WOOD RESEARCH
60 (1): 2015
59-70

DRYING CHARACTERISTICS OF RUBBERWOOD BY IMPINGING HOT-AIR AND MICROWAVE HEATING

Thanate Ratanawilai, Chayut Nuntadusit, Nuchtida Promtong
Prince of Songkla University, Faculty of Engineering
Department of Industrial Engineering
Songkhla, Thailand

(Received May 2013)

ABSTRACT

A potential continuous microwave heating method, and an impinging hot-air drying method have been employed to characterize efficacy of two alternatives rubberwood drying. Rubberwood sample was 1 in. thick 46 in. long with width ranging from 1 to 4 in. Two drying experiments include a hot-air heating where temperature and jet flow velocity were kept at 60-80°C and maximum 10 $m.s^{-1}$, respectively, and a microwave heating with a maximum power input of 200 W. Results revealed that drying times in impinging hot-air exhibited significantly shortened drying time as compared with microwave heating method. The increasing width size resulted in decrease of the specific energy consumption values in both methods. The statistical analysis is also conducted to evaluate an accurate effect of similar temperature between two techniques and rubberwood with varying widths on mechnical properties. It is positive to assert that both methods are practicable without residual stresses inside rubberwood after drying.

KEYWORDS: Microwave heating, hot-air, rubberwood, mechanical and physical properties.

INTRODUCTION

The wood from rubber tree or para rubber tree (*Hevea brasilliensis* Muell. Arg.) has been used for a wide range of products. Before utilizations, rubberwood factory processes essentially include logs acquisition, sawing, borax-based chemical solution impregnation, drying, inspection, storage and distribution. Drying is a most important process to be carried out as it is one of the energy-intensive processes with desired targets in shorter drying times at appropriate drying temperature while rendering minimal quality deterioration. Practices by different factories vary in technical details. In an industrial-scale operation, the heat, mostly transferred by steam in a closed conduit, is supplied via conventional lumber-drying kiln, providing drying temperature in the range of 60-85°C. The required final moisture content (MC) of a product varies from 6 to 16 % depending on its intended applications. Drying time depends on the wood thickness. This usually takes 7 to 12 days under conventional drying, which is rather time and energy consuming. Many researchers on wood drying have aimed over the years to reduce energy consumption and material losses via many methods, such as, a traditional kiln drying at low temperature (De Boever et al. 2011), accelerated conventional temperature drying (Srivaro et al. 2008), superheated steam (Yamsaengsung and Buaphud 2006), superheated steam vacuum drying (Yamsaengsung and Sattho 2008), microwave drying (Makoviny 2010; Vongpradubchai and Rattanadecho 2009; Du et al. 2005; Hansson and Antti 2003) and combined microwave and hot-air drying (Promtong et al. 2012). Microwave energy application in particular has been investigated due to an advantage on rapidity over conventional methods. Woods investigated yielding successful desirable outcomes include: southern pine strands, softwood, Norway spruce, and Scots pine (Vongpradubchai and Rattanadecho 2009; Du et al. 2005; Hansson and Antti 2003). Although heating by microwave is recognized as a rapid treatment due to directly absorbed electromagnetic energy by the water molecules, it is nonetheless characterized by a certain degree of non-uniformity and edge overheating in temperature distribution with poor product quality. Several studies have also looked at different factors that affect the heating non-uniformity depending on the cavity configuration, material properties, and mode of operation (Li et al. 2011; Marra et al. 2010; Manickavasagan et al. 2006). In addition, the use of microwave power in the relative permittivity and the relative dielectric loss factor of wood depend on the kind of wood, MC, temperature and fiber direction. Especially during heating, wood properties will change, such as incidence of warping, distortions and splits encountered, if the process is not properly controlled. Moreover, the non-uniform airflow effect is particularly difficult to resolve in industrial wood drying kilns (Sun et al. 2004). Airflow patterns have been investigated in conventional heat-and-vent timber kilns to determine appropriate design modifications that will promote more uniform flows and heating (Nijdam and Keey 2002). The influence of fan speed reduction and flow uniformity in a stack during kiln drying was also investigated (Majka 2012). As for another successful alternative, jet impingement has been efficiently employed to achieve uniform temperatures by forced the higher rate of air convection and induced turbulence in drying or dehydration of moist substrates, like food or plates, among other applications (De Bonis and Ruocco 2011; Moreira 2001; Braud et al. 2001). Impinging zone was characterized by Maurel and Solliec (Wahlby et al. 2000) and other studies have also looked at the importance of factors affecting efficiency of jet impingement systems in industrial applications (Sarkar and Singh 2003; Maurel and Solliec 2001). The flow and heat transfer between an impinging jet and impinged surface depends on many parameters such as nozzle-to-wall spacing, Reynolds numbers, distance from the stagnation point or design of the injection. When drying in ovens, the rate of evaporation, surface temperature and property of the product are the most important process parameters, causing desirable localized heating. According to Walhby and Skjoldebrand (2002), heating of buns studied with air velocities varied from 2 to 12 $m.s^{-1}$ in an impingement oven and Xue and Walker (2003) demonstrated how temperature and product loading affected humidity inside an impingement oven. A major advantage of impingement technology, as indicated above, is the higher achievable heat transfer rates. The addition of air impingement oven had one half the required cooking time as compared to the conventional oven (Li and Walker 1996). All these benefits lead to the conclusion that it is of high potential that microwave and impinging hot-air drying are taken into account in the development of wood drying process. Both heating uniformity is a great challenge toward reducing drying times and provide a quality guideline for the industrial wood application. The main objective of this study hence is to explore and charaterize rubberwood drying from an industrial perspective using the two above methods, physical and mechanical properties included. Outcome of the findings is anticipated to be a helpful step in any further investigations on the subject.

MATERIAL AND METHODS

The rubber tree is major economic important plant in the South of Thailand. The rubber tree has been last long for 25 years of age to extract the latex, and consequently, it is cut down. Therefore, all wood samples used in the experiments were sawn from thse rubberwood timbers and were selected only the highest quality and mostly used in the industry. The samples with the length of 1168.4 mm, have minimum length of 935 mm (80 % of the total length) without any defects such as black knots, cracks, black lines, bad fungus, blue stains, bucks and cores, were obtained from Woodwork Advanced Co., Ltd. Songkhla province, Thailand. In each experiment, prepared three sample pieces were together dried with the acceptable space on each piece of wood under limited cavity size. Rubberwood samples that was widely used in furniture, 25.4 thick 1168.4 mm long with width ranging from 25.4 to 101.6 mm, were produced and impregnated with borax-based chemical solution prior to drying. The experimental system, shown in Fig. 1, consists of two heat sources, one for the application of hot-air and the other for the generation of microwave.

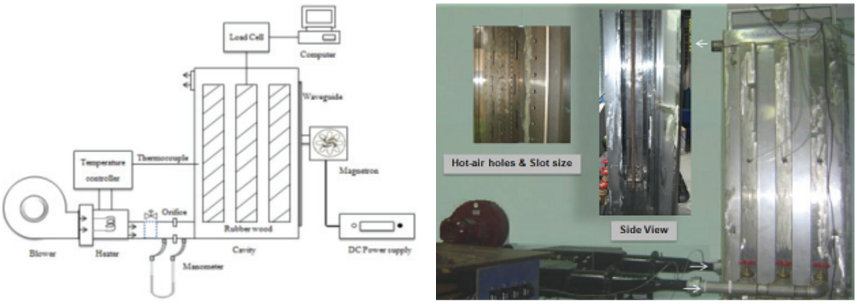

Fig. 1: Schematic diagram of the hot air - microwave dryer.

The laboratory-scale drying chamber cavity has been designed to fit general wood sizes in furniture industries, having an inside dimension, in mm, of 599.44 (width) x 200.66 (depth) x 1501.14 (height). The dual hot-air drying unit with temperature controller consists of a blower, a 3 kW electric heater, and a valve. Each 2 HP 3000 rpm air blower is connected to a 38.1 mm dia. pipe with its shaft fitted with the electric heater. Temperature measurements were conducted employing a thermocouple type K. Hot air was blown through six 38.1 x 38.1 mm rectangular tubes placed at the front and the back of the three vertically fixed samples within the chamber. The orifice of free jet flow has a diameter of 10.16 mm with spacing between the jets of five times the orifice diameter, i.e. every 50.8 mm. During experiment, the Reynold number of the computation is constant at $Re = VjD/\nu = 4.800$ ($T_j = 70.0°C$, $D = 10$ mm, $V_j = 10$ $m.s^{-1}$) that the flow has fully turbulent features. A 0.001 kg precision load cell with a maximum capacity of 5 kg is integrated into the computer system for online weight measurement of the samples. The load cell, with a string holder for continuous weight recording of the sample, is placed on top of the drying chamber to record every 5 min the weight of the middle rubberwood sample. The other two samples were weighed before and after each experiment. Moisture content was calculated based on dry basis. As for the microwave, connected to the other side of the chamber which houses the three samples, the 2.45 GHz device has a maximum power of 200 W. It is operated through a magnetron connected to a power supply. Energy is dissipated through 2 rectangular waveguides situated between the three samples. The drying experiment thus consisted of two parts with a hot-air heating where temperature and jet flow velocity were kept at 60-80°C and maximum 10 m.s^{-1}, respectively, and a microwave heating with a maximum power input of 200 W. The drying design for the 25.4 thick 1168.4 mm long rubberwood samples with varying widths (25.4, 50.8, 76.2 and 101.6 mm) is as follows: 1) hot-air drying of 50.8 mm width samples at temperature of 60-80°C to evaluate the dried rubberwood properties so that the most appropriate temperature with optimum drying time with least defects could be selected to further determine the effects on different width sizes employing the same hot air drying technique, and 2) drying of the rubberwood with varying widths employing the 200 W microwave.

On the surface of each sample, three temperature measurements, one at the center and another two at two evenly-spaced positions along the length, were measured every 2 h with the thermocouple. After the weight became almost constant, physical properties of the dried wood regarding occurrence of drying defects such as cup, bow spring and visual colors were evaluated. Moreover, the dried rubberwood was cut for case hardening to assess initial acceptability through prong test with U bend performance. In addition, mechanical properties on maximum stresses in compression parallel and perpendicular to grain according to ASTM D143 2007, BS 373 2012 and ISO 3787 2004, and shear strength parallel to grain according to BS 373 2012 and ISO 3346 1975 were carried out. Additional measurements were made to evaluate the modulus of elasticity and the modulus of rupture in static bending according to BS 373 2012, and hardness according to ISO 3350 1975. All mechanical tests were performed in triplicates in a temperature and humidity controlled laboratory employing a Lloyd Universal Testing Machine. The average values of mechanical properties obtained from two heat sources were statistically (Student's *t*-test) compared whereas the null hypothesis was that the average of each property into two heat-sources would be same. If the $p\text{-value} > 0.05$, the null hypothesis is true whereas the $p\text{-value} < 0.05$ indicates that the given data failed to prove the null hypothesis and, therefore, there is a change in the property with the different heat source. Besides, the effects of wood width subjected to hot-air drying and microwave drying on mechanical properties were also evaluated by analysis of variance (ANOVA), and then a comparison of the means was done with Tukey's multiple comparison test. All the statistical analyses used a 5 % significance level ($\alpha = 0.05$).

RESULTS AND DISCUSSION

Drying rate

For hot air drying experiments within the 60-80°C temperature range, when the hot air temperature was maintained at 80°C reduction of moisture content from around 55 to 15 % was achieved in approx. 7 h, as depicted in Fig. 2, albeit with excessive bending defects. With temperature maintained at 70 and 60°C, the required final moisture content of 15 % was reached in about 9 and 18 h, respectively, without resulting in excessive defects. For reproducibility test, the drying time of was significantly reduced due to higher moisture evaporation rates with increased temperature level. This result has been reported by several authors (Kechaou and Maalej 2000; Azzouz et al. 2002). However, the operating temperature at 70°C was thus determined to be the most appropriate temperature of the hot air drying technique considering the lesser time of drying while maintaining the desirable physical properties of minimal defects on the dried wood product.

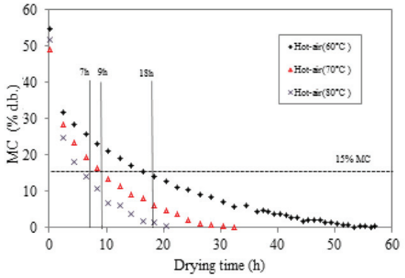

Fig. 2: Drying curve of rubberwood (in mm, 1168.4 long x 25.4 thick x 50.8 wide) by hot-air drying at 60, 70 and 80°C.

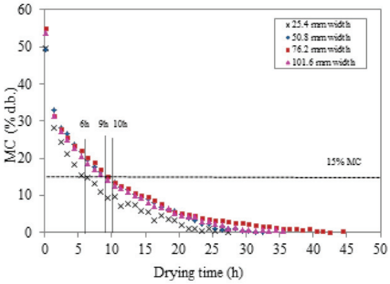

Fig. 3: Drying curve of rubberwood with varying width size for hot-air at 70°C.

The varying width size tests in subsequent experiments were conducted in triplicates under the chosen hot air drying temperature of 70°C and the results are shown in Fig. 3. In this case, the average reduction of the initial moisture content value of 52 % to less than 15 % was reached after 6, 9, 10 and 10 h for the drying widths of 25.4, 50.8, 76.2 and 101.6 mm, respectively. This implies that it is possible to dry 25.4 mm thick rubberwood of size larger than 50.8 mm wide together to attain similar dryness at same time and temperature.

On the other hand, the average time required under the 200 W microwave drying, as evidenced in Fig. 4, from an average initial wood moisture content of 54 to 15 % percent was 16, 20, 26 and 29 h for the 25.4, 50.8, 76.2 and 101.6 mm width samples, respectively. Obviously, as the width of the rubberwood increased, the time required to achieve a certain moisture level increased. The surface temperature of all wood samples were around 40°C after 2 h and increased to nearly 70°C then leveled off until the final moisture contents of the wood samples approached zero under continuous maximum magnetron power output. During drying, the warm-up periods for all samples were almost identical regardless of sample widths. An evaporation period ensued until their surface temperatures increased up to a common plateau. This is plausibly due to certain temperature dependent properties and surface evaporating effects on different rubberwood widths. Due to the air was saturated around wood and oven during drying, results in high humidity inside oven different from hot air circulation heating method and becomes

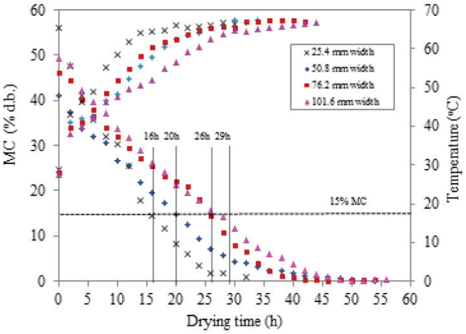

Fig. 4: Drying curve and average temperature change of dried rubberwood with varying width size for microwave drying at 200 W.

less effective evaporation of moisture from the rubberwood. In drying time compared, working at 70°C of impinging hot-air drying instead of at approximate temperature 70°C of microwave drying (200 W), was shortened about 63, 55, 62 and 66 % for the 25.4, 50.8, 76.2 and 101.6 mm width samples, respectively. However, the results at pilot scale indicate that our impinging hot-air and microwave dryings are both faster to dry rubberwood than conventional drying method from 168 h to less than 6-29 h in various wood widths.

Physical properties

After removal from the chamber cavity all samples were visually inspected, as shown in Tab. 1. Each test was conducted with 9 samples (3 samples in triplicates for each width size). Of the 9 samples on the 25.4 mm wide samples subjected to the hot-air (70°C) drying method, 3 pieces exhibited bow-and-spring defect; on the 50.8 mm samples 2 pieces exhibited bow defect; on the 76.2 mm samples 1 pieces exhibited spring defect; on the 101.6 mm samples not one piece exhibited any kind of defects. For the microwave drying (200 W), 4 out of 9 pieces of the 25.4 mm wide samples were rejected with bow-and-spring defect; 4 out of 9 of the 50.8 mm with bow defect; 1 out of 9 of the 76.2 mm with crack defect; and for the 101.6 mm, 1 out of 9 with spring defect plus 1 with bow-and-spring defect. The ends of the 50.8 mm wide dried rubberwood remained relatively flat after being subjected to impinging hot-air at 70°C, as can be visualized in Fig. 5a. In contrast, hot-air at 80°C had an effect, shown in Fig. 5b, in increasing the curvatures at their ends. The color after drying by either hot-air or microwave exhibited minimal changes from the originals. The overall colour apperance on all dried rubberwood surface retained its white-cream (A-1) characteristics, which is the most preferred appearance category. Moreover, results of both drying methods from prong tests revealed no bends to slight bends in the prongs, as depicted in Fig. 6, indicating no residual stresses from drying.

Tab. 1: Physical properties on all dried rubberwood of 9 samples on each width size.

Defects	**Hot-air**				**Microwave**			
	25.4 mm	**50.8 mm**	**76.2 mm**	**101.6 mm**	**25.4 mm**	**50.8 mm**	**76.2 mm**	**101.6 mm**
Bow	-	2	-	-	-	4	-	-
Spring	-	-	1	-	-	-	-	1
Crack	-	-	-	-	-	-	1	-
Bow and Spring	3	-	-	-	4	-	-	1

Fig. 5: Physical property resulted: a) After drying with impinging hot-air at 70°C, b) After drying with impinging hot-air at 80°C.

Fig. 6: Prong test of the dried rubberwood from different width size of the sample: a) 25.4 mm b) 50.8 mm c) 76.2 mm d) 101.6 mm.

Mechanical properties

Results from mechanical properties tests for the hot-air and the microwave dryings are in Tab. 2.

Tab. 2: Results of statistical analysis for the mechanical properties of dried rubberwood.

Property	**Method**	**Width size**			
		1	**2**	**3**	**4**
MOE (MPa)	Hot-air	14868Aa	11146Ba	9690Ba	12264ABa
	Microwave	10919Ab	13962Aa	13767Ab	12400Aa
MOR (MPa)	Hot-air	109.3Aa	97.4Aa	102.8Aa	111.4Aa
	Microwave	102.7Aa	114.0Aa	110.7Aa	113.1Aa
Shear strength parallel to grain (MPa)	Hot-air	17.1Ba	15.9Ba	21.1Aa	17.4Ba
	Microwave	18.6Aa	22.5Ab	19.7Aa	23.6Ab
Compressive strength parallel to grain (MPa)	Hot-air	59.4Aa	44.6Ba	54.0ABa	52.9ABa
	Microwave	52.3Aa	56.0Aa	59.3Aa	63.8Aa
Compressive strength perpendicular to grain (MPa)	Hot-air	15.2Ba	12.1Ba	23.4Aa	15.0Ba
	Microwave	23.8Aa	22.7Aa	17.3Bb	20.9Ab
Hardness (N)	Hot-air	5763.0Aa	5050.0Aa	5991.0Aa	5052.0Aa
	Microwave	7166.1Aa	7051.8Ab	6455.6Aa	6330.6Ab

The ability of wood to resist loads depends on a number of factors, including the type, direction, and duration of loading; ambient conditions of moisture content and temperature; and the presence or absence of defects such as knots and splits. Wood stiffness is generally more significant than wood strength for mechanical performance. In the measure of wood stiffness, the average modulus of elasticity (MOE) value of the 25.4 mm width wood samples subjected to hot-air drying was found to be higher than those of other sizes. Statistical analysis of the mechanical data using paired comparison design (student's t-test) between the impinging hot-air and microwave drying was established and summarized in Tab. 2. Value for the 25.4 mm wood samples under hot-air drying (suffix a) was found to be significantly higher compared with sample subjected to microwave drying (suffix b). In contrast, value for the 76.2 mm width wood samples under hot-air drying (suffix a) has significantly lower compared with sample subjected to microwave drying (suffix b). while for the 2 and 101.6 mm insignificantly different MOE values from both drying methods (suffix a) were obtained. Furthermore, the effects of wood width on the modulus of elasticity were also analyzed with the ANOVA and the Tukey's test. However, before analysis of ANOVA the normality checking of data is important. Fig. 7a displays normal probability plots of the residuals for MOE in hot-air. The good linear fit in this plot indicates that the residuals are close to normally distributed. Likewise, there is no indication of possible outliers, such as faulty experiment cases with particularly large residuals (Montgomery 2009). The plot of residuals vs. fitted values in Fig. 7b exhibits no obvious patterns that would suggest adding the data, to account for that pattern. If the residuals had such structure, the data would not be appropriate (Montgomery 2009). In Tab. 2, the ANOVA revealed that the effect of wood width subjected to hot-air drying significantly (P-value = 0.002) affects the modulus of elasticity.

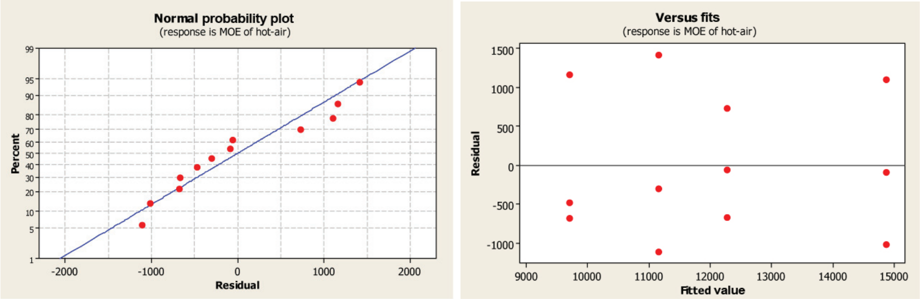

Fig. 7: Normality checking for MOE in hot-air; a) normal probability plot of residuals and b) plot of residuals versus fitted values.

Then, the Tukey's test also indicates that 25.4 mm width wood sample (suffix A) has significantly higher modulus of elasticity than 50.8 and 76.2 mm width samples (suffix B), whereas 25.4 mm width wood sample (suffix A) has insignificantly higher modulus of elasticity than 101.6 mm width wood sample (suffix A). In contrast, the effect of wood width subjected to microwave drying insignificantly (P-value = 0.383) affects the modulus of elasticity. Values of the modulus of rupture (MOR), which is a measure of material breaking strength, for the 25.4 mm, 76.2 mm and the 101.6 mm obtained under hot-air drying were found to be rather similar to that of the corresponding same sizes under microwave drying, while for the 50.8 mm the average of those from hot-air drying was slightly lower than those from microwave drying. There was no significant difference between the impinging hot-air (suffix a) and microwave (suffix a) method to dry rubberwood. MOR and MOE averages for each width size from both drying methods were observed to be higher than the referencing values except for MOR of the 50.8 mm (97.4 MPa) and 76.2 mm (102.84 MPa) under hot-air drying, which were slightly lower than that of the reference value (107.06 MPa), and might be because of variation of wood. Modulus of rupture reflects the maximum load-carrying capacity in bending and is proportional to the maximum moment borne by the specimen. It is also a well-known common accepted strength criterion though it is not a true stress because the formula by which it is calculated is valid only within the elastic range. Nevertheless such comparison of rubberwood data ought to be helpful in furniture design.

For shear strength parallel to grain test, with shear failure typically occurring on both sides of the middle support, the shearing strength values found were mostly higher when subjected to microwave drying than those found under hot-air drying. The average shear strengths in both drying methods were observed to be higher than both reference values for any width sizes. Because wood is highly orthotropic, it is very difficult to get it to fail in shear perpendicular to the grain.

Furthermore, it had been reported that effect of temperature has no significance on the mean MOR, MOE, and on the shear strength, of lumber after drying under high temperature (Thiam et al. 2002). However, this reseach found that there is significant difference at 5 % significance level (α=0.05) between the impinging hot-air (suffix a) and microwave (suffix b) drying at similar temperature (70°C) for the 50.8 and 101.6 mm width samples on shear strength parallel to grain.

For compression strength tests of the rubberwood, these were performed with load applied parallel to, and perpendicular to the grain. The compressive strength parallel to grain values for those subjected to microwave drying were observed to increase with increasing width size. The 25.4 mm width sample in hot-air drying is the only group that exhibited slightly higher value compared with the group subjected to microwave drying. The greatest compressive strength parallel to grain values was found in the 101.6 mm width size and there was no significant difference between two source drying techniques (suffix a). The wood after drying can be used for high constructions works which require high compressive strength parallel to the grain. As for the mean compressive strength perpendicular to grain, it was found that the 25.4 mm width group after microwave drying yielded the highest average value, whereas the results of the 50.8 mm group after hot-air drying yielded the lowest. Values for the 25.4 and 50.8 mm wood samples under hot-air drying (suffix a) have insignificantly lower compared with sample subjected to microwave drying (suffix a), whereas the 76.2 and 101.6 mm width were significantly difference between both drying methods. Compressive strength parallel to the grain is usually much greater than that perpendicular to the grain. Approx. 90 % of the wood cells are aligned vertically (known as grain) and the remaining percentage is present in bands (known as rays). This means that there is a different distribution of cells on the 3 principal axes; this is the main reason for the anisotropy present in timber. Compressive strength of wood perpendicular to the grain is simply a matter of the resistance offered by the wood elements to being crushed or flattened. Therefore, the strength of wood under forces perpendicular to the grain is relatively small. Finally, the mean hardness showed a slight trend to decrease in microwave drying from 25.4 to 101.6 mm width but were higher than those of same sizes under hot-air drying. The effect of the most mean values differences of the 50.8 and 101.6 mm width is statisticially significant in both drying methods. The values of hardness found were all higher than that reported by Yamsaengsung and Buaphud (2006) as well as Killman and Hong (2000), indicating and confirming that rubberwood is sufficiently hard for various furnishing applications.

Results of different width size rubberwood derived from the conducted experiments and tests reveal that all wood sizes after subjected to either drying method, be it hot air or microwave, had higher, and hence better, mechanical properties than reference values; that rubberwood with 25.4 mm width size yielded the highest MOE by hot-air drying method; that compressive strength perpendicular to grain of the 25.4 mm by microwave drying and the 76.2 mm by hot air drying were among the highest; that the 101.6 mm width rubberwood by microwave drying gave the highest MOR, highest parallel-to-grain shear strength, and highest parallel-to-grain compressive strength; and that hardness by microwave drying was highest.

Energy consumption

The energy consumption of hot-air was generated by blower and heater whereas the energy requirement of microwave was consumed by the power delivered to water load. The specific energy consumption (SEC) of wood drying is defined as the energy per unit weight loss of drying process. The SEC values of both techniques were tabulated in Tab. 3.

Tab. 3: Energy consumption of hot air drying and microwave heating.

Heat source	Condition	Width sizes (mm)	Drying time (h)	Energy (kWh)	SEC (MJ.kg^{-1})
Hot air	60°C	50.8	18	0.92	6.11
	80°C	50.8	7	0.36	2.55
	70°C	25.4	6	0.32	4.14
		50.8	9	0.45	3.19
		76.2	10	0.51	2.38
		101.6	10	0.53	2.10
Microwave	200 W	25.4	16	4.1	43.03
		50.8	20	5	28.04
		76.2	26	6.4	23.02
		101.6	29	7.25	19.94

It is obviously found that the SEC values for those subjected to microwave drying were observed to have the higher values than that of hot air, resulting in higher energy requirement for drying process. Also, the SEC values for those subjected to microwave drying or hot air were found to decrease with increasing width size.

CONCLUSIONS

After reaching constant weight, the time required for impinging hot-air drying from an initial wood moisture content range of approximately 54 down to 15 % moisture content is 10 h, which is much less than the 29 h needed for microwave drying under same constraints. The time required to achieve a certain moisture level of rubberwood for both drying methods increases with increasing width size, with hot air method yielding a plateau much sooner. For hot air drying the optimal temperature for drying is 70°C. For microwave drying, the average initial surface temperature of the wood after 2 h is 40°C and subsequently increases to approx. 60-70°C at the center and at the two ends of the wood surface. The average moisture reduction time by hot air drying was 6 and 9 h for drying widths of 25.4 and 50.8 mm whereas 10 h were spent for drying widths of both 76.2 and 101.6 mm, implying that it is possible to dry rubberwood of size larger than 50.8 mm wide together to attain similar dryness at same time and temperature. However, this is not applicable under microwave drying since the time required differs widely; from 16, 20, 26 to 29 h for the 4 corresponding increasing sizes. In addition, the energy consumption of drying process by microwave heating was found much higher than that of hot air. More importantly, both experimental results obtained - though at pilot scale – indicate great potentials of the 2 processes by drastic reduction of drying times, while giving not much sign of residual stresses, retaining natural color of the wood, as well as improving certain mechanical properties of the dried products.

ACKNOWLEDGMENTS

The authors gratefully acknowledge financial support from the Rubberwood Technology and Management Research Group (ENG-54-2-7-11-0137-S) and Prince of Songkla University (ENG550113S), Thailand.

REFERENCES

1. Azzouz, S., Guizani, A., Jomma, W., Belghith, A., 2002: Moisture diffusivity and drying kinetic equation of convective drying of grapes. J. Food Eng. 55(4): 323-330.
2. Braud, L.M., Moreira, R.G., Castell-Perez, M.E., 2001: Mathematical modelling of impingement drying of corn tortillas. J. Food Eng. 50(3): 121-128.
3. De Boever, L., Vansteeenkiste, D., Stevens, M., Van Acker, J., 2011: Kiln drying poplar wood at low temperature: Beam distortion in relation to wood density, tension wood occurrence and moisture distribution. Wood Research 56(2): 245-256.
4. De Bonis, M.V., Ruocco, G., 2011: An experimental study of the local evolution of moist substrates under jet impingement drying. Int. J. Therm. Sci. 50(1): 81-87.
5. Du, G., Wang, S., Cai, Z., 2005: Microwave drying of wood strands. Drying Technology 23(1): 1-16.
6. Hansson, L., Antti, A.L., 2003: The effect of microwave drying on Norway spruce woods strength: A comparison with conventional drying. J. Mater. Process. Technol. 141(1): 41-50.
7. Kechaou, N., Maalej, M.A., 2000: Simplified model for determination of moisture diffusivity of date from experimental drying curves. Drying Technology 18(4-5): 1109-1125.
8. Killman, W., Hong, L.T., 2000: Rubberwood – the success of an agricultural by-product. ftp://ftp.fao.org/docrep/fao/x4565e/X4565E10.PDF. Accessed March, 19, 2013.
9. Li, A., Walker, C.E., 1996: Cake baking in conventional, impingement and hybrid ovens. J. Food Sci. 61(1):188-191.
10. Li, Z.Y, Wang, R.F., Kudra, T., 2011: Uniformity issue in microwave drying. Drying Technology 29(6): 652-660.
11. Majka, J., 2012: The influence of fan speed reduction on airflow uniformity in timber stack during kiln drying. Wood Research 57(3): 479-488.
12. Makoviny, I., 2010: Microwawe drying of wood –cement composites. Wood Research 55(2): 115-124.
13. Manickavasagan, A., Jayas, D.S., White, N.D.G., 2006: Non-uniformity of surface temperature of grain after microwave treatment in an industrial microwave dryer. Drying Technology 24(12): 1559-1567.
14. Marra, F., De Bonis, M.V., Ruocco, G., 2010: Combined microwaves and convection heating: A conjugate approach. J. Food Eng. 97(1): 31-39.
15. Maurel, S., Solliec, C., 2001: A turbulent plane jet impinging nearby and far from a flat plate. Exp. Fluids 31(6): 687-696
16. Montgomery, D.C., 2009: Design and analysis of experiments. 7 ed.: John Wiley & Sons, Inc.
17. Moreira, R.G., 2001: Impingement drying of foods using hot air and superheated steam. J. Food Eng. 49(4): 291-295.
18. Nijdam, J.J., Keey, R.B., 2002: New timber kiln designs for promoting uniform airflows within the wood stack. Chem. Eng. Res. Des. 80(7): 739-744.
19. Promtong, N., Ratanawilai, T., Nuntadusit, C., 2012: Effect of combined microwave heating and impinging hot-air on rubberwood drying. Adv. Mat. Res. 538-541: 2413-2416.
20. Sarkar, A., Singh, R.P., 2003: Spatial variation of convective heat transfer coefficient in air impingement applications. J. Food Sci. 68(3): 910-916.
21. Srivaro, S., Wongprot, T., Matan, N., Kyokong, B., 2008: Accelerated conventional temperature drying of 30 mm thick rubberwood lumber. Songklanakarin J. Sci. Technol. 30(4): 475-483.

22. Sun, F., Carrington, C.G., Anderson, J.A., Sun, Q., 2004: Air flow patterns in dehumidifier wood drying kilns. Chem. Eng. Res. Des. 82(10): 1344–1352.
23. Thiam, M., Milota, M.R., Leichti, R.J., 2002: Effect of high-temperature drying on bending and shear strengths of western hemlock lumber. For. Prod. J. 52(4): 64-68.
24. Vongpradubchai, S., Rattanadecho, P., 2009: The microwave processing of wood using a continuous microwave belt drier. Chem. Eng. Process. 48(5): 997-1003.
25. Wahlby, U., Skjoldebrand, C., Junker, E., 2000: Impact of impingement on cooking time and food quality. J. Food Eng. 43(3): 179-187.
26. Wahlby, U., Skjoldebrand, C., 2002: Reheating characteristics of crust formed on buns, and crust formation. J. Food Eng. 53(2): 177-184.
27. Xue, J., Walker, C.E., 2003: Humidity change and its effect on baking in an elevetrically heated anir jet impingement oven. Foor Res.Int. 36(6): 561-569.
28. Yamsaengsung, R., Buaphud, K., 2006: Effect of superheated steam on the drying of rubberwood. Songklanakarin J.Sci. 28(4): 803-816.
29. Yamsaengsung, R., Sattho, T., 2008: Superheated steam vacuum drying of rubberwood. Drying Technology 26(6): 798-805.

Thanate Ratanawilai, Chayut Nuntadusit, Nuchtida Promtong
Prince of Songkla University
Faculty of Engineering
Department of Industrial Engineering
Hat Yai
Songkhla 90112
Thailand
Corresponding author: thanate.r@psu.ac.th