + MC_0} \tag{2}$$

where m_0 and m_{od} represent the initial and oven-dry weight of the specimens in groups A to F, respectively.

Finally, the moisture content throughout the whole process and the ultimate weight gain of every group were determined according to the calculated data and Eq. 3 and Eq. 4,

$$MC = \frac{M - M_{od}}{M_{od}} \times 100\% \tag{3}$$

$$WG = \frac{M_{od} - m_{od}}{m_{od}} \times 100\% \tag{4}$$

where MC is the moisture content of impregnated specimens during the course of drying, M is the recorded weight during the dewatering process, and M_{od} is the recorded oven-dry weight of the impregnated samples, and WG is the ultimate weight gain of each impregnated block.

RESULTS AND DISCUSSION

The moisture content at different periods, drying rate at different stages, and weight gain of impregnated groups are presented in Tables 2 to 4, respectively.

Table 2. Moisture Content and Its Standard Deviation at Different Periods

	0 h (%)	σ0	10 h (%)	σ1	13 h (%)	σ2	16 h (%)	σ3	19 h (%)	σ4
A	165.05	0.1424	120.74	0.0458	39.47	0.0636	12.03	0.0464	11.33	0.0479
B			131.28	0.0449	51.16	0.0788	12.12	0.0399	10.89	0.0377
C			140.73	0.0439	62.92	0.0574	18.23	0.0584	16.11	0.0636
D			119.32	0.0459	43.88	0.0568	11.82	0.0462	11.14	0.0457
E			129.32	0.0670	47.35	0.0536	19.93	0.0353	19.45	0.0347
F			130.93	0.0546	48.28	0.0557	20.30	0.0654	19.79	0.0654
G			132.57	0.1304	48.36	0.1203	2.94	0.0196	1.08	0.0021

Table 3. Drying Rate at Different Periods

	A	B	C	D	E	F	G
0-10 h (%/h)	4.43	3.38	2.43	4.57	3.57	3.41	3.25
0-13 h (%/h)	9.66	8.76	7.86	9.32	9.05	8.98	8.98
0-16 h (%/h)	9.56	9.56	9.18	9.58	9.07	9.05	10.13
0-19 h (%/h)	8.09	8.11	7.84	8.10	7.66	7.65	8.63

Table 4. Weight Gain and its Standard Deviation for Impregnated Groups

	A	B	C	D	E	F
WG (%)	9.85	9.37	14.40	9.23	17.10	17.18
σ	0.0478	0.0383	0.0619	0.0463	0.0347	0.0647

Effects of Frequency and Processing Time on the Drying Rate

The drying rate of groups A to G at different periods is presented in Table 3 and Fig. 1.

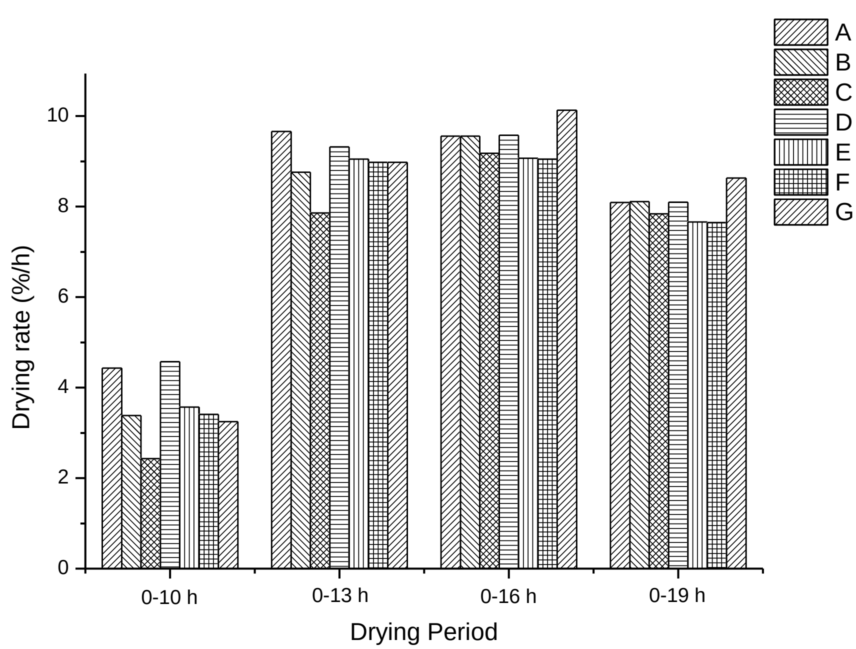

Fig. 1. Drying rate at different periods

Overall, most of the average drying rates of the ultrasound-assisted impregnated groups were larger in the earlier stage 10 h or 13 h, and smaller in the later course 16 h or 19 h compared to the blank group G. In addition, a difference in the drying rate between the experimental groups can be seen in Table 3 and Fig. 1, indicating that the ultrasonic frequency and processing time had comprehensive effects on the dewatering speed of the impregnated samples.

In the periods of 0 to 10 h and 0 to 13 h, a general result is presented that, with the same processing time, the drying rate will increase with increasing frequency, and the fastest drying rate is even larger than that of the blank group. However, with the same frequency, the drying rate presents a decreasing tendency with increasing ultrasonic processing time. During the drying stage of 0 to 16 h and 0 to 19 h, when the processing time is the same, the groups with a lower frequency generally have a higher drying rate, while using equal frequencies causes a drying rate decline, along with an increase in processing time.

Effects of Frequency and Processing Time on Weight Gain

The weight gain for the phenolic resin in groups A through F are shown in Table 4. Wood resin absorption was affected both by ultrasonic frequency and treating time. When the frequency was 28 kHz, the weight gain rates for groups A and B were noticeably smaller than that of group C, while at a frequency of 40 kHz, similar resin absorption occurred between groups E and F, whose resin gains were evidently higher than that of group D. When the processing time remained invariant, the groups with higher frequency manifested a larger resin weight gain rate compared with the lower frequency group, and the largest difference appeared between groups B and E, with a processing time of 40 min.

As a type of porous material, wood is suffused with countless channels, which are filled with the free water present in green wood. Thus, when green timber is immersed into a liquid medium (generally constituting a chemical solution), a continuum liquid system consisting of the water in and around the wood could form. Ultrasound spreads in this continuum liquid system, and then it splits and even breaks down the pit membranes by the cavitation effect, improving the wood permeability (He *et al.* 2012, 2013). At the same time, the timber is surrounded by phenolic resin, which would move into the wood at a faster rate due to the improved permeability and the ultrasonic effects (Furuno *et al.* 2003). However, the increased absorption of the phenolic resin oppositely reduces the permeability of the impregnated wood. Therefore, a competition between the previous improvement and the following restraint of the permeability ensues, with the main factors being ultrasonic frequency and processing time. The previous improvement of the permeability is beneficial for the weight gain of resin, while the overall results of the competition results make great differences with respect to the subsequent wood drying rate.

Generally, the permeability influences the dewatering course of free water, which corresponds to the drying stage of the preceding 13 h in this study. The course of 13 h to 19 h could be considered the stage where dewatering of the bound water occurs, as the wood moisture content at 16 h was already below the fiber saturation point.

The similar weight gain in groups A, B, and D indicates a similar resistance to permeability. However, the different drying rates of these groups reveals the various promoting effects to permeability. That is, according to the same tendency of their drying rate, the promoting effect of group A was the strongest, while group B was the weakest.

However, the drying rate of both groups A and D is larger than that of control group G, showing that the accelerating influence of A and D is stronger than their inhibiting effect. These analyses could be applied to the other groups as well.

As a result, it could be concluded that, with constant frequency, shorter processing times will lead to stronger and faster improving effects and drying speed. With unchanged treating time, a lower frequency results in a weaker promoting effect, particularly as the processing time is increased.

With regard to the dewatering of bound water, it could be concluded that larger weight gain results in smaller release rate of the bound water. The adsorbed resin has a dominant effect on the dewatering of bound water. During the drying process, the gained resin occurs solidification and this becomes intensified when the free water is removed. The solidified resin fills in the moisture migration channel and inhibits the dewatering rate of bound water.

CONCLUSIONS

1. Ultrasonic frequency and processing time comprehensively affected the drying course of impregnated wood, whose drying rate is faster in the 0 to 10 h and 0 to 13 h periods, and slower in the 0 to 16 h and 0 to 19 h groups, compared with that of the blank group G.
2. In the earlier 13 h dewatering stage, when the treatment time remained constant, in general, a higher frequency resulted in a faster drying course. Meanwhile, for the same frequency, the drying speed presented a decreasing tendency with increasing ultrasonic time.
3. During the drying period of 0 to 16 h and 0 to 19 h, when the processing time was the same, the groups with lower frequency generally had higher drying rates, while for groups with the same frequency, the drying rate declined with increasing processing time.
4. With constant frequency, a shorter processing time resulted in a stronger permeability improving effect, while for groups with the same treating time, lower frequencies led to weaker promoting effects, particularly for longer processing times.
5. In the context, the improvement of drying rate is due to the promoted permeability, which is of benefit for the movement of moisture. The accelerated movement effectively prevents the development of too much moisture gradient and excessive drying stress. Consequently, the ultrasound technique has little negative influence on the wood mechanical resistance.

ACKNOWLEDGMENTS

This paper was supported by the National Natural Science Foundation of China – Study on the moisture migration mechanism during ultrasonic-assisted wood vacuum superheated steam drying (31270604).

REFERENCES CITED

Duan, X., Zhang, M., Li X. L., and Mujumdar, A. S. (2008). "Ultrasonically enhanced osmotic pretreatment of sea cucumber prior to microwave freeze drying," *Drying Technology* 26(4), 420-426. DOI: 10.1080/07373930801929201

He, Z. B., Guo, Y. H., Yi, S. L., and Zhang B. G. (2012). "Preliminary study of wood ultrasound-vacuum combined drying dynamics," *Journal of Beijing Forestry University* 34(2), 133-136. DOI: 10.13332/j.1000-1522.2012.02.026

He, Z. B., Yang, F., Peng, Y. Q., and Yi, S. L. (2013). "Ultrasound-assisted vacuum drying of wood: Effects on drying time and product quality," *BioResources* 8(1), 855-863. DOI: 10.15376/biores.8.1.855-863

Feng, R. (2006). "Ultrasound propagation in gas, liquid and solid medium," in: *Ultrasound Handbook*, Z. P. Li (ed.), Nanjing University Press, Nanjing, China.

Fuente-Blanco, S. D. L., Sarabia, R. F. D., Acosta-Aparicio, V. M., Blanco-Blanco, A., and Gallego-Juárez, J. A. (2006). "Food drying process by power ultrasound," *Ultrasonics* 44 (suppl. 1), e523-e527. DOI: 10.1016/j.ultras.2006.05.181

Furuno, T., Imamura, Y., and Kajita, H. (2003). "The modification of wood by treatment with low molecular weight phenol-formaldehyde resin: A properties enhancement with neutralized phenolic-resin and resin penetration into wood cell walls," *Wood Science and Technology* 37(5), 349-361. DOI: 10.1007/s00226-003-0176-6

Gallego-Juarez, J. A., Rodriguez-Corral, G., Gálvez Moraleda, J. C., and Yang, T. S. (2007). "A new high-intensity ultrasonic technology for food dehydration," *Drying Technology an International Journal* 17(3), 597-608. DOI: 10.1080/07373939908917555

Li, X. D. (2005). "Soaking treatment of wood flame-proof and new technology," *Liaoning Chemical Industry* 34(10), 439-442.

Li, X. D., Hao, W. X. and Qi, X. Y. (2006). "Application of ultrasonic wave in soaking methods of wood treated with fire retardants," *Fujian Forestry Science and Technology* 33(1), 64-66, 79. DOI: 10.13428/j.cnki.fjlk.2006.01.017

Luo, J. S. (2000). "A general discussion on flame retardant treatment of wood," *China Forest Products Industry* 27(2), 7-9.

Legay, M., Person, S. L., Boldo, P., Gondrexon, N., and Bontemps, A. (2011). "Enhancement of heat transfer by ultrasound: review and recent advances," *International Journal of Chemical Engineering* 2011, 670108. DOI: 10.1155/2011/670108

Soria, A. C., and Villamiel, M. (2010). "Effect of ultrasound on the technological properties and bioactivity of food: A review," *Trends in Food Science and Technology* 21(7), 323-331. DOI: 10.1016/j.tifs.2010.04.003

Wang, L. L., Yue, K., Lu, W. D., and Liu, W. Q. (2015). "Flame retardation of fast-growing poplar wood modified with low molecular weight boracic acid compounding phenol-formaldehyde resin," *Journal of Anhui Agricultural University* 42(4), 511-514. DOI: 10.13610/j.cnki.1672-352x.20150626.008

Zhang, B. G., and Liu, D. Y. (2006). "Exploring a new developing way of wood drying technology in China," *China Forest Products Industry* 33(4), 3-6.

Zhao, Z. J., He, Z. B., Shang, T. O., Yang, F., and Yi, S. L. (2014). "Preliminary study on ultrasound-assisting wood impregnation at atmospheric pressure," *Wood Processing Machinery* 25(2), 47-50. DOI: 10.13594/j.cnki.mcjgjx.2014.02.014

Article submitted: September 3, 2015; Peer review completed: November 22, 2015; Revised version received and accepted: December 5, 2015; Published: January 12, 2016.
DOI: 10.15376/biores.11.1.1951-1958