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Microwave Drying of Wood Strands

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Abstract: Characteristics of microwave drying of wood strands with different initial moisture contents and geometries were investigated using a commercial small microwave oven under different power inputs. Temperature and moisture changes along with the drying efficiency were examined at different drying scenarios. Extractives were analyzed using gas chromatography/mass spectrometry (GC/MS). The results showed that the microwave drying process consisted of three distinct periods (warm-up period, evaporation period, and heating-up period) during which the temperature, moisture change, and drying efficiency could vary. Most of the extractives were remnant during microwave drying. It was observed that with proper selections of power input, weight of drying material, and drying time, microwave drying could increase the drying rate, save up to 50% of energy consumption, and decrease volatile organic compound (VOC) emissions when compared with the conventional drying method.

Keywords: Microwave drying; Wood strand; Temperature; Moisture content; Energy efficiency; Extractives

INTRODUCTION

The major concerns in the regular hot-air strand drying method are tremendous amounts of energy consumption and low drying efficiency.

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In addition, the conventional hot air drying method degrades the quality of strands and produces more volatile organic compounds (VOCs) due to the high drying temperature. Microwaves, as an alternative, can dry wood strands under lower temperature and higher rates, produce relatively uniform moisture content, and result in low VOC emissions, because they interact directly with the water molecules in wood to generate heat.[1,2] During the past 50 years, research has been conducted to investigate microwave drying of solid wood products and veneer.[1–10]

Microwave heating involves placing wood products in a microwave field, which is oscillating at hyper-frequency (300 MHz–300 GHz). The wood products could be quickly heated to the boiling point of water throughout their whole volumes.[4] Antti and his coworkers[3,5–7] conducted extensive studies on microwave drying of ash, beech, oak, pine, and spruce lumbers. Due to potential internal pressure built-up and failures, they concluded that the microwave drying method was most suitable for thin pieces of lumber, veneer, or strands.

Temperature and moisture distributions during drying are highly correlated with the internal drying stresses. Harris and Taras[8] compared moisture content distribution, stress distribution, and shrinkage of red oak lumbers dried in a radio-frequency/vacuum drying process with these in the conventional kiln process. Zielonka[9,10] provided the mathematical equations of the moisture content and temperature versus heating time for drying of spruce lumbers. No reports have been found in the literature that investigates the temperature and moisture distributions in wood strands or flakes during microwave drying.

Wood drying is one of the most dominant sources of VOC emissions in the wood product industry. Boswell and Hunt[11] reported that particle drying accounted for about 75% of the VOC emissions while pressing accounted for only 20%. The total amount of VOC emissions was approximately equivalent to 1 to 2 kg per oven-dried ton (ODT) of wood furnishes.[12] Among the VOC emissions the most notable were α-, β-pinene, and their ramifications.[13,14] Since VOC emission came mainly from extractives, the changing of extractives in wood furnishes could be used to estimate VOC emission. Wang[15] and Ting et al.[16] reported that VOC emissions from pure wood particles after thermal and pressure treatments were similar to the ones under the conditions used for commercial production of particleboard.

The overall goal of this study was to provide insight in understanding the characteristics of microwave drying of wood strands. The specific objectives of this study were: (1) to investigate distributions of temperature and moisture content during microwave drying of wood strands; (2) to determine suitable drying conditions to reach 2% target moisture content; (3) to evaluate energy consumptions for microwave drying of wood strand; and (4) to evaluate the effect of microwave strands drying on VOCs emissions.

MATERIALS AND METHODS

A local oriented strand board (OSB) mill provided Southern pine strands. The average geometry of strands was about 111 × 35 × 1 mm with initial average moisture content of 80% db (dry basis). The moisture content was determined by oven drying at 103°C until the mass change over three hours was less than 0.1%.[17] A commercial microwave oven (Panasonic NN-S761) with oven cavity dimensions of 278 × 469 × 470 mm and operation frequency of 2450 MHz was used. The nominal microwave power output was 687 W as calibrated based on the method of the International Microwave Power Institute.[18] The turntable inside the oven was used only in studies of the drying method on extractives. For the purpose of comparison with convective drying, a conventional electric oven with internal dimensions 550 × 610 × 730 mm was used (Fisher ISOTEM oven model 501). An electric balance (Denver Instrument XL-6100) with accuracy of 0.1 g and fiber-optic temperature transducers with an accuracy of 1°C (Fiso Signal Conditioner UMI-4) were used respectively, to monitor the weight and temperature of the sample during drying. The test setup is illustrated in Fig. 1. Changes of specimens' weight were monitored using the electric balance from which the shelf with the specimen (either the bed of wood strands or a solid wood sample) was suspended. The temperature sensor inserted into the centre of the bed of strands measured the mean temperature of strands, identified here as the surface temperature (c.f., experiments on solid wood drying). After microwave drying, the samples were oven-dried to determine the final moisture content.

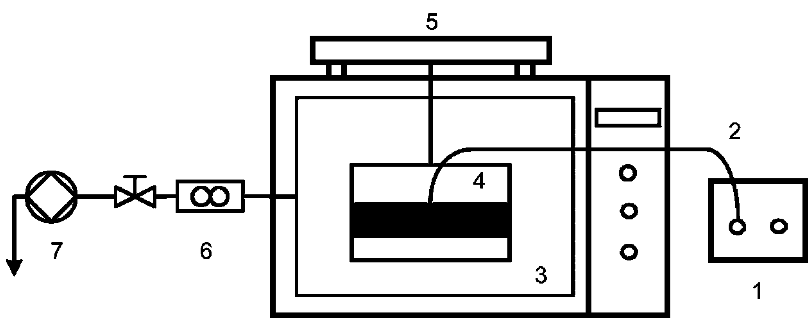

Figure 1. Schematic diagram of the test equipment: 1) Fiber optical data logger, 2) fiber optical temperature sensor, 3) microwave oven, 4) sample container, 5) electric balance, 6) flow meter, 7) vacuum pump.

In order to remove evaporated water, the microwave oven had a hole cut in one side, then sealed and ventilated through a horn-shape connector between a flow meter and a vacuum pump. The flow ratio was adjusted by a valve and measured by the flow meter. The energy performance was quantified in terms of the energy required to heat and evaporate a unit mass of water (MJ/kg), and defined as

$$UEC = \frac{t_{\mathrm{on}} \times P \times (1 + m_i)}{M_i \times (m_i - m_f)}$$

where t_{on} = total drying time (s); P = microwave power output (W); M_i = initial mass (kg); m_i = initial moisture content (fraction, dry basis); and m_f = final moisture content (fraction, dry basis).

In order to examine extractive changes, 200 g of strands were dried using the microwave oven with a turntable. The final moisture content was about 5.2% db. The drying temperature was maintained below 80°C by interval power input. As reference, the 200 g of strands were dried in a convectional oven at 250°C until the final moisture content reached zero. Another 200 g of strands were dried at room temperature until the final moisture content reached 8.4% db. After drying, all strands were powdered and screened through a 40 mesh screen and then extracted with methylene chloride for 24 h using a Sohxlet extraction apparatus. A total of 120 g of wood powder was extracted. The extracted chloride solutions were then mixed and condensed to 10 mL. The mixture then was analyzed using gas chromatography/mass spectrometry (GC/MS). A 30-m HP-5 column with 5% cross-linked phenymethylsiloxane was used to separate the chemical compounds. The GC injector temperature was set at 280°C. Helium was used as a carrier with a flow rate of 0.7 mL/min. The GC oven temperature was started at 40°C and held for 4 min. Then the temperature was programmed to 280°C at 10°C per min and held for 8 min. The ionizer voltage of MS detector was 70 eV, and the temperature was 200°C. The scan range of molecular weights was 40 to 500 amu. For each sample, 0.5 μL mixture was injected into GC/MS. Comparing integrated areas under peak spectrums of each compound in GC/MS chromatograms, information about extractive changing was obtained. The remnant ratio (RR) is defined as the rate of the amount of a compound remaining in strands after microwave or oven drying to the amount of the corresponding compound before drying.

RESULTS AND DISCUSSIONS

Microwave power input and the mass of drying materials in the microwave oven were found to have a dominant effect on the drying quality.

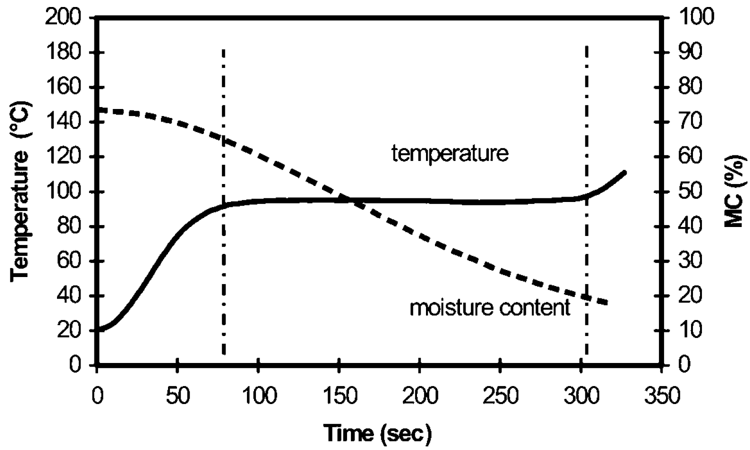

Figure 2. Typical temperature and MC changes during microwave drying (power input = 687 W and drying mass = 100 g).

A term of (power input)/mass (PIM) ratio is used in this study to characterize the microwave drying process. Typical curves describing strand temperature and MC change during microwave drying are shown in Fig. 2. The temperature curve during the microwave drying process usually exhibits three distinct periods: 1) a warm-up period which can be characterized by quick rising temperatures and slow water loss; 2) an evaporation period in which most water evaporates and the drying temperature reaches a plateau; 3) a heating-up period in which moisture evaporation slows down and the surface temperature increases rapidly. A similar pattern of temperature and MC changes is observed for the convective drying process. However, during microwave drying, the warm-up period was shorter and the plateau temperature was relatively higher (boiling point of water), which could increase the drying rate. Furthermore, the surface temperature of specimens during microwave drying begins to rapidly increase at relatively high MC (20% in Fig. 2).

Temperature

There are many factors that affect drying temperatures. During microwave drying, the warm up period depends upon the energy input and the drying weight or the combining parameter: PIM ratio as shown in Figs. 3 and 4. Higher PIM ratio results in not only fast temperature increases during the warm-up period, but in high plateau temperatures as well. In the warm up period, before the temperature reached the

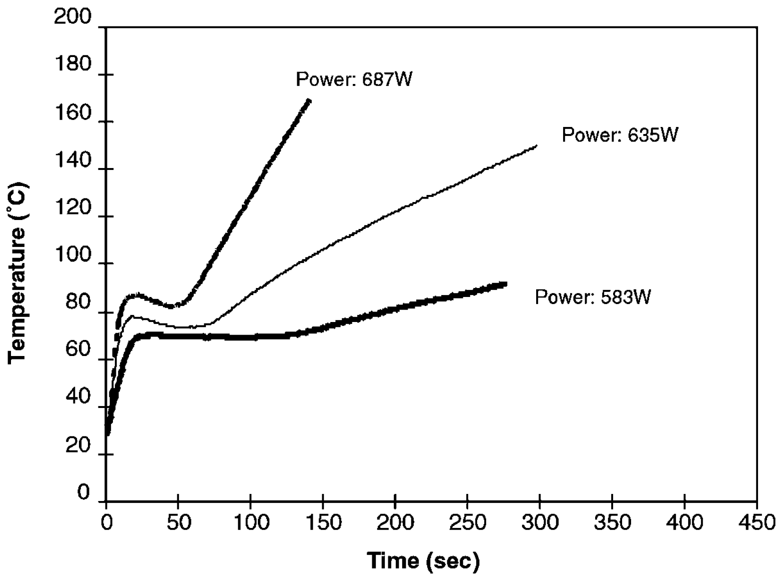

Figure 3. Temperature changes during microwave drying of 50 g of wood strands at different power inputs.

boiling point the energy is mainly used to build up heat for temperature rising. Moisture changes are relatively small. The notable characteristics during microwave drying is when the drying temperature is close to the boiling point, the fast evaporation of water results in the decrease of the strand's surface temperature, especially in the case of higher PIM ratio (Figs. 3 and 4). This phenomenon has never been observed during conventional oven drying processes.

During the final drying stage, the strand surface temperatures start to increase rapidly due to excessive heat built-up inside the specimens. Unlike the conventional drying method in which the surface temperatures increase only after most water has been evaporated, the sharp increase of surface temperatures at relatively early drying processes (with about 20% MC) could cause partial charring to the surface if the process is not properly controlled. The higher PIM ratio results in the temperature increase at even higher moisture contents. For example, when 50 g of drying material was placed in the microwave oven under the full power input, the temperature in the heating-up period started to increase at 60% MC. However, when the material was dried under the medium power input, the temperature increased at 30% MC. Usually, the temperature would increase so high that some charring would occur on the flake surfaces, especially at high PIM ratios.

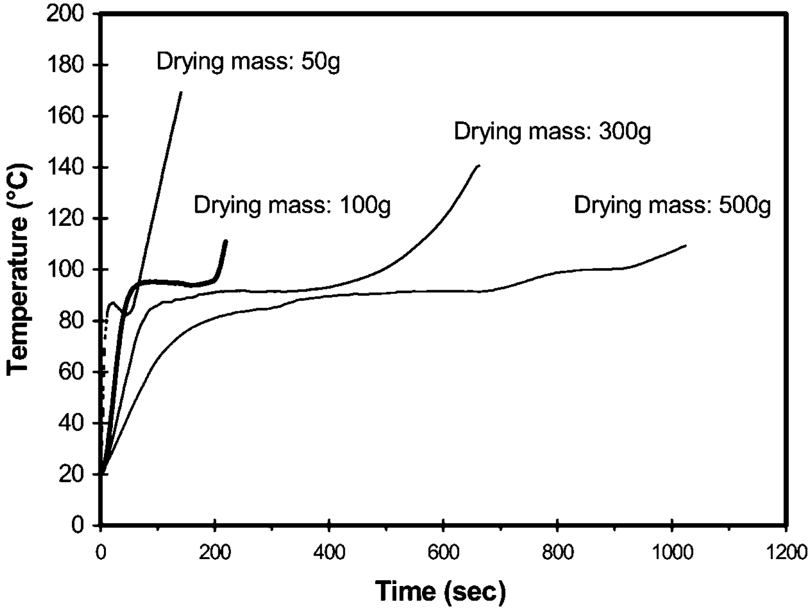

Figure 4. Temperature changes during microwave drying under 687 W power input for different drying weights.

Further observations indicate that higher PIM ratios result in not only shorter warm up periods and higher plateau temperatures, but also shorter plateau periods. That means a high PIM ratio will increase drying efficiency or moisture removal efficiency by reducing the drying time. The reason is that under high PIM ratios more microwave energy has been transferred to the drying material, which increases the temperature and moisture evaporation. Unlike the convective drying method, which relies on high surrounding temperature to transfer thermal energy, microwave drying generates the heat by oscillating polar molecules throughout the whole volumes of the drying materials. Less energy is wasted to increase the temperature of the surroundings. Normally, the air temperature or surroundings temperature in microwave drying was about 40–60°C which is significantly less than the one in convective drying.

The geometry of drying materials has effect on the drying process during microwave drying. Figure 5 shows temperature changes of thin strands (46.63 × 24.39 × 0.31 mm) and thick strands (114.54 × 32.37 × 1.85 mm) during microwave drying with the power input of 687 W for 18 minutes. The thick strands appear to have short warm-up periods due to less surface areas for convective cooling.

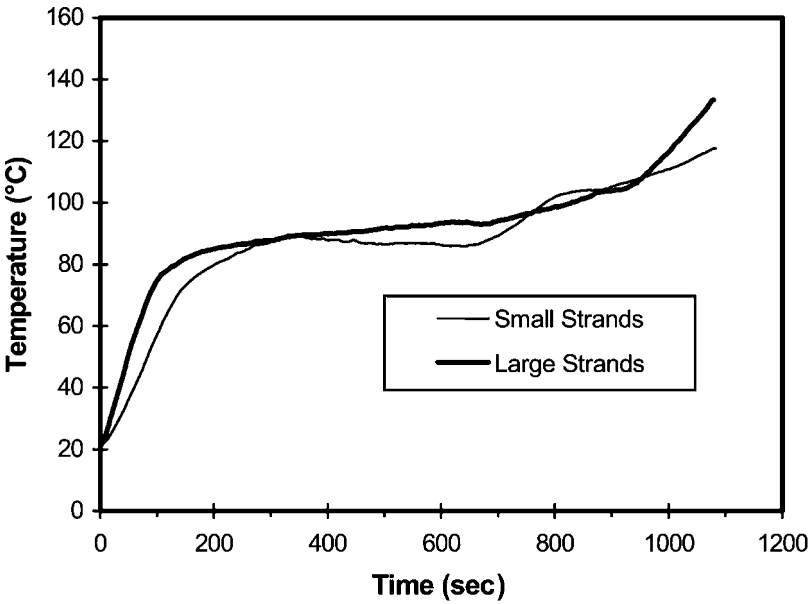

Figure 5. The effect of strand geometry on temperature changes during microwave drying.

Moisture Content

All wood furnishes used to make wood composites must be dried to have a proper MC range (usually 4% to 8%) before blending with adhesives. The initial average moisture content of furnishes varied from 60% to over 100%. In order to examine the effect of initial moisture contents on temperature changes, three groups of 200 g strands with different MCs (high (80%), medium (35%), and low (18%)) were dried in the microwave oven with a power input of 687 W, respectively. Figure 6 shows the moisture changes for the three different groups and Fig. 7 shows the different temperature responses for the three groups. For the low MC group, there is no obvious warm-up period. But the temperature is continuously increasing. Under the condition of a uniform microwave field, dry wood furnishes with different MC will result uniform final MC, the reason is that high moisture content furnishes always absorb more microwave energy, appear fast warm-up and fast moisture evaporating. To obtain a uniform microwave field and to avoid the charring problems for nonuniform MC, a turntable was used in this study to make the strands rotating in the microwave field. It was found that with proper control

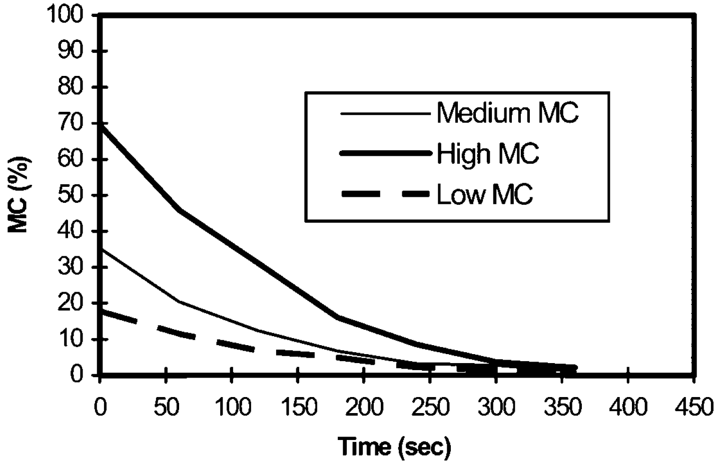

Figure 6. The moisture changes of the three different groups during microwave drying.

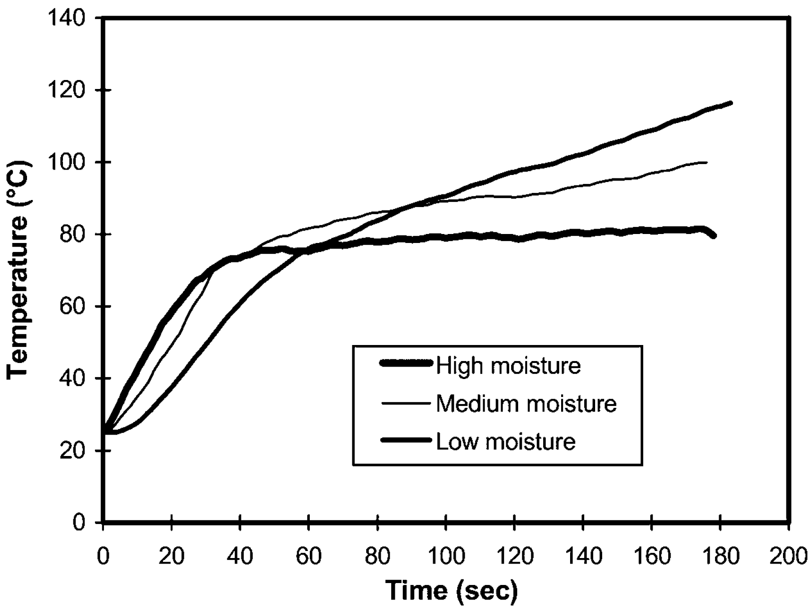

Figure 7. The effect of initial MCs on temperature changes during microwave drying.

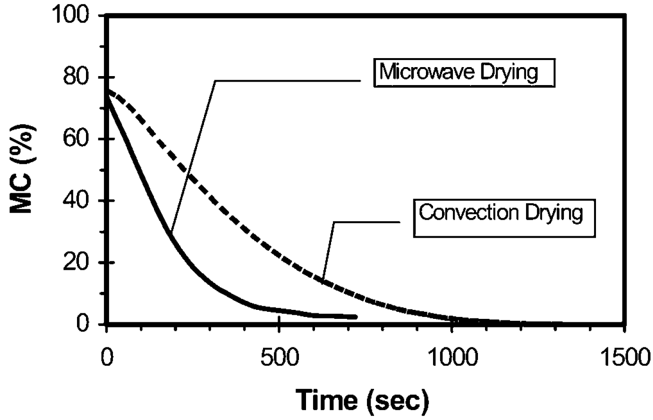

Figure 8. Comparison of moisture change rates for the two drying methods.

of PIM ratios and drying times, the strands on the turntable could be dried to an average of 2% MC without any charring damage.

Comparisons of moisture changes and water loss between the microwave drying (input power 687 W) and the convective drying (250°C) for 200 g strands are shown in Figs. 8 and 9, respectively. The results indicate that microwave drying is faster in drying wood strands than the convective drying method.

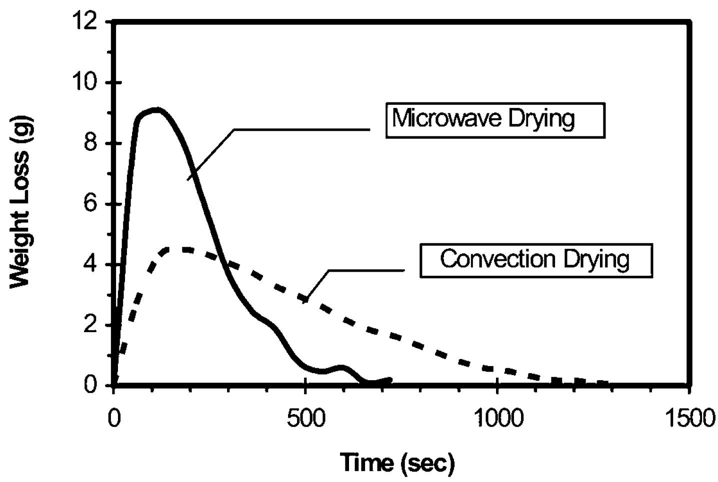

Figure 9. Comparison of weight loss for the two drying methods.

Table 1. Surface and core temperature changes during microwave drying

	Temperature (°C)			
	Sample 1[a]		Sample 2[b]	
Time (seconds)	Surface	Core	Surface	Core
0	21.7	21.66	21.52	21.84
10	34.24	42.44	35.06	66.18
20	64.58	65.96	73.64	96.76
30	86.38	90.94	90.76	98.46
40	90.84	98.8	93.18	99.18
50	92.48	99.62	92.48	99.62
60	93.22	101.42	96.24	100.42
90	93.68	102.94	93.68	99.06
120	92.02	102.16	93.34	99.14
150	95.66	102.28	90.54	99.7
180	98.68	104.34	89.58	101.82

[a]147.9 mm long, 89.7 mm wide, 8.2 mm thick, initial moisture content = 95.7%.
[b]152.9 mm long, 87.4 mm wide, 7.0 mm thick, initial moisture content = 96.3%.

The sample of wood strands represents the bed of porous material formed from individual strands separated by air layer of undefined thickness. Thus, the temperature sensor inserted into this sample indicates a temperature being a resultant of the strand's surface temperature and the air temperature in the bed voids. To examine by how much the measured temperature differs from the surface temperature, a set of experiments were performed with the samples of solid wood. Table 1 shows that a solid pine specimen of 147.9 mm long, 89.7 mm wide, and 8.2 mm thick reached the boiling point after 50 seconds microwave heating at the input power 687 W. The surface temperature is slightly lower than the core temperature as air cooling happens on the surface. At the boiling point this difference is of about 10% so it is reasonable to accept that the fiber optic sensor inserted into the bed of wood strands measures the strands' temperature.

Air circulation and successful removing of the steam are very important steps in controlling the microwave drying process. Three groups of strands with almost identical geometry and initial MC of 77% were tested in the different air discharging flow rate (which is defined as discharging air volume (*L*) per minute). After 11 min, the final MC was 12.1% for the group with discharging flow rate of 8 L/min, 9.8% MC for the one with discharge rate of 16 L/min, and 5.3% MC for the one with discharging rate of 22 L/min. Therefore, careful selection of discharging air rate could control the drying speed to avoid some drying-stress inducing defects. A further detailed study is needed for optimizing the microwave drying processes (air discharge rate, PIM ratio, and drying time) to ensure a successful drying of wood strands.

Unit Energy Consumption

Unit energy consumption, defined previously as unit energy required for evaporating water from the wood (MJ/kg), was used to describe the drying energy consumption. Different microwave drying scenarios, under the same power input (687 W), were performed to investigate the effects of drying weights, moisture contents, and drying times on the energy efficiencies. The results shown in Table 2 indicate that under the same input power the drying weight plays an import role in energy efficiency. Too little drying material in microwave drying will waste some energy. It is estimated that the PIM ratios between 1.5 to 2.5 W/*g* are the best selections for energy efficiency. The different DEs for different drying processes (high MC to medium MC, medium MC to low MC, and high MC to low MC) indicate that the energy consumption within the microwave drying process may be different depending upon the MC. The liquid water found in the lumen of wood is often referred to as free

Table 2. Unit energy consumption for different microwave drying scenarios

Drying weight (kg)	Initial MC (%)	Final MC (%)	Drying time (s)	UEC* (MJ/kg)
0.025	78.2	7.4	300	20.75
0.025	7.4	3.7	180	143.58
0.025	78.2	3.7	480	31.55
0.100	74.6	29.3	240	6.35
0.100	29.3	17.6	80	6.07
0.100	74.6	17.6	320	6.73
0.300	77.8	29.5	375	3.16
0.300	29.5	17.3	120	2.92
0.300	17.3	5.1	180	3.96
0.300	77.8	5.1	675	3.78
0.500	73.9	30.2	705	3.85
0.500	30.2	17.1	210	2.87
0.500	17.1	6.8	180	2.81
0.500	73.9	6.8	1095	3.90

*Unit energy consumption.

water and the water within the cell wall is called bound water. The fiber saturation point is defined as the moisture content at which the cell walls are saturated but no free water remains in the cell cavities. Moisture content of the individual cell walls at the fiber saturation point is usually about 30 percent, but may be lower for some species. The bound water is held by adsorption forces, mainly hydrogen bonds. Removing the bound water requires more energy than the free water. It is found that microwave drying is more efficient in drying wood strands in the 17 to 30% moisture range. When compared with traditional three-pass drying processes which require about 3.5–4.4 MJ energy to evaporate one kilogram of water at high moisture contents (100 to 185% range) and about 4.4–5.4 MJ/kg at lower moisture contents (18 to 33% range),[19] microwave drying techniques could save energy consumption up to 50% in drying thin wood strands.

Extractives

The amount and composition of the components released during wood drying depend on the drying technique employed (the material being dried, the drying temperature, and the drying time). Table 3 shows the

Table 3. Extractive changes under different drying methods (a turntable was used)

Composite	Retention time (min)	Microwave drying (remnant ratio)	Oven drying (remnant ratio)
Hexanal	~4.3	0.261	0.025
Heptanal	~6.6	0.315	0.026
α-Pinene	~7.5	1.547	0.015
Camphene	~7.9	1.200	N/A
2-Heptenal	~8.1	0.707	N/A
β-Pinene	~8.7	0.695	0.014
Octanal	~9.5	0.684	0.122
3-Carene	~9.5	0.448	0.140
Hexanoic	~9.9	0.689	N/A
Limonene	~10.0	0.373	N/A
Nonanal	~12.5	0.518	0.068
Octanoic acid	~14.9	0.617	0.125
2-Decenal	~16.2	0.895	0.139
Nonanoic acid	~16.6	0.903	0.249

weight of the identified chemical compounds that remain in the furnish after drying. The results show that the remnant ratios of all extracted components after microwave drying are all higher than those after conventional oven drying. This indicates that VOC emission of microwave drying is less than the convective oven drying method. The percentages of change of individual chemical compounds are different. It was estimated that about 90% of extractives were emitted during conventional oven drying, while only about 30% of extractives were emitted during microwave drying. Table 3 also shows the remnant ratios for the α-pinene and camphene were over 1.0 and could be from other chemical components. This needs a further confirmation.

CONCLUSIONS

Characteristics of temperature, moisture content, and unit energy consumption during microwave drying of wood strands (80% southern pine and 20% hardwood) were examined in this study and compared with the conventional drying process. The typical curve of temperature change during the microwave drying of strands indicates that there were normally three distinct periods: warm-up, water evaporation, and heating-up. Water evaporated faster during the early drying process when the MC was high. Water then evaporated at a decreasing rate when the MC was decreasing. During the heating-up period when the strand's MC was low, some of the microwave energy was used to heat up the strands. The temperature of strands would sometimes be so high that the strand surfaces would char. A turntable, which rotated the strands in the microwave field, was an effective way to prevent the charring problems. Due to its unique heating mechanism, the microwave drying method could provide faster strand drying, low VOC emission, and more energy efficiency when compared with the convective drying method. The microwave drying technique could save energy consumption up to 50% in drying thin wood strands.

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REFERENCES

1. Resch, H. Microwave for the drying of wood products. Holz als Roh- und Werkstoff **1968**, *26* (9), 317–324.
2. Barnes, D.; Admiraal, L.; Pike, R.L.; Mathur, V.N.P. Continuous system for the drying of lumber with microwave energy. For. Prod. J. **1976**, *26* (5), 31–41.
3. Antti, A.L.; Zhao, H.; Turner, I. An investigation of the heating of wood in an industrial microwave applicator: Theory and practice. Drying Technology **2000**, *18* (8), 1665–1676.
4. Chen, P.; Schmidt, P.; Sanio, M. An exploratory study of microwave heating in drying of hardwood veneer. J. Microwave Power and Electromagnetic Energy **1990**, *25* (1), 53–59.
5. Antti, A.L. Microwave drying of hardwood: Simultaneous measurements of pressure, temperature, and weight reduction. For. Prod. J. **1992**, *42* (6), 49–54.
6. Antti, A.L. Microwave drying of pine and spruce. Holz als Roh-und Werkstoff **1995**, *53*, 333–338.
7. Antti, A.L.; Perre, P. A microwave applicator for on line wood drying: Temperature and moisture distribution in wood. Wood Science and Technology **1999**, *33*, 123–138.
8. Harris, R.A.; Taras, M.A. Comparison of moisture content distribution, stress distribution, and shrinkage of red oak lumber dried by a radio-frequency/vacuum drying process and a conventional kiln. For. Prod. J. **1984**, *34* (1), 44–54.
9. Zielonka, P.; Gierlik, E. Temperature distribution during conventional and microwave wood heating. Holz als Roh- und Werkstoff **1999**, *57*, 247–249.
10. Zielonka, P.; Dolowy, K. Microwave drying of spruce: Moisture content, temperature, and heat energy distribution. For. Prod. J. **1998**, *48* (6), 77–80.
11. Boswell, J.T.; Hunt, M.L. A survey of air emission from reconstituted wood plants. In Proc. of 25th Inter. Particleboard/Composite Material Symp.; Maloney, T.M., Ed.; Washington State Univ.: Pullum, WA, 1991; 125–146.
12. National Council for Air and Stream Improvement (NCASI). Volatile organic compound emissions from wood products manufacturing facilities. Part V. Oriented Strandsboard. Tech. Bull. No. 771. Research Triangle Park, NC: NCASI, 1999.
13. Banerjee, S. Mechanisms of terpene releases during sawdust and flake drying. Holzforschung **2000**, *55* (4), 413–416.
14. Lawrence, P.O.; Hittmeler, M.E.; Hooda, U.; Yan, H.; Su, W.; Banerjee, S. HAPS release from wood drying. Environ. Sci. Technol. **2000**, *34* (11), 2280–2283.
15. Wang, W.; Gardner, D.J. Investigation of volatile organic compound press emissions during particleboard production: Part 1. UF-bound southern pine. Forest Prod. J. **1999**, *49* (3), 65–72.

16. Ting, J.; Gardner, D.J.; Baumann, M.G.D. Volatile organic compound emissions arising from the hot-pressing of mixed-hardwood particleboard. Forest Prod. J. **2002**, *52* (11/12), 66–77.
17. American Society for Testing and Materials. Standard Test Methods for Direct Moisture Content Measurement of Wood and Wood-based Materials. ASTM Designation D 4442-92 (Reapproved 1997). ASTM: Philadelphia, 2001.
18. Anonymous. A procedure for power output measurement of consumer microwave ovens. Microwave World **1989**, *10* (5), 15.
19. Koch, P. Utilization of hardwoods growing on southern pine sites. Agriculture Handbook No. 605, 2929. U.S. Govt. Print. Off.: Washington, DC, 1985.