Measurements of Thermal and Dielectric Properties of Medium Density Fiberboard with Different Moisture Contents

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The thermal and dielectric properties of medium density fiberboard (MDF) with different moisture contents were measured by light flash and the parallel-plane capacitor method, respectively. The results show that increasing moisture content has a positive effect on both thermal properties and dielectric properties. The higher the moisture content, the higher the thermal conductivity and dielectric properties were. The thermal conductivity of MDF with different moisture contents varies in the temperature range of 25 to 150 ºC in a double-hump pattern rather than a proportional pattern. The dielectric constant decreases with increasing frequency up to 1000 MHz. The dielectric loss factor undulates within the frequency range of 1 to 100 MHz, and the peak value occurs at around 10 MHz. The results presented in this study can be used for radio frequency heating, wood building energy, material design, and radio frequency evaluation.

Keywords: Moisture content; Thermal properties; Dielectric properties; Temperature dependence; Frequency dependence

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INTRODUCTION

Medium density fiberboard (MDF) is widely used as an engineered wood product for construction and furniture-making because of its favorable physical and mechanical properties, ease of machining, ready availability, and cost effectiveness. Thin MDF panels are often used as a substrate to produce curved laminated furniture components by hot pressing with radio-frequency heating. However, this important industrial practice is still based on empirical knowledge. Around 5.0% of the final products have malfunctioned due to dimensional stability, according to the data collected by authors within the Pear River delta area in China. It is of great importance, but challenging to understand the effects of hot-pressing time, temperature, and pressure on the mechanical behaviors and quality of this type of final product. One of the challenging issues is the accurate evaluation of heat and mass transfer during hot pressing with radio frequency because there is no an effective way to measure the temperature and its distribution inside a sample. Numerical simulation of this hot-pressing process with radio frequency may be a feasible, inexpensive, and effective way for manufacturers to optimize processing parameters, reduce cost, and improve product quality (Zombori *et al.* 2001). Knowledge of thermal conductivity plays an important role in predicting heat transfer in wood during its processing as well as during the use of wood products (Olek *et al.* 2003). The dielectric properties are necessary for the calculation of the energy required to drive the temperature change during radio frequency heating. Intensive studies have reported that the thermal properties of solid wood are affected by wood species, grain angle, density, temperature, anatomic and morphological properties of wood structure, and moisture content (Kol 2009; Forest Products Laboratory 2010; Yapici *et al.* 2011). A linear equation for thermal conductivity of solid wood as a function of density and moisture content as well as the thermal conductivity and specific heat of wood building materials was provided in order to improve energy design of wood frame buildings and the evaluation of their performance (TenWolde *et al.* 1988). The thermal properties of wood in the green state have been determined by the transient plane source technique recently with linear relationship between the thermal properties and moisture content (Dupleix *et al.* 2005). In addition, the dielectric properties of wood are strongly influenced by wood species, density, moisture content, grain direction, temperature, and frequency (Torgovnikov 1993; Olmi *et al.* 2000; Daian *et al.* 2005). There have been only limited studies on the thermal and dielectric properties of wood-based materials. The thermal conductivity of wood-based fibers and particle panel materials and the effects of wood-based panel characteristics on thermal conductivity have been studied (Lewis 1967; Kamke and Zylkowski 1989) without specific values of MDF. Nearly no literature about coupled effects of moisture content on the temperature-dependent thermal and frequency-dependent dielectric properties of MDF were found.

MDF is a composite material and has different thermal and dielectric properties from those of solid wood that are related to the types of resin used, technologies, and manufacturers (Kamke and Zylkowskiv 1989). The objective of the present study was to provide more basic information on the coupled effects of moisture content on the temperature-dependent thermal and frequency-dependent dielectric properties of MDF, with the ultimate purpose of developing a computer simulation of hot pressing with radio frequency.

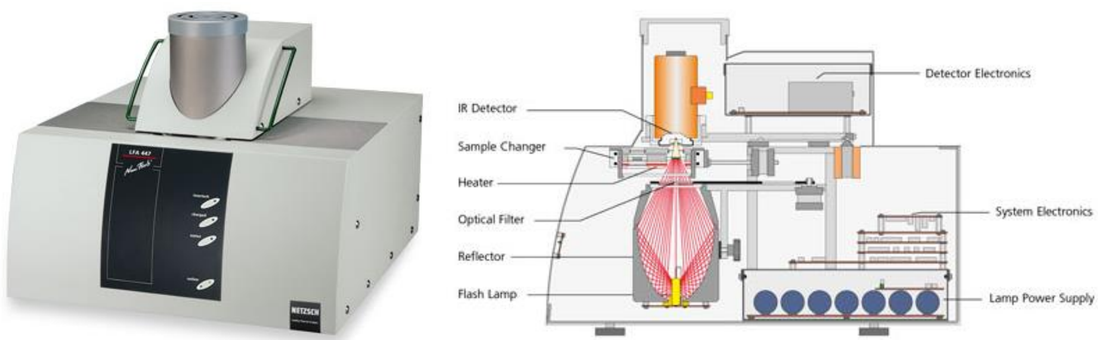
EXPERIMENTAL

Commercially available MDF of thickness 2.64 mm and with urea-formaldehyde (UF) bonding of eucalyptus species (*Eucalyptus* spp.), was provided by Foursea Furniture Ltd. for this study. The initial moisture content measured at a temperature of 25 ºC and 65% relative humidity was 8.0%. Thirty samples with dimensions of 10 mm$\times$10 mm were equally divided into three groups, which were conditioned to be of average moisture contents of 8.0, 4.0, and 0.0% (oven-dried), respectively, with the purpose of studying the effect of moisture content on thermal properties. The samples were pre-heated in a chamber to obtain target moisture contents by monitoring the masses of samples and sealed in a plastic bag before testing. The densities of samples with 8.0, 4.0, and 0.0% moisture content were quickly measured under 25 ºC and 65 % relative humidity with average values of 796, 782, and 765 kg/m^3, respectively. Thermal diffusivity (α) was measured directly across the thickness direction using a light flash system as shown in Fig. 1 (NETZSCH, LFA 447 NanoFlash®) when the temperatures were 25, 50, 75, 100, 125, and 150 ºC. The temperature range was chosen as it encompasses the conditions of heat pressing and adhesive curing temperature (Zhou *et al.* 2012). The samples were placed flat in the sample changer as illustrated in Fig. 1, which provides a schematic of the measurement device. The test was replicated three times at each temperature for each sample. Specific heat capacity (C) was computed by a comparison method using Proteus® software. Thermal conductivity was obtained using Equation 1,

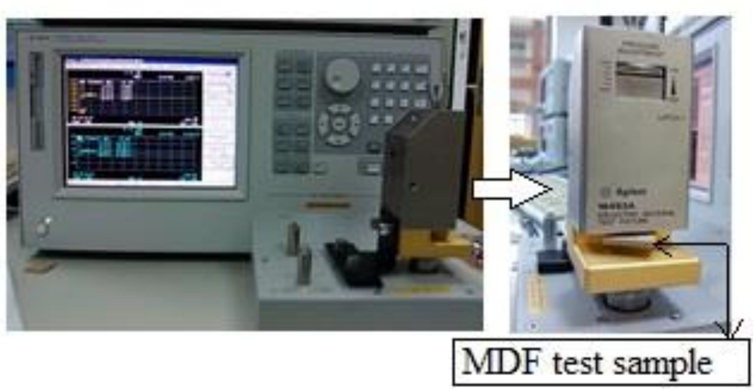
$$\lambda = \alpha \times \rho \times C \tag{1}$$

where α is the thermal diffusivity (m^2/s), ρ is the density of MDF (kg/m^3), and C is the specific heat capacity (kJ/ kg / ºC).

Thirty samples with dimensions of 20 mm×20 mm were equally divided into three groups, and the groups of specimens were conditioned with the same method described above to have moisture contents of 8.0, 4.0, and 0.0% (oven-dried), respectively, with the purpose of studying the effect of moisture content on the dielectric properties at room temperature. The dielectric properties were examined using a RF impedance/material analyzer (Agilent, E4991A) with a dielectric material test fixture (Agilent, 16453A), as shown in Fig. 1. Each specimen was scanned 16 times across the thickness direction while the frequency ranged from 1 MHz to 1 GHz, with a resolution of 5 MHz. The sixteen outputs were averaged to obtain the spectra of relative dielectric constants and loss factors. The relative dielectric constants and loss factors at frequencies of 6.78, 13.56, 27.12, and 40.68 MHz were generated using an IBASIC program.



a) LFA 447 *NanoFlash*® Light Flash System (NETZSCH 2013)



b) RF impedance/ material analyzer with a dielectric material test fixture

Fig. 1. Set-up of thermal and dielectric properties measurements; a) experimental set-up for thermal properties; b) experimental set-up for dielectric properties

RESULTS AND DISCUSSION

The thermal conductivities of MDF with different moisture contents in the temperature range of 25 to 150 ºC are shown in Fig. 2. The thermal conductivities presented here were calculated using Eq. 1 based on the values of thermal diffusivity, specific heat capacity, and density. The effect of temperature on the thermal conductivities of 2.6-mm MDF with different moisture contents shows a similar pattern of double humps rather than a proportional pattern reported in most literature (Suleiman *et al.* 1999; Yu *et al.* 2011; Harada *et al.* 1998; Lewis 1967). The thermal conductivity increased with temperature up to 50 ºC and then decreased with increasing temperature in the range of 50 to 100 ºC for the first hump. Suleiman *et al.* (1999) reported that the thermal conductivity of oven-dried birch increased slightly when the temperature increased from 20 to 100 ºC. It was also reported that the transverse thermal conductivities of five wood species in China increased proportionally with temperature up to 90 ºC (Yu *et al.* 2011). Harada *et al.* (1998) measured the thermal conductivities of some Japanese wood species up to 270 ºC, and the variations below 100 ºC were not clearly revealed. It was reported that the thermal conductivities of oven-dried fiber- and particle-based materials increased with temperature up to 60 ºC (Lewis 1967).Conductivity values varied with the moisture content of MDF. Water is more conductive than either the cell wall or air. The higher the moisture content, the higher will be the thermal conductivity. The fitting curves of the relationship between thermal conductivity and temperature are nonlinear and are better expressed as a quadratic equation when the moisture content levels are 12.6% and 15.8% for solid wood (Yu *et al.* 2011).

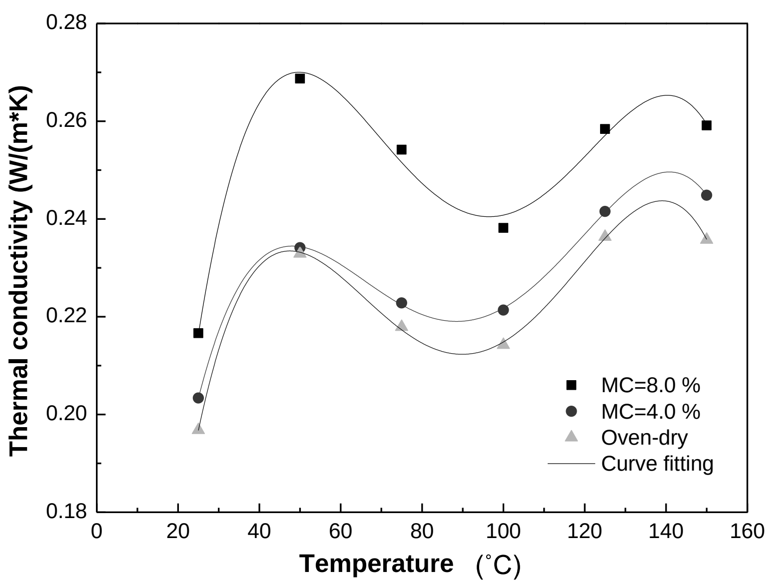


Fig. 2. Thermal conductivity in the temperature range of 25 to 150 ºC

Nonlinear fitting curves at different moisture content levels shown in Fig. 2 can be described as follows,

$$\lambda = -0.050 + 0.0174 * T - 3.264e-4 * T^2 + 2.463e-6 * T^3 - 6.446e-9 * T^4$$

$(R^2 = 0.951 \text{ and MC} = 8.0\%)$ (2)

$$\lambda = 0.030 + 0.012 * T - 2.265e-4 * T^2 + 1.783e-6 * T^3 - 4.821e-9 * T^4$$
$(R^2 = 0.998 \text{ and MC} = 4.0\%)$ (3)

$$\lambda = -0.0132 + 0.0140 * T - 2.763e-4 * T^2 + 2.179e-6 * T^3 - 5.913e-9 * T^4$$
$(R^2 = 0.996 \text{ and MC} = 0.0\%)$ (4)

where λ is thermal conductivity and T is temperature in the range of 25 to 150 ºC.

The relative dielectric constants and loss factors of MDF with different moisture contents in the frequency range of 1 to 1000 MHz are shown in Fig. 3. The relative dielectric constants and loss factors increased with moisture content. The relative dielectric constant and loss factor at 8.0% moisture content were significantly greater than those at 4.0% moisture content and oven-dried samples. The relative dielectric constant and loss factor at 4.0% were slightly greater than that of oven-dried samples. These results are most likely due to the impact of water on the dielectric properties. Kabir *et al.* (1998) reported that the dielectric properties of rubber wood increased with moisture content up to 30% in both grain directions at low and microwave frequencies. Sahin and Ay (2004) reported that the dielectric properties of three hardwood Euramerican hybrids (poplar, alder, and oriental beech) at 9.8 GHz increased with moisture content in the range of 0 to 28%. Some researchers have reported that the dielectric properties of three softwood species at 3 GHz increased with moisture content ranging from 6.0 to 35% in the longitudinal, radial, and tangential directions (Peyskens *et al.* 1984).

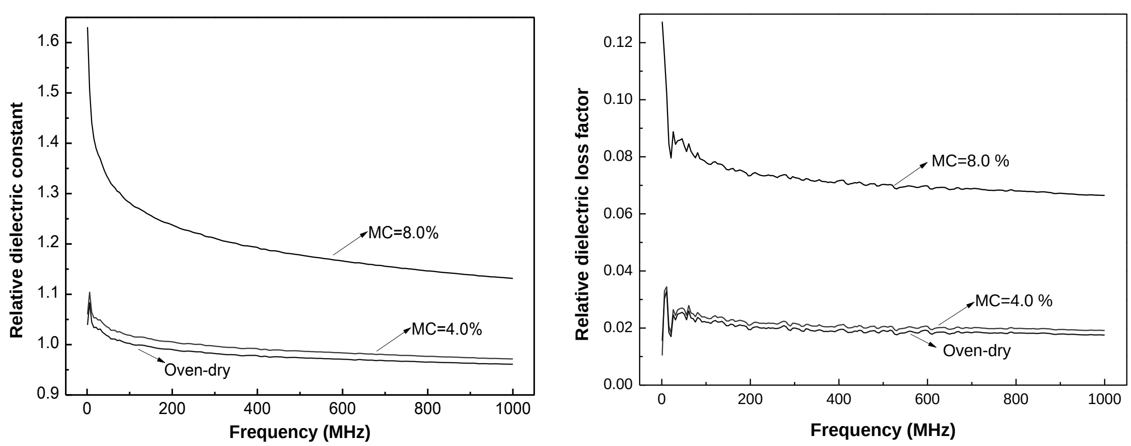


Fig. 3. Relative dielectric constant and loss factor of MDF with different moisture contents in the frequency range of 1 to 1000 MHz

The dielectric properties at 8.0% moisture content decreased abruptly in the frequency range of 1 to 100 MHz and thereafter changed slowly with further increases in frequency. Similar decreasing patterns of the dielectric properties of both the 4.0% moisture content and oven-dried samples were also observed in the frequency range of 6 to 100 MHz. However, the peak values of the dielectric properties occurred around 6 MHz when the moisture contents were 4.0% and 0.0%. These patterns were similar to the findings of Kabir *et al.* (2001), who showed that the dielectric properties of rubber wood have a strong relationship with frequency. The variations of the relative dielectric loss factor were different from those of the relative dielectric properties in the frequency range of 1 to 100 MHz. It can be observed from Fig. 3 that the peak values of the dielectric loss factor occurred at 10 MHz. The relative dielectric loss factor with different moisture contents undulates within the frequency range of 1 to 100 MHz. Thereafter, it decreased with increasing frequency.

The most common frequencies used for radio-frequency heating in the panel furniture industry include 6.78, 13.56, 27.12, and 40.68 MHz. The relative dielectric constants and loss factors of MDF with different moisture contents at 6.78, 13.56, 27.12, and 40.68 MHz are summarized in Table 1. Both the moisture content and frequency affect the relative dielectric constant and loss factor at these frequencies, as discussed before. The results presented here provide basic important information on the dielectric properties of MDF for computer simulation of the radio-frequency heating process.

Table 1. Dielectric Properties of MDF at Industrial Radio Frequencies

Moisture content	Dielectric properties	Frequency/ MHz							
		6.78		13.56		27.12		40.68	
		Mean	SD (COV)	Mean	SD (COV)	Mean	SD (COV)	Mean	SD (COV)
8.4%	ε'	1.4976	0.0241 (3.01%)	1.4254	0.0431 (0.03%)	1.3765	0.0400 (2.91%)	1.3464	0.0389 (2.89%)
	ε''	0.1137	0.0068 (5.96%)	0.0936	0.0048 (5.18%)	0.0878	0.0046 (5.23%)	0.0859	0.0045 (5.24%)
4.0%	ε'	1.0874	0.0316 (2.90%)	1.0488	0.0321 (3.06%)	1.0392	0.0315 (3.04%)	1.0303	0.0310 (3.01%)
	ε''	0.0310	0.0021 (6.77%)	0.0258	0.0024 (9.16%)	0.0245	0.0018 (7.05%)	0.0252	0.0022 (8.56%)
Oven-dry	ε'	1.0825	0.0409 (3.78%)	1.0424	0.0410 (3.93%)	1.0341	0.0392 (3.79%)	1.0251	0.0385 (3.75%)
	ε''	0.0320	0.0028 (8.61%)	0.0258	0.0021 (8.22%)	0.02414	0.0024 (9.85%)	0.0253	0.0022 (8.87%)

ε' is relative dielectric constant; ε'' is relative dielectric loss factor; SD is standard deviation; and COV is coefficient of variation.

CONCLUSIONS

The coupled effects of moisture content on the temperature-dependent thermal and frequency-dependent dielectric properties of MDF were studied with the ultimate purpose of developing a computer simulation of hot pressing with radio frequency. The main findings are as follows:

1. The thermal conductivity of MDF with different moisture content varies in the temperature range of 25 to 150 ºC in a double-hump pattern, rather than a proportional pattern.

2. The dielectric constant decreases with increasing frequency up to 1000 MHz. The dielectric loss factor undulates in the frequency range of 1 to 100 MHz, and the peak value occurs at around 10 MHz.

3. Basic information on the thermal and dielectric properties of MDF is provided as a precursor to future work on computer simulation of hot pressing at radio frequencies.

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