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Microwave and Hot Air Drying of Wood Using a Rectangular Waveguide

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In this study, the microwave and hot air drying of wood using a rectangular waveguide (TE_{10} mode) were investigated experimentally. Most important, this study focuses on the investigation of drying phenomena under a microwave environment. In this analysis, the effects of the irradiation time, hot air temperature, sample thickness, and microwave power level on overall drying kinetics were studied. The results showed that the variations of irradiation time, microwave power level, hot air temperature, and sample thickness played an important role in overall drying kinetics. These findings are significant for further research in similar studies. Further quantitative validation of experimental data could be very useful, especially in providing information for developing high-performance microwave drying processing.

Keywords Drying; Microwave; Porous media; Rectangular waveguide; Wood

INTRODUCTION

The drying of wood is the most energy-intensive and costly process in the forest products industry. Conventional wood dryers function under the basis of convective heat transfer from circulating hot air to the surface of wood, followed by subsequent conductive heat transfer from the surface to the center of wood. These dryers require a considerable amount of energy and long drying times in order to obtain high-quality woods. Therefore, innovative wood drying methods have been researched and studied. Unlike conventional heating, where heat is applied externally to the surface of the material, microwave irradiation penetrates and simultaneously heats the bulk of the material. When properly designed, microwave drying systems offer several advantages over several mechanical methods, including reduction of drying time, high energy efficiency, and improvements in product quality for various industrial applications.[1–21] Microwave drying of wood products, however, has not been used to a larger extent in wood industries due to insufficient knowledge of the complex interaction between wood structure and drying process parameters as well as the higher investment expenses. Recently the development of inexpensive and reliable microwave sources has been of increasing attraction to applications in the wood industry.

Microwave drying is one of the most interesting methods for drying materials. The application of volumetric heating could decrease the gradients of temperature and moisture during drying, resulting in an increase in the rate of heat transfer in wood. During the past decade, there have been many successful examples of microwave applications, including the heating and drying of foods, drying of textiles, freeze-drying processes, heating and drying of ceramics, heating and drying of concrete, vulcanizations of rubber, and drying of wood. A number of analyses of the microwave heating process have appeared in the recent literature.[1–34] Excellent reviews of the drying techniques in dielectric materials using microwave energy have been presented by Mujumdar,[1] Metaxas and Meridith,[2] and Schubert and Regier.[3] Investigations on microwave drying of wood have been performed in the last 20 years. Many authors[22–26] have emphasized the advantages of microwave drying over convective drying. Turner[26] pointed out the suitability of combined microwave and convective drying for evaporation of water out of wood. However, there still remain obstacles to be overcome in applying microwave drying technology to the wood industry. One of the difficulties is that the microwave power absorbed by moist wood depends mainly on the moisture content, and this absorbed power is required to move the water out of the wood for uniform power distribution with an on–off type of microwave system at fixed power output. Moschler and Hanson[33] developed a prototype microwave-based moisture sensor system suitable for the kiln drying of hardwood lumber. Li et al.[34] studied the mechanism of moisture and heat transfer within wood during microwave–vacuum drying (MVD), and a

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one-dimensional mathematical model to describe the process of wood MVD was established and verified by numerous experiments.

In this study, microwave and hot air drying of wood are investigated experimentally using a rectangular waveguide at an operating frequency of 2.45 GHz. Microwave power level, hot air temperature, and sample thickness are taken into account to study the effects of drying phenomena taking place.

THE RELATED THEORY

Drying with Microwave Energy

In convective drying, dry air is used to take away surface water saturation from the dried sample, therefore creating a pressure gradient between the surface and inner part, which causes moisture migration from inside the sample to the surface. In this process, the temperature gradient will enhance the ability of dry air to remove water from the surface and increase the moisture migration rate within the sample. But there are many disadvantages with this method. Among these are low energy efficiency and lengthy drying time during the falling rate period. This is mainly caused by rapid reduction of surface moisture and consequent shrinkage, which often results in reduced heat transfer.

Unlike conventional heating, where heat is applied externally to the surface of the material, microwave irradiation penetrates and simultaneously heats the bulk of the material. During applied microwave energy, the resonance effect can occur inside the material, which results in the field distribution not having an exponential decay from the surface. In some cases the highest field strength, and therefore power density, can actually occur in the center of the sample. This is caused by the interference of waves reflected from the back side of the sample. This mechanism pushes moisture out of the product with great efficiency, as the moisture content of the product decreases. When properly designed, microwave drying systems have several advantages over conventional mechanical methods, including reducing the drying times, high energy efficiency, and offer improvements in product quality for various industrial applications.

Fundamental Equation of Heat Generation with Microwave

Dielectric materials absorb and alter microwaves to heat energy, which is called *density of microwave power absorbed* (Q) and relates to electric field and magnetic field.[2] In analysis of dielectric heating, the root mean square value of the electric field intensity E is normally used to evaluate the microwave energy absorbed. Thus, the microwave energy absorbed or local volumetric heat generation term can be defined as Eq. (1):

$$Q = \varpi \varepsilon_0 \varepsilon_r'' E^2 = 2\pi f \varepsilon_0 \varepsilon_r' (\tan\delta) E^2 \quad (1)$$

where E is the electric field intensity, dependent upon position; f is the microwave frequency; ω is the angular velocity of microwave; ε_r' is the relative dielectric constant, which described energy absorption, transmission, and reflection at the microwave electric field; ε_0 is the permittivity of air; and tan δ is the loss tangent coefficient that indicates the ability of the product to absorb microwave energy.

Corresponding to Eq. (1), in the case of the amount of impact of tan δ, a lack of specimen penetration by the microwave without heat generation lowered the loss tangent coefficient, thus decreasing its impact on the absorbed microwave energy and volumetric heating. However, this could change at higher temperatures depending on relevant variables such as specific heat capacity and the characteristics and size of the material.

When the material is heated unilaterally, it is found that as the dielectric constant and loss tangent coefficient can vary, the penetration depth will be changed and the electric field within the dielectric material is altered. The penetration depth is used to denote the depth at which the power density has decreased to 37% of its initial value at the surface.[20]

$$D_p = \frac{1}{\frac{2\pi f}{\upsilon}\sqrt{\frac{\varepsilon_r'\left(\sqrt{1+\left(\frac{\varepsilon_r''}{\varepsilon_r'}\right)^2}-1\right)}{2}}} = \frac{1}{\frac{2\pi f}{\upsilon}\sqrt{\frac{\varepsilon_r'\left(\sqrt{1+(\tan\delta)^2}-1\right)}{2}}} \quad (2)$$

where D_P is the penetration depth, ε_r'' is the relative dielectric loss factor, and υ is the microwave speed. The penetration depth of the microwave power is calculated according to Eq. (2), which shows how it depended on the dielectric properties of the material. It is noted that products with huge dimensions and high loss factors may occasionally overheat a considerably thick layer on the outer layer. To prevent such phenomenon, the power density must be chosen so that enough time is provided for the essential heat exchange between the boundary and core. If the thickness of the material is less than the penetration depth, only a fraction of the supplied energy will be absorbed. Furthermore, the dielectric properties of wood specimens typically showed moderate loss depending on the actual composition of the material. A greater amount of moisture content revealed a greater potential for absorbing microwaves. For all wood specimens, a decrease in the moisture content typically decreased ε_r'', accompanied by a slight increment in D_P.

EXPERIMENTAL SETUP

The experimental apparatus is shown in Fig. 1. The microwave system is a monochromatic wave of TE_{10}

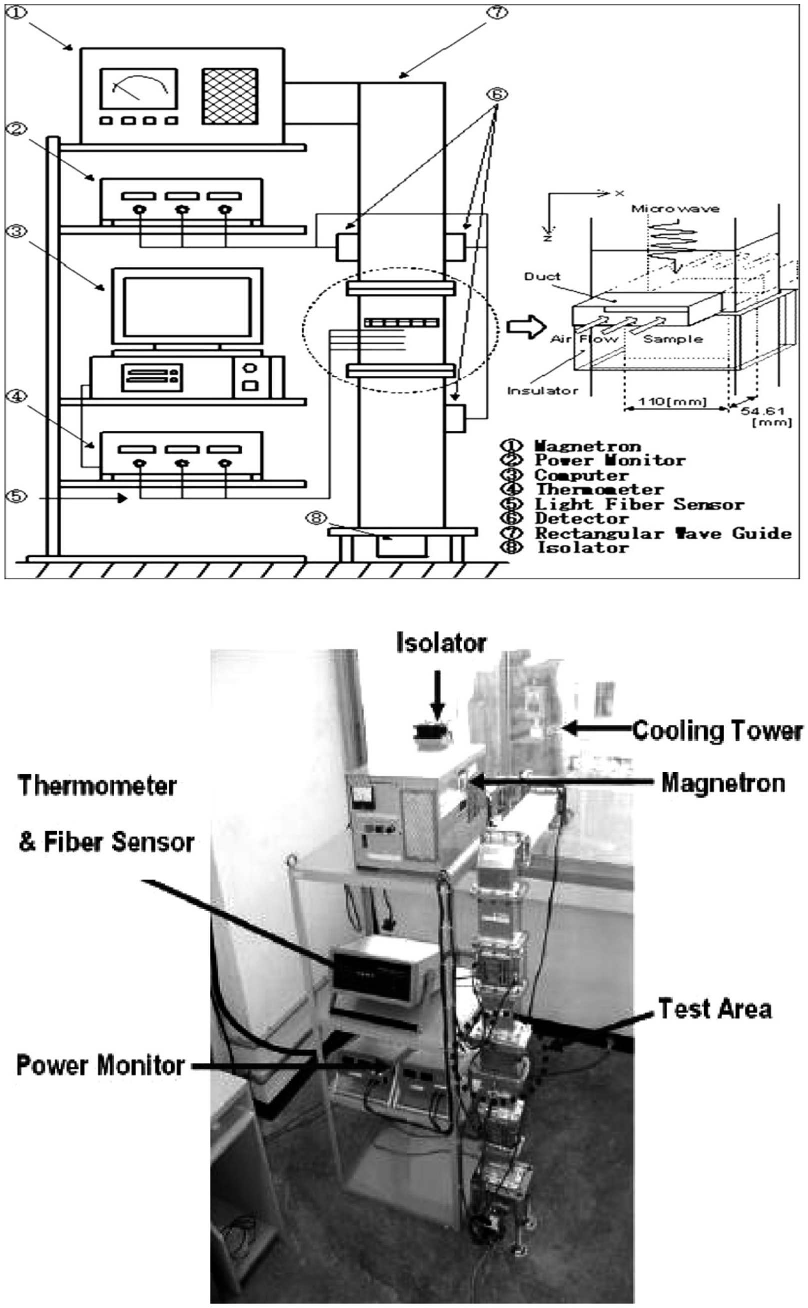

FIG. 1. Microwave using a rectangular waveguide.

mode operating at a frequency of 2.45 GHz. Microwave is generated by magnetron and is transmitted along the z-direction of the rectangular waveguide with inside dimensions of $109.2\,\text{mm} \times 54.61\,\text{mm}^2$ toward a water load that is situated at the end of the wave guide. On the upstream side of the sample, an isolator is used to trap any microwave reflected from the sample to prevent the microwave from damaging the magnetron. The powers of incident, reflected, and transmitted waves are measured by a wattmeter using a directional coupler (model DR-5000, Micro Denshi, Japan). The microwave power input can be adjusted in the range of 0–1500 W. The microwave leakage is controlled below the U.S. Department of Health and Human Services' (DHHS) standard of 5 mW/cm^2. Figure 2 illustrates the positions of the microwave power measurement that consist of incident wave (A), reflected wave (B), transmitted wave (C), and reflected wave from the dummy load (D). According

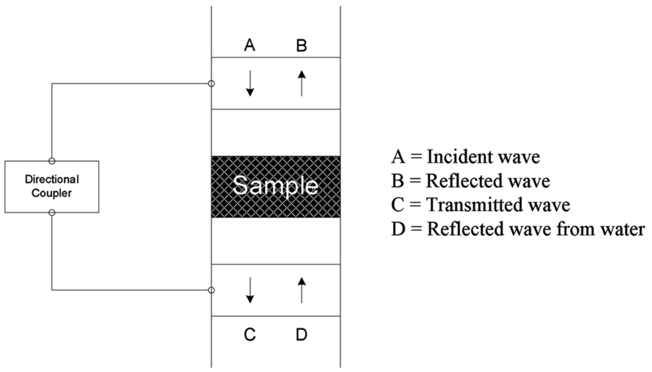

FIG. 2. Microwave power measurement.

to Fig. 2, the microwave power absorption can be estimated from Eq. (3):

$$\text{Microwave power absorption} = A - B - C + D \quad (3)$$

A fiber-optic thermometer (Fluoroptic, model 790, accurate to ±0.5°C, Luxtron, Santa Clara, CA) is employed for the temperature measurement. The fiber-optic probes are inserted into the center of sample with positions of 5, 15, and 25 mm, which measure from the surface of sample, as shown in Fig. 3. The hot air, generated electrically, travels through a duct toward the upper surface of the sample situated inside the test section. The outside walls of the test section are covered with insulation in order to reduce heat loss to the ambient. The flow outlet and temperature can be adjusted at a control panel.

The wood samples as received having initial temperature and moisture content of 28°C and 90% (dry basis), respectively, are naturally selected. The wood samples are prepared in two different thicknesses, namely, with dimensions of 108 mm × 53 mm, 50 mm (thickness), and 108 mm × 53 mm, 80 mm (thickness), respectively. The wood samples are filled in a polypropylene container with a thickness of 1 mm that does not absorb microwaves.

The dielectric properties for wood samples are measured at 25°C using a portable dielectric network analyzer (μWaveAnalyzer, Püschner, Bremen, Germany) over a frequency band of 1.5–2.6 GHz as shown in Fig. 4. The portable dielectric measurement kit allows for measurements of the complex permittivity over a wide range of

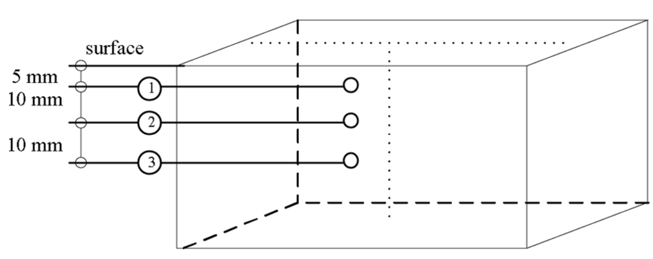

FIG. 3. Positions of temperature measurement.

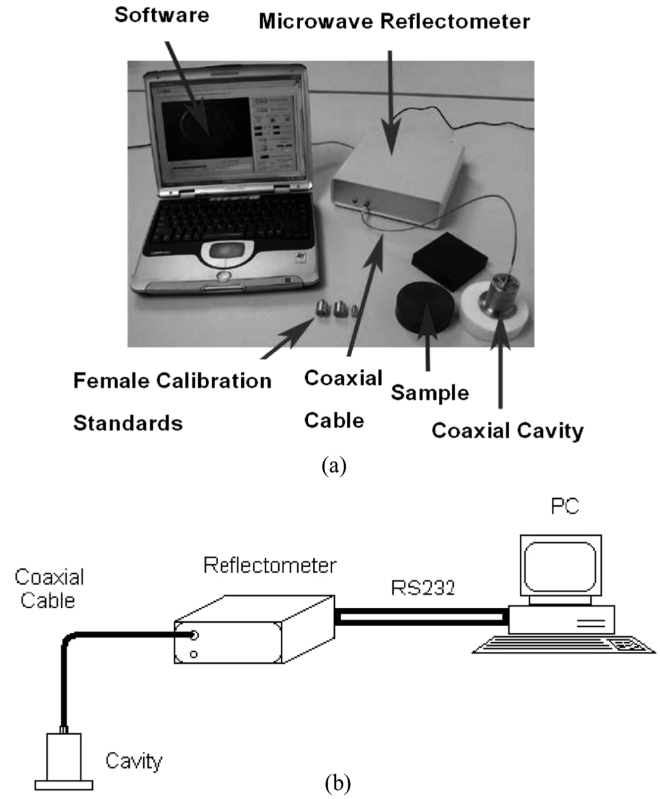

FIG. 4. Portable dielectric network analyzer.

solid, semi-solid, granular, and liquid materials. It performs all of the necessary control functions, treatment of the microwave signals, calculation, data processing, and results representation. The software controls the microwave reflectometer to measure the complex reflection coefficient of the material under test (MUT). Then it detects the cavity resonant frequency and quality factor and converts the information into the complex permittivity of the MUT. Finally, the measurement results are displayed in a variety of graphical formats or saved to disk.

In this study, the uncertainty in the results might come from the variations in humidity, room temperature, and human error. The uncertainty in drying kinetics is assumed to result from errors in the measuring weight of the sample. The calculated uncertainties in weight in all tests are less than 2.78%. The uncertainty in temperature is assumed to result from errors in adjusting input power, ambient temperature, and ambient humidity. The calculated uncertainty associated with temperature is less than 2.82%.

RESULTS AND DISCUSSION

In this section, the effects of various parameters on drying kinetics are investigated. The results are divided into three parts: the first part is the effect of microwave power level, the second part is the effect of hot air temperature, and the last part is the effect of sample thickness.

Effect of Microwave Power Level

Figure 5 shows the temperature and moisture profiles with respect to elapsed time as parameters of microwave power level ($P = 50$ W and $P = 100$ W) with fixed the sample thickness ($z = 50$ mm) and hot air temperature ($T_\infty = 40°C$). It is found that at a high microwave power level, the temperature profile of the wood continuously rises faster than that in the case of low microwave power level. On the other hand, at a high microwave power level, the moisture profile of the wood continuously decreases faster than that in the case of low microwave power level. This is because in the case of high microwave power level, the bulk of wood receives the largest amount of microwave power, which would correlate to microwave energy absorbed and depends on the changing in the configuration of electric field in the wood due to the variation of moisture contents,[16] which is shown in Fig. 6. The microwave power absorption can be roughly estimated by using Eq. (3) where it is divided by unit volume of wood (W/m^3). The distributions of temperature and moisture profiles within wood sample at various positions ($z = 5$, 15, and 25 mm) are illustrated in Figs. 5a, 5b, and 5c, respectively. Figure 5a shows the effect of microwave power level on temperature and moisture profiles. As shown in Fig. 5a, temperature profiles within the wood sample rise up rapidly to about 100°C and about 115°C for powers of 50 and 100 W, respectively, during 0–30 min. This is because of the large moisture content, which corresponds to a higher dielectric loss factor. In this stage, a majority of the microwave can be absorbed within the wood sample as shown in Fig. 6. As the drying proceeds (30–150 min), the moisture content decreases because a majority of the moisture content is removed from the wood

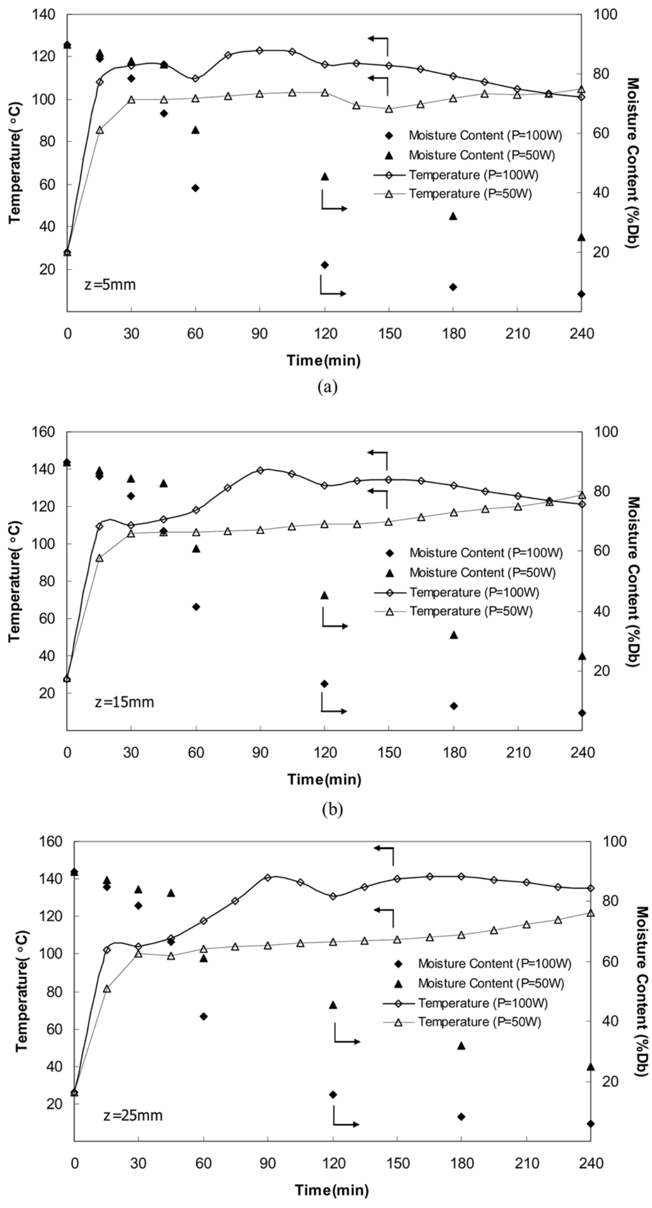

FIG. 5. Temperature and moisture profiles with respect to elapsed time; $T_\infty = 40°C$, sample thickness of 50 mm: (a) $z = 5$ mm; (b) $z = 15$ mm; and (c) $z = 25$ mm.

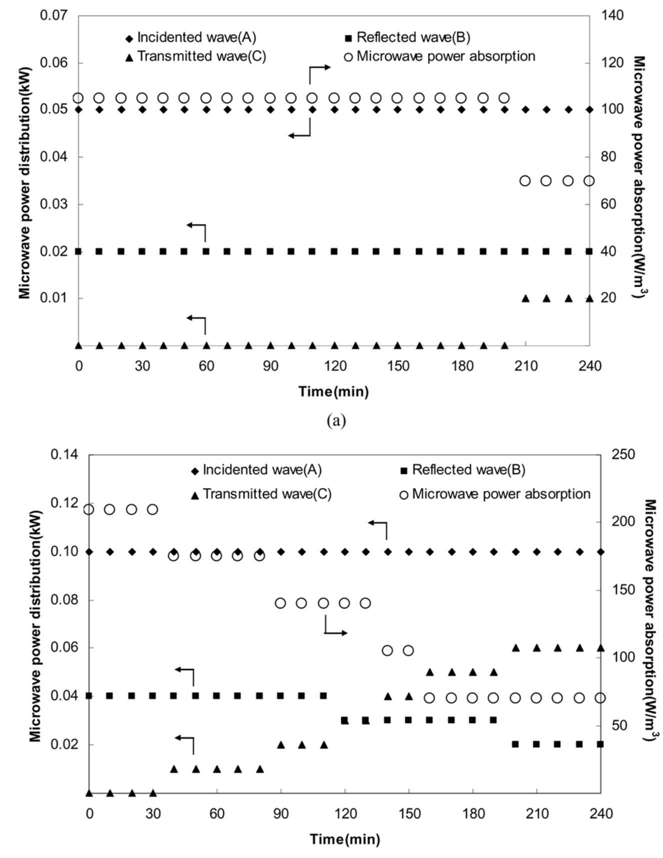

FIG. 6. Microwave power distribution and microwave power absorption with respect to elapsed time; $T_\infty = 40°C$, sample thickness of 50 mm: $P = 50$ W; $P = 100$ W.

and consequently leads to a decrease in microwave power absorption with increasing transmitted wave (Fig. 6). During this stage of drying, the dielectric properties are significantly affected by moisture content. At about 150 min, the temperature distribution for microwave power level of 100 W starts to drop because the moisture content and dielectric loss factor are decreased, along with microwave power absorption, as shown in Fig. 6. Nevertheless, near the end of the drying process the moisture content is reduced continuously because the water content inside the wood is removed. This decreases the microwave power absorption within the wood sample. Thus, equilibrium is reached between microwave drying and convective losses by lowering the wood temperature.

Figure 7 shows the temperature and moisture profiles with respect to elapsed times in the case of $P = 100\,\text{W}$, $T_\infty = 40°\text{C}$, and sample thickness $z = 50\,\text{mm}$ of different positions (z-direction). At the early stages (0–50 min), temperature is highest at the leading edge of the wood sample ($z = 5\,\text{mm}$) because of the strong effect of convective drying together with microwave energy absorption when both types of energy are supplied simultaneously where the leading edge of the wood sample is still wet. As the drying process process (50–240 min), the temperature at the center of wood sample ($z = 25\,\text{mm}$) is higher than in other parts. This is because the microwave is uniformly generated further inside the wet region of the wood sample where the leading edge of the wood sample is totally dried. The latterarises from the fact that the dielectric loss factor as well as microwave power absorption in the dry region are low, corresponding to a lower temperature in this region. In the early stages of drying, the large moisture content while corresponds to a higher dielectric loss factor. A majority of the microwave can be absorbed within the wood sample as shown in Fig. 6. The capillary action plays an important role in the moisture migration mechanism and maintains a good supply of liquid to the surface. Continued drying would cause the average moisture content inside the wood sample to decrease and leads to decreased microwave power absorption. Nevertheless, during long stages of drying, the vapor diffusion effect plays an important role in the moisture migration mechanism because of the sustained vaporization that is generated within the wood sample.

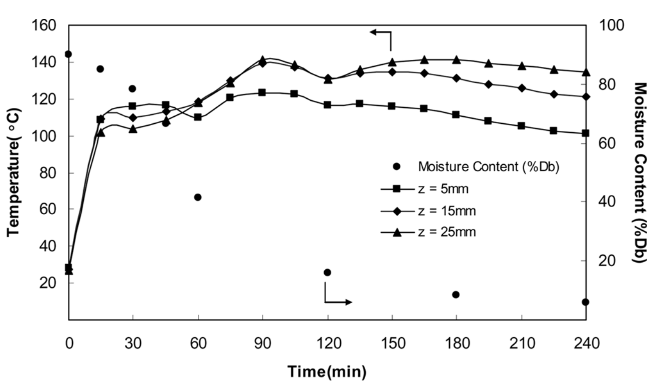

FIG. 7. Temperature and moisture profiles with respect to elapsed time; $T_\infty = 40°\text{C}$, sample thickness of 50 mm, $P = 100\,\text{W}$.

Effect of Hot Air Temperature

Figure 8 shows the temperature and moisture profiles with respect to elapsed times as parameters of hot air

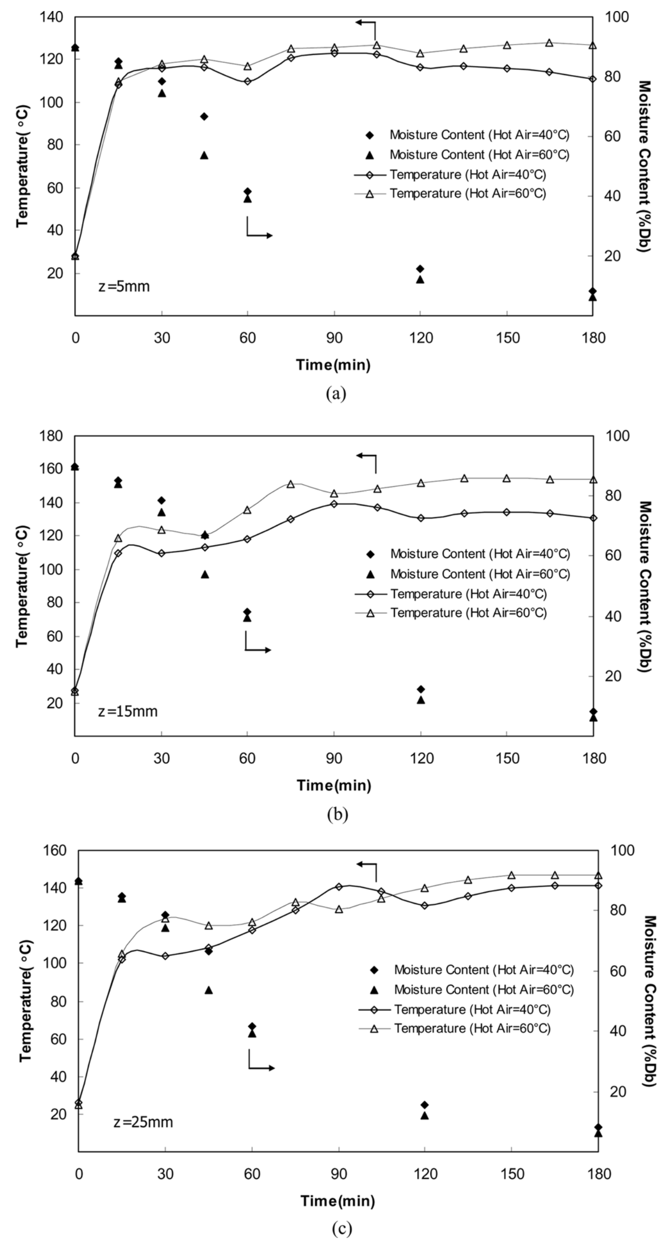

FIG. 8. Temperature and moisture profiles with respect to elapsed time; $P = 100\,\text{W}$, sample thickness of 50 mm: $z = 5\,\text{mm}$; $z = 15\,\text{mm}$; and $z = 25\,\text{mm}$.

temperature ($T_\infty = 40°C$ and $T_\infty = 60°C$) with fixed microwave power level ($P = 100$ W) and sample thickness ($z = 50$ mm). It is found that at a high hot air temperature, the temperature profile of the wood sample continuously rises faster than that in the case of low hot air temperature. The reason is that in the case of high hot air temperature, convective drying is strong while the microwave energy is still supplied. For the moisture profile, in the early stages of drying, the large moisture content corresponds to a higher dielectric loss factor. A majority of the microwave can be absorbed within the wood sample as shown in Fig. 9. When the drying time increases, the microwave power absorption is lowered because the moisture content decreases. This result is due to the influence of capillary pressure and vapor diffusion, which drives the moisture to the sample surface of wood sample. Figures 8a, 8b, and 8c display the profiles of temperature and moisture within the wood sample at various positions ($z = 5$, 15, and 25 mm). Figure 8a shows the effect of hot air temperature on temperature and moisture profiles. As seen in Fig. 8a, convection carries the water from the inside to the leading edge of the wood sample and microwave is simultaneously used to heat inside the wood sample. At this stage the microwave power absorption is high and the transmitted wave is zero as shown in Fig. 9. This is because the moisture content is high, corresponding to the higher dielectric loss factor. Furthermore, near the end stage of the drying process as the moisture content inside the wood is reduced, the microwave power absorption decreases accordingly.

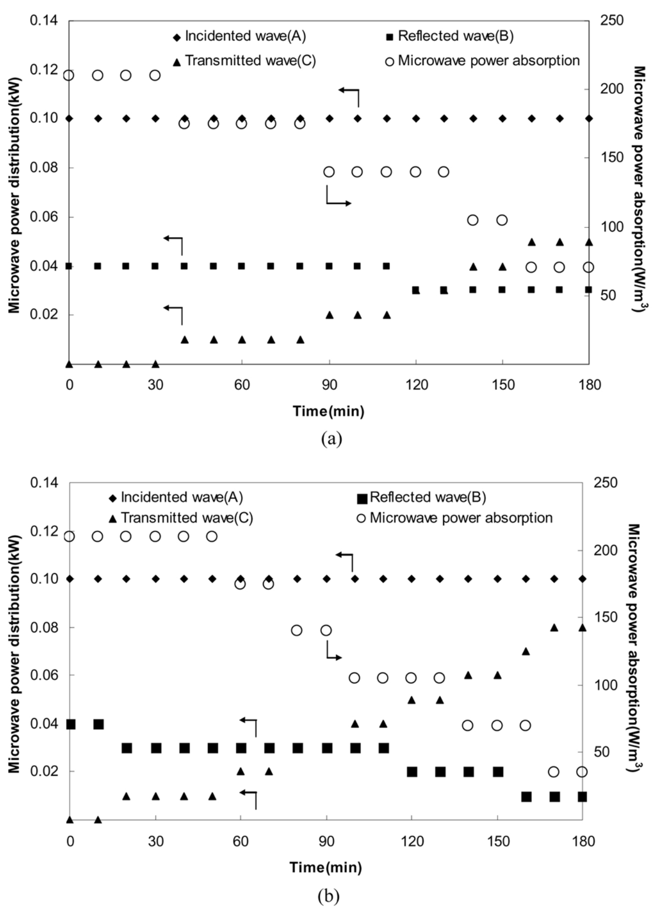

FIG. 9. Microwave power distribution and microwave power absorption with respect to elapsed time; $P = 100$ W, Sample thickness of 50 mm: (a) $T_\infty = 40°C$ and (b) $T_\infty = 60°C$.

Figure 10 shows the temperature and moisture profiles with respect to elapsed times in the case of $P = 100$ W, $T_\infty = 60°C$, and sample thickness ($z = 50$ mm) of different positions (z-direction). Considering the same microwave power level and thickness of the wood sample, it is observed that the temperature is highest at $z = 15$ mm. This may be due to the optimum balanced between microwave supplied energy and the hot air convective side. This point is very interesting for future research on the combined microwave and hot air drying process. In the early stages of drying, the large moisture content while corresponds to a higher dielectric loss factor. A majority of the microwave can be absorbed within the wood sample as shown in Fig. 9. As the drying process proceeds, the microwave power absorption would eventually decrease due to the characteristics of the moisture profile as shown in Fig. 7.

Effect of Sample Thickness

Figure 11 shows the temperature and moisture profiles with respect to elapsed times as parameters of sample thickness ($z = 50$ and 80 mm) with fixed the microwave power level ($P = 100$ W) and hot air temperature ($T_\infty = 40°C$). The temperature distribution shows a clear evidence of wavy behavior. During the first stage the temperature profile of thin wood continuously rises faster than in the case of thick wood. This is because of the effect of stronger resonance when the ratio of sample thickness and penetration depth is small. As the drying process

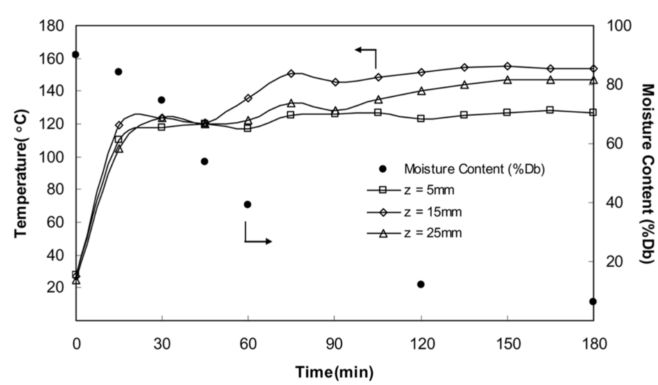

FIG. 10. Temperature and moisture profiles with respect to elapsed time; $P = 100$ W, sample thickness of 50 mm, $T_\infty = 60°C$.

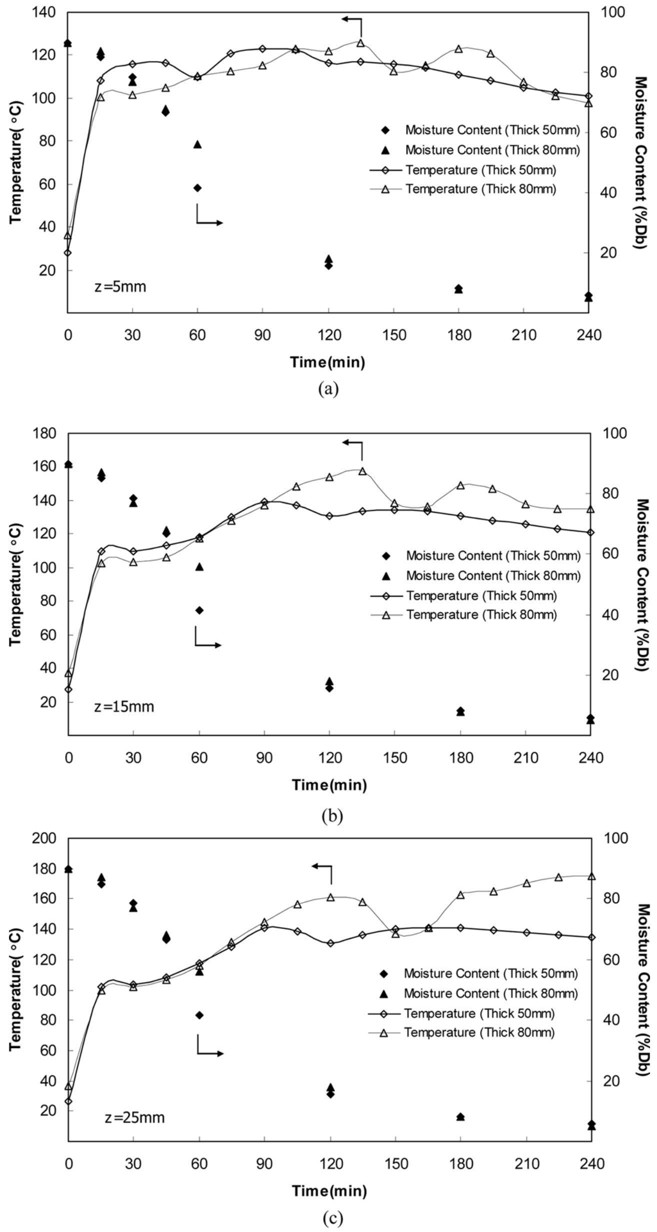

FIG. 11. Temperature and moisture profiles with respect to elapsed time; $P = 100$ W, $T_\infty = 40$°C: $z = 5$ mm; (b) $z = 15$ mm; and (c) $z = 25$ mm.

proceeds (100–240 min), the temperature profile in the case of thick wood rises faster than in the case of thin wood. This is because the thick wood, where the moisture content still remains in the lower region of wood sample, can absorb the microwave power for a longer time as compared to the thin wood. Thus, the stronger interaction between the moist sample and resonance effect remains in case of the thick wood, as opposed to the case of the thin wood, where the moisture content is very low. The microwaves can easily transmit through the dried wood sample. The temperature and moisture profiles within the wood sample at various positions ($z = 5$, 15, and 25 mm) are shown in

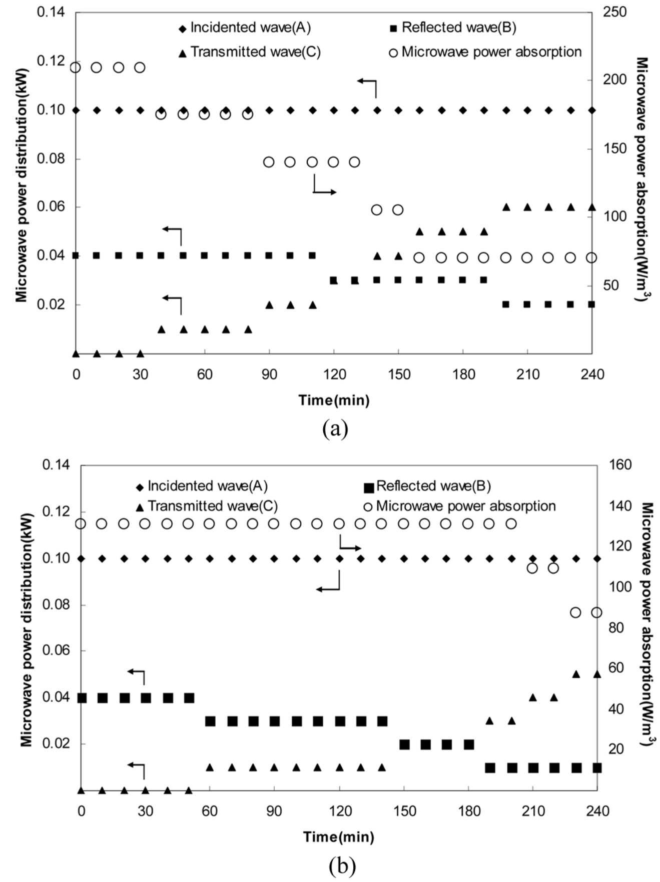

FIG. 12. Microwave power distribution and microwave power absorption with respect to elapsed time; $P = 100$ W, $T_\infty = 40$°C: (a) sample thickness of 50 mm and (b) sample thickness of 80 mm.

Figs. 11a, 11b, and 11c, respectively. Figure 11a shows the effect of sample thickness on temperature and moisture profiles. During the first stage, the temperature profile within wood sample rises up rapidly in bothcases. Because of the large moisture content, a majority of the microwaves can penetrate into the wood sample, resulting in high microwave power absorption, as shown in Fig. 12. For the next stage (around 60–120 min), the percentage of moisture content of the thin wood is decreased faster than the thick wood, as shown in Table 1, with the drying rate of the thin wood ($\approx 0.3\%$/min) higher than that of the thick wood ($\approx 0.2\%$/min). However, the result in this case due to the bulk of thin wood displays the largest amount of energy absorbed, which correlates with the penetration depth and depends on the configuration of the electric field as well as the wavelength inside the wood sample. It is observed that the strong resonance of the waves causes a wavy temperature profile in the thick wood. Furthermore, near the end stage of the drying process, the moisture content inside the wood is reduced. This decreases the microwave power absorption and the penetration depth of the dried wood is increased as shown in Table 2.

TABLE 1
Summary of drying kinetics

Microwave power level (W)	Sample thickness (mm)	Hot air temperature (°C)	Initial moisture content (% dry basis)	Final moisture content (% dry basis)	Drying rate (%/min)
50	50	40	90	30	0.19
	50	60	90	30	0.27
	80	40	90	20	0.15
	80	60	90	20	0.21
100	50	40	90	8	0.29
	50	60	90	8	0.48
	80	40	90	6	0.23
	80	60	90	6	0.44

TABLE 2
Dielectric properties of wood sample and penetration depth

	Data			
	Relative dielectric constant (ε'_r)	Relative dielectric loss factor (ε''_r)	Loss tangent coefficient (tanδ)	D_p (m)
Present study	1.591	0.033	0.021	1.470
Lehne et al.[25]	2.419	0.036	0.015	1.669
Datta and Anantheswasan[4]	1.5–4	0.015–0.04	0.01	1.946–3.178
Buffer[27]	1.2–5	0.02–0.5	0.017–0.417	0.174–2.090

Figure 13 shows the temperature and moisture profiles with respect to elapsed times in the case of $P = 100$ W, $T_\infty = 40$°C, and sample thickness ($z = 80$ mm) of different positions (z-direction). At the early stage of drying (0–60 min), temperature inside the wood sample is similar throughout. It is strongly affected by forced convective drying associated with microwave absorbed during simultaneous energy supply. In addition, the top surface of the sample is still wet. As drying proceeded (60–240 min), the temperature at the center of the wood sample ($z = 25$ mm) increased more than those of the other positions. This is because microwave energy directly penetrates and then generates heat within the wood sample. Furthermore, the moisture profiles of the wood sample as illustrated in Fig. 13 decrease with increased drying time. Thus, the drying process can cause a decrease of moisture content inside the sample, and consequently decrease microwave energy absorption within the sample as shown in Fig. 12.

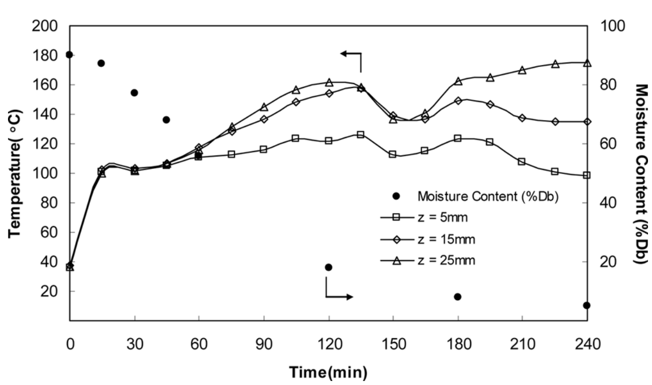

FIG. 13. Temperature and moisture profiles with respect to elapsed time; $P = 100$ W, sample thickness of 80 mm, $T_\infty = 40$°C.

CONCLUSIONS

The experiment of microwave and hot air drying of wood using a rectangular waveguide has been conducted. The following paragraph summarizes the conclusion of this study.

1. The effects of microwave power level, hot air, and sample thickness on the microwave power absorption, temperature, and moisture profiles within the wood sample are clarified in detail.
2. The drying rate of the wood sample strongly depends on the microwave power level and hot air temperature. The drying rate increases as the microwave power level and hot air temperature increase. This is because the

electromagnetic heat generation is proportional to the electric field intensity and stronger convective heating.

3. The effect of sample thickness corresponds to the microwave power absorption, especially when the wood has a larger volume. The thicker wood is able to absorb the microwave power for a longer drying time. Then the effect of strong resonance results in wavy temperature distribution.

This knowledge is fundamental to understanding the drying process using combined microwave energy and convective hot air and to aid researchers in understanding the basis of drying in porous media and can be applied in the industrial field.

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