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Temperature-dependent dielectric properties of honey associated with dielectric heating

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ABSTRACT

Dielectric properties of pure yellow-locust and jujube honey and their water solutions at seven final water content levels from 17.4% to 42.6% were measured with an open-ended coaxial-line probe from 10 to 4500 MHz at 20–80 °C. The results showed that the dielectric constants of pure honey increased with increasing temperature when frequency was above 40 MHz. For honey solutions, the dielectric constant decreased with increasing temperature at the lower frequencies, but increased at the higher frequencies. At any given water content, the relaxation frequency shifted to a higher frequency with increasing temperature, while the loss factor peaks showed little change. There was a strong negative linear correlation between penetration depth and frequency in log–log plot for pure honey at 20–80 °C. The research will be helpful in developing effective honey pasteurization processes with radio-frequency and microwave dielectric heating.

1. Introduction

Honey is a valuable nutrient product containing large amounts of various sugars and small amounts of amino acids, lipids, vitamins and minerals (Cereser Camara and Laux, 2010). During beehive handling, honey extracting, and processing, cross contaminations of mesophiles, aerobics, fungi and yeasts (most of them osmophiles) and foodborne pathogens are important food safety issues for final honey products (Tosi et al., 2002). To inactivate microorganisms, pasteurization processes are usually used prior to industrial packaging. Thermal treatments are used not only to control yeasts and ensure product quality, but also to dissolve sugar crystals, retard the natural crystallization process, and ensure quality stability (Escriche et al., 2009; Turhan et al., 2008). However, conventional thermal treatments with high temperature and long time are detrimental to honey quality due to slow heat conduction (Zhou et al., 2006). For example, it may destroy vitamins and bio-nutrients, and produce a simultaneous decrease in diastase activity and increase in hydroxymethylfurfural (HMF) content, which are international parameters used as controls to limit thermal treatment applications (Tosi et al., 2002). It is reported that when honey was heated at 75 °C for 90 min, HMF value was 1.33, but it increased to 11.24 and 73.78 when heated at 90 °C and 100 °C for 90 min, respectively (Turhan et al., 2008). To guarantee honey quality, the pasteurization temperature is usually controlled below 80 °C, and an advanced thermal treatment technology with high heat efficiency is desirable.

Dielectric heating, including radio-frequency (RF) and microwave (MW) dielectric heating, holds potential for pathogen controls in honey, because it involves the direct transfer of electromagnetic energy into bulk materials and provides fast and volumetric heating (Wang et al., 2007). Moreover, the major advantage of RF and MW treatments over conventional thermal methods is that the processing time is short and the heating is uniform throughout the products, which result in better product quality and higher pasteurizing efficiency. However, the information on dielectric properties is essential in developing successful pasteurization processes, and in selecting optimal frequency ranges and bed thickness for uniform treatments based on RF and MW energy (Wang et al., 2003).

Frequency, temperature and water content have been proved to be the most important factors influencing dielectric properties of food materials (Içier and Baysal, 2004; Sosa-Morales et al., 2010; Venkatesh and Raghavan, 2004). Several works also show that frequency and water content are important factors influencing dielectric properties of honey, but the studies were only undertaken at room temperature (Ahmed et al., 2007; Guo et al., 2010c; Puranik et al., 1991). In honey pasteurization processes, the sample temperature increases from room temperature to the lethal level that

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inactivates the targeted pathogens. Therefore, the objectives of this study were to investigate the influence of temperature, from 20 to 80 °C, on the dielectric properties behavior from 10 to 4500 MHz of yellow-locust and jujube floral honey at seven water content levels from 17.4% to 42.6% using the open-ended coaxial-line probe technology, and to determine their penetration depths at selected RF and MW frequencies for uniform dielectric heating.

2. Materials and methods

2.1. Honey

Yellow-locust honey and jujube honey of Chinese floral sources of yellow-locust tree (*Robinia pseudoacacia* L.) and Chinese jujube (*Ziziphus jujube*) were used in this study. The botanical origins were chosen as they are the most popular types produced and consumed in China. The sample, packed by Shaanxi Dangdai Honey Industry Co., Ltd. in October 2009, was purchased from the factory, which locates in Yangling, Shaanxi, China. There were no crystals in the honey samples. The initial water contents in yellow-locust and jujube honey lots were 17.4% and 17.6%, respectively. The main sugar contents for yellow-locust honey were 46.2% fructose, 31.5% glucose and 1.4% sucrose, and were 41.6% fructose, 33.2% glucose and 1.8% sucrose for jujube honey. These compositions were reported by the packer. Of which, the water content was determined by refractometry, measuring the refractive index according to AOAC methods (AOAC 969.38, 1998). Fructose, glucose and sucrose were identified and determined by high performance liquid chromatography according to GB18932.22-2003 (2003).

2.2. Dielectric properties measurements

A vector network analyzer (Agilent E5071C, Agilent Technologies, Malaysia), connected to an open-ended coaxial-line probe (85070E, Agilent Technologies, Penang, Malaysia) with a coaxial cable (N6314A, Agilent Technologies, Penang, Malaysia) was used to measure dielectric properties of honey samples. The network analyzer measured the reflection coefficient at the probe-sample interface. Agilent Technologies 85070D dielectric probe kit software was used to calculate the dielectric properties (dielectric constant and dielectric loss factor) of the samples. The detailed procedure of calibration and dielectric measurement has been reported elsewhere (Guo et al., 2010c). The dielectric properties of honey samples were measured from 10 to 4500 MHz at 101 discrete frequencies on a logarithmic scale. The data at the two frequency extremes (10 and 4500 MHz) of the measured frequency range were further used for analysis of results together with three interesting frequencies applied in heating applications, such as one RF (27 MHz) and two MW frequencies (915 and 2450 MHz) allocated by the US Federal Communications Commission (FCC).

2.3. Procedures

Predetermined amounts of deionized water were added to each 200 g pure honey, with 17.4% and 17.6% initial water contents in yellow-locust and jujube honey, to prepare honey-water solutions with different final water contents of 22.1%, 26.2%, 30.3%, 34.4%, 38.5% and 42.6% as a ratio of the mass of honey to the mass of solution at room temperature. The masses were measured with an FA2104A Electronic Balance (Shanghai Precision & Scientific Instrument Co., Ltd., Shanghai, China) with precision of 0.0001 g.

The sample at each water content level was poured into three glass centrifuge tubes, 28 mm in inner diameter and 50 mm in height, to a depth of 47 mm. After the network analyzer and coaxial-line probe were calibrated, the tube was clipped in position under the probe so that the end of the probe was completely immersed in the sample. When no bubble was observed between probe and sample, the constant temperature water bath (DK-98-1, Tianjin Taisite Instrument Ltd., Tianjin, China) was raised with a laboratory jack to submerge the tube in the water bath. A rubber lid, 2-mm thick, with a hole for the probe was used to cover the tube to prevent moisture loss. The dielectric properties measurement system is shown in Fig. 1. Dielectric properties of each sample were measured at 20, 30, 40, 50, 60, 70 and 80 °C. A precalibrated type-T thermocouple sensor was used to measure the sample temperature in the sample center. The sample temperature was controlled by circulating water in the water bath. When the sample temperature reached the designated testing level, one frequency sweep for dielectric properties measurement over the whole frequency range was performed within 1 min. After three measurements at each temperature, the water bath was adjusted to the next temperature level, and the sample temperature reached the set point in about 13 min. Between replicates, the probe was cleaned with water and wiped dry. Mean values and standard deviations of nine readings in triplicate at each temperature for each water content level were reported.

2.4. Penetration depth

To realize rapid and uniform pasteurizing or thermal treatment, the optimum frequency should be selected. The penetration depth, D_p, of electromagnetic wave in materials is defined as the depth where the electromagnetic power is reduced to $1/e$ ($e = 2.7183$) of its surface value (von Hippel, 1954). It is an important parameter in evaluating heating uniformity, and designing electromagnetic heating instrument. Penetration depth is a function of wavelength and the dielectric properties of the material. Its calculation method in food materials has been reported elsewhere (Guo et al., 2010c). The penetration depths of yellow-locust and jujube honey samples with different water contents and at different temperatures were calculated according to the measured dielectric properties.

3. Results and discussion

3.1. Dielectric constant

The measured dielectric constants of yellow-locust honey with 17.4% and 30.3% water contents at 20–80 °C from 10 to 4500 MHz are shown in Fig. 2(a) and (b), respectively. They show that as frequency effects, temperature also played a major role in dielectric spectra of honey samples. The dielectric constant decreased with increasing frequency at any temperature. But at any frequency above about 40 MHz, for yellow-locust pure honey (17.4% water content), the dielectric constant increased with increasing temperature. The dielectric constant at 20 °C was the lowest throughout

Fig. 1. Dielectric properties measurement system.

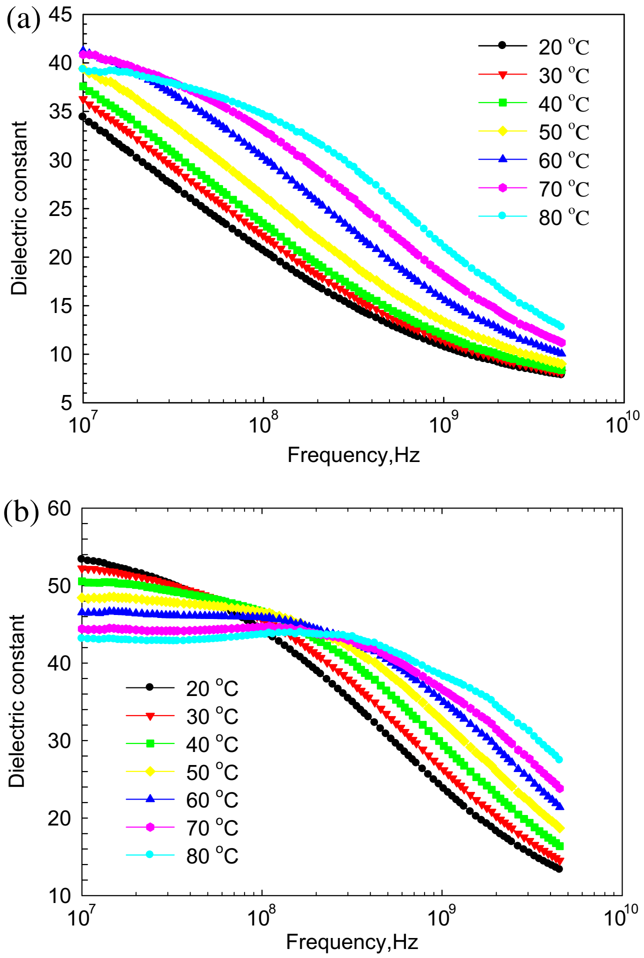

Fig. 2. The measured dielectric constants of yellow-locust honey solutions with 17.4% (a) and 30.3% (b) water contents at indicated temperatures as a function of frequency.

the frequency range (Fig. 2(a)). For the honey solution with 30.3% water content, the dielectric constant decreased with increasing temperature at lower frequencies, and increased with temperature at higher frequencies (Fig. 2(b)). Moreover, the increasing temperature not only slowed the decrease of dielectric constant with frequency, especially in Fig. 2(b), but also made the dielectric constant decrease from sharply to slowly at lower frequencies and from slowly to sharply at higher frequencies with increasing frequency. For example, when frequency increased from 10 to 100 MHz, the dielectric constant of yellow-locust honey solution with 30.3% water content decreased from 53 to 44 at 20 °C, but stayed at about 43 at 80 °C (Fig. 2(b)).

The temperature-dependent behavior of the dielectric constant of honey solution with 30.3% water content is similar to that of water at 0–75 °C (Mudgett, 1986). The same trend was also found for apple juice with 88.5% water content at 10–90 °C from 200 MHz to 20 GHz (Nelson and Bartley Jr., 2001). However, the trend is different from that of the pure honey sample.

The change in dielectric properties with temperature depends on the free and bound water contents in food materials (Calay et al., 1995). For pure honey, the water was mainly in bound form. The dielectric polarization attributable to bound water is much less than that to free water. For honey solutions with 30.3% water content, free water contributes much more than bound water. The inverse dependence of the dielectric constant on temperature in 17.4% and 30.3% honey samples at lower frequencies suggests that bound water and free water played dominant roles in 17.4% pure honey and 30.3% honey solution, respectively. The dielectric constant spectra of other honey samples with different water contents were similar to that of the 30.3% moisture sample. The temperature dependence of dielectric constants of jujube honey samples was similar to that of yellow-locust honey. Tables 1 and 2 show the measured average and standard deviation of dielectric constant of yellow-locust and jujube honey with various water contents at 20–80 °C and selected frequencies of 10, 27, 915, 2450 and 4500 MHz, respectively.

The effect of temperature on the dielectric constant of yellow-locust honey samples with different water contents at 915 MHz is shown in Fig. 3. When the water content of honey solution was less than or equal to 30.3%, the dielectric constant increased with temperature. For higher moisture contents, the curves exhibited maxima at about 60, 50 and 40 °C for water contents of 34.4%, 38.5% and 42.6%, respectively. The phenomena of dielectric constant increased with increasing temperature were also found in chickpea, green pea, soybean and lentil flour with 8–20% water content at 20–90 °C (Guo et al., 2008, 2010a).

3.2. Dielectric loss factor

The measured dielectric loss factors of yellow-locust pure honey and honey solution with 17.4% and 30.3% water contents, respectively, from 10 to 4500 MHz at 20–80 °C are shown in Fig. 4. They show a prominent dielectric relaxation in honey. The loss factor of pure honey at 27 MHz decreased with increasing temperature above 40 °C, which results in improving heating uniformity in RF processed honey, because the hot spots will absorb less RF power. However, the loss factor increased with temperature when the frequency was above 1000 MHz (Fig. 4(a)). For example, with MW heating at 2450 MHz, this may result in non-uniform heating in honey, because hot spots would heat even faster.

Fig. 4(b) also shows that the relaxation frequency, f_r, of yellow-locust honey solution with 30.3% water content increased with increasing temperature, but the maxima for loss factors stayed at about 13.1 ± 0.1 from 20 to 80 °C. The loss factor decreased with temperature from 100 to 400 MHz. When temperature was higher than 40 °C, obvious decrease in loss factor with frequency below 100 MHz at a given temperature indicated that ionic conduction played a dominant role (Guo et al., 2010b; Wang et al., 2005, 2008).

A similar trend in loss factor with temperature was also observed at other water contents, and the role of ionic conduction increased with increasing water content at low frequencies. Similar dependence of the loss factor on temperature was also found in jujube honey at various water contents. Tables 3 and 4 list the relaxation frequencies and maximum values of loss factor for yellow-locust and jujube honey solutions with various water contents at 20–80 °C over the frequency range from 10 to 4500 MHz.

The characteristic of shifting relaxation frequency to higher frequency with increasing temperature in honey samples is similar to the behavior of water (Mudgett, 1986). For example, relaxation frequency of water at 0 and 25 °C was about 7.7 and 18.02 GHz, respectively.

The loss factor of yellow-locust honey solutions with various water contents as a function of temperature at 915 MHz is shown in Fig. 5. For pure honey, the dielectric loss factor increased with increasing temperature. But at the water content from 22.1% to 30.3%, the loss factor had a peak. It decreased with temperature at the water content from 34.4% to 42.6%. This was probably caused by the balance between ionic conduction and dipole rotation at 915 MHz (Wang et al., 2005). Increasing water content resulted in deceasing relative ionic conduction in the honey solution, and thus increasing dipole rotation of free water (Komarov et al., 2005).

Table 1
Dielectric properties (mean ± standard deviation) of pure yellow-locust honey (17.4%) and its solutions with seven water contents at seven temperatures and five selected frequencies.

Water content (%)	Frequency (MHz)		Temperature (°C)						
			20	30	40	50	60	70	80
17.4	10	ε'	35.4 ± 1.2	36.3 ± 1.1	37.6 ± 0.3	39.4 ± 1.1	41.2 ± 0.8	40.9 ± 0.2	39.3 ± 0.6
		ε''	7.8 ± 0.6	8.5 ± 0.4	8.8 ± 0.4	7.0 ± 0.7	5.8 ± 0.4	4.5 ± 0.2	4.2 ± 0.5
	27	ε'	28.1 ± 1.0	30.1 ± 0.1	31.6 ± 1.0	34.3 ± 0.6	37.4 ± 0.2	38.4 ± 0.5	38.0 ± 1.1
		ε''	8.9 ± 0.2	9.2 ± 0.2	9.3 ± 0.2	8.6 ± 0.2	7.4 ± 0.1	5.8 ± 0.4	4.3 ± 0.2
	915	ε'	11.1 ± 0.4	11.7 ± 0.4	12.3 ± 0.2	13.8 ± 0.4	16.2 ± 0.3	18.8 ± 0.5	21.8 ± 0.7
		ε''	4.8 ± 0.2	5.2 ± 0.6	5.8 ± 0.3	6.6 ± 0.2	7.8 ± 0.1	8.8 ± 0.1	9.4 ± 0.1
	2450	ε'	8.8 ± 0.2	9.2 ± 0.3	9.5 ± 0.2	10.4 ± 0.3	11.9 ± 0.2	13.5 ± 0.4	15.7 ± 0.6
		ε''	3.3 ± 0.2	3.7 ± 0.2	4.0 ± 0.3	4.7 ± 0.2	5.9 ± 0.1	7.0 ± 0.2	8.1 ± 0.2
	4500	ε'	7.9 ± 0.2	8.1 ± 0.3	8.4 ± 0.1	9.0 ± 0.2	10.1 ± 0.2	11.2 ± 0.3	12.8 ± 0.5
		ε''	2.7 ± 0.1	3.0 ± 0.1	3.3 ± 0.2	3.9 ± 0.2	4.9 ± 0.1	5.9 ± 0.2	7.1 ± 0.3
22.1	10	ε'	44.5 ± 0.3	45.3 ± 0.2	46.1 ± 0.8	45.3 ± 0.6	44.3 ± 0.2	43.3 ± 0.8	41.3 ± 0.6
		ε''	6.9 ± 0.2	6.1 ± 0.3	4.9 ± 0.5	3.9 ± 0.2	3.8 ± 0.8	4.9 ± 0.3	7.3 ± 0.4
	27	ε'	39.0 ± 0.2	40.6 ± 0.1	42.0 ± 0.6	42.9 ± 0.3	43.0 ± 0.1	42.5 ± 0.6	40.8 ± 0.4
		ε''	9.1 ± 0.1	8.5 ± 0.1	7.5 ± 0.1	5.7 ± 0.1	4.5 ± 0.1	3.9 ± 0.1	3.9 ± 0.2
	915	ε'	15.4 ± 0.1	16.5 ± 0.1	18.1 ± 0.3	21.6 ± 0.2	24.6 ± 0.3	28.2 ± 0.1	30.6 ± 2.5
		ε''	7.8 ± 0.1	8.5 ± 0.0	9.1 ± 0.1	10.3 ± 0.1	10.8 ± 0.0	10.7 ± 0.0	9.7 ± 0.1
	2450	ε'	11.3 ± 0.0	12.0 ± 0.1	13.0 ± 0.2	15.2 ± 0.1	17.4 ± 0.2	20.5 ± 0.1	23.2 ± 1.5
		ε''	5.6 ± 0.1	6.1 ± 0.0	6.8 ± 0.1	8.3 ± 0.1	9.4 ± 0.1	10.4 ± 0.1	10.8 ± 0.1
	4500	ε'	9.6 ± 0.0	10.0 ± 0.0	10.8 ± 0.2	12.3 ± 0.1	13.9 ± 0.2	16.2 ± 0.0	18.5 ± 0.3
		ε''	4.5 ± 0.1	5.0 ± 0.0	5.6 ± 0.1	7.0 ± 0.1	8.2 ± 0.1	9.5 ± 0.1	10.4 ± 0.2
26.2	10	ε'	50.1 ± 0.3	49.6 ± 0.2	49.0 ± 0.2	47.1 ± 0.1	44.9 ± 0.2	42.0 ± 0.3	39.7 ± 0.3
		ε''	5.5 ± 0.5	5.5 ± 0.4	5.2 ± 0.2	6.0 ± 0.2	7.6 ± 0.3	11.6 ± 0.2	15.1 ± 0.4
	27	ε'	46.9 ± 0.0	47.0 ± 0.1	47.6 ± 0.0	46.7 ± 0.1	45.0 ± 0.1	42.6 ± 0.2	40.5 ± 0.2
		ε''	7.7 ± 0.1	7.1 ± 0.1	5.9 ± 0.1	4.9 ± 0.1	4.6 ± 0.1	5.4 ± 0.1	6.3 ± 0.1
	915	ε'	20.7 ± 0.0	22.1 ± 0.2	25.4 ± 0.3	29.4 ± 0.2	32.1 ± 0.1	34.6 ± 0.1	35.5 ± 0.0
		ε''	11.2 ± 0.0	11.7 ± 0.1	12.4 ± 0.0	12.4 ± 0.0	11.7 ± 0.1	10.1 ± 0.1	8.7 ± 0.0
	2450	ε'	14.1 ± 0.0	15.0 ± 0.1	17.4 ± 0.2	20.6 ± 0.1	23.2 ± 0.2	26.5 ± 0.2	28.6 ± 0.0
		ε''	8.4 ± 0.0	9.1 ± 0.1	10.4 ± 0.1	11.7 ± 0.0	12.3 ± 0.0	12.2 ± 0.0	11.5 ± 0.0
	4500	ε'	11.3 ± 0.0	11.9 ± 0.1	13.5 ± 0.2	15.9 ± 0.1	18.0 ± 0.1	20.9 ± 0.2	23.1 ± 0.0
		ε''	6.9 ± 0.0	7.5 ± 0.1	8.8 ± 0.1	10.3 ± 0.1	11.4 ± 0.1	12.1 ± 0.0	12.2 ± 0.0
30.3	10	ε'	53.4 ± 0.2	52.2 ± 0.8	50.6 ± 1.1	48.4 ± 0.7	46.5 ± 0.7	44.4 ± 0.9	43.1 ± 1.2
		ε''	4.4 ± 0.2	4.6 ± 0.4	5.4 ± 0.7	6.8 ± 0.3	8.9 ± 0.4	12.8 ± 0.8	19.5 ± 3.0
	27	ε'	50.6 ± 0.2	50.4 ± 0.6	49.5 ± 0.9	48.0 ± 0.6	46.2 ± 0.5	44.2 ± 0.8	42.8 ± 1.0
		ε''	6.3 ± 0.1	5.5 ± 0.1	4.8 ± 0.2	4.5 ± 0.2	4.7 ± 0.1	5.6 ± 0.3	7.8 ± 1.0
	915	ε'	25.0 ± 0.2	27.4 ± 0.1	30.6 ± 0.1	33.5 ± 0.6	36.0 ± 0.4	37.1 ± 0.4	38.9 ± 1.5
		ε''	12.7 ± 0.1	13.1 ± 0.1	13.1 ± 0.0	12.4 ± 0.1	11.1 ± 0.2	9.5 ± 0.1	7.8 ± 0.6
	2450	ε'	16.9 ± 0.3	18.7 ± 0.1	21.2 ± 0.1	24.1 ± 0.7	27.2 ± 0.6	29.6 ± 0.5	32.9 ± 2.2
		ε''	10.3 ± 0.1	11.2 ± 0.2	12.2 ± 0.2	12.9 ± 0.1	12.9 ± 0.1	12.4 ± 0.1	11.3 ± 0.4
	4500	ε'	13.3 ± 0.3	14.5 ± 0.2	16.4 ± 0.1	18.7 ± 0.6	21.4 ± 0.5	23.8 ± 0.5	27.5 ± 2.2
		ε''	8.5 ± 0.1	9.5 ± 0.2	10.8 ± 0.2	11.9 ± 0.0	12.7 ± 0.0	12.9 ± 0.0	12.9 ± 0.1
34.4	10	ε'	56.4 ± 0.6	54.7 ± 0.6	52.7 ± 0.7	50.4 ± 1.0	47.5 ± 1.1	44.5 ± 1.8	41.1 ± 2.4
		ε''	5.2 ± 0.4	6.5 ± 0.4	8.6 ± 1.1	11.4 ± 0.4	15.1 ± 0.6	19.6 ± 0.6	24.3 ± 0.3
	27	ε'	55.2 ± 0.8	54.1 ± 0.6	52.6 ± 0.6	50.5 ± 0.9	47.6 ± 1.0	44.7 ± 1.6	41.3 ± 1.9
		ε''	5.4 ± 0.1	5.0 ± 0.1	5.1 ± 0.3	5.5 ± 0.1	6.5 ± 0.2	8.0 ± 0.1	9.5 ± 0.1
	915	ε'	30.3 ± 1.3	33.4 ± 1.9	36.0 ± 1.8	38.1 ± 1.6	39.1 ± 1.5	38.9 ± 1.1	37.4 ± 2.3
		ε''	15.9 ± 0.7	15.6 ± 0.7	14.7 ± 0.7	13.2 ± 0.8	11.3 ± 0.8	9.6 ± 0.7	8.1 ± 0.8
	2450	ε'	19.4 ± 1.0	21.9 ± 1.5	24.6 ± 1.6	27.4 ± 1.6	29.8 ± 1.5	31.1 ± 1.1	31.2 ± 1.7
		ε''	13.0 ± 0.8	13.9 ± 1.1	14.3 ± 1.4	14.2 ± 1.0	13.4 ± 0.9	12.2 ± 0.9	10.6 ± 0.6
	4500	ε'	14.6 ± 0.1	16.5 ± 0.4	18.6 ± 0.5	21.1 ± 0.5	23.5 ± 0.4	25.2 ± 0.1	26.0 ± 0.2
		ε''	10.0 ± 0.9	11.2 ± 1.2	12.1 ± 1.3	12.7 ± 1.3	12.7 ± 1.3	12.2 ± 1.2	11.2 ± 1.1
38.5	10	ε'	58.1 ± 0.4	56.4 ± 0.3	54.0 ± 0.4	51.1 ± 1.1	47.9 ± 1.6	44.4 ± 1.2	41.8 ± 0.9
		ε''	8.2 ± 0.4	10.5 ± 0.3	13.6 ± 0.4	16.8 ± 0.4	21.3 ± 0.5	26.8 ± 0.7	33.3 ± 0.3
	27	ε'	57.5 ± 0.3	55.9 ± 0.4	53.7 ± 0.3	50.8 ± 1.1	47.7 ± 1.5	44.2 ± 1.1	41.5 ± 0.7
		ε''	5.0 ± 0.1	5.3 ± 0.2	5.8 ± 0.1	6.7 ± 0.1	8.1 ± 0.1	9.9 ± 0.2	12.1 ± 0.1
	915	ε'	39.3 ± 0.4	41.8 ± 0.6	43.1 ± 0.5	43.4 ± 0.3	42.9 ± 0.9	41.5 ± 0.7	40.5 ± 0.4
		ε''	15.2 ± 0.1	14.0 ± 0.2	12.2 ± 0.2	10.3 ± 0.3	8.4 ± 0.3	6.8 ± 0.1	5.3 ± 0.1
	2450	ε'	27.4 ± 0.3	30.5 ± 0.4	33.0 ± 0.5	34.9 ± 0.1	36.1 ± 0.6	36.5 ± 0.7	37.1 ± 0.3
		ε''	16.0 ± 0.1	16.1 ± 0.2	15.6 ± 0.0	14.5 ± 0.3	12.9 ± 0.4	11.0 ± 0.2	8.9 ± 0.2
	4500	ε'	20.6 ± 0.3	23.2 ± 0.3	25.7 ± 0.5	27.9 ± 0.0	29.9 ± 0.3	31.1 ± 0.6	32.8 ± 0.1
		ε''	14.7 ± 0.1	15.6 ± 0.2	15.9 ± 0.1	15.6 ± 0.2	14.8 ± 0.4	13.5 ± 0.3	11.7 ± 0.2
42.6	10	ε'	60.7 ± 0.2	58.9 ± 0.5	56.1 ± 0.9	55.1 ± 0.7	52.0 ± 1.6	49.7 ± 1.3	47.3 ± 0.2
		ε''	9.0 ± 1.0	11.6 ± 1.0	15.6 ± 1.3	20.0 ± 0.9	25.7 ± 0.8	32.8 ± 0.2	39.9 ± 0.9
	27	ε'	60.0 ± 0.1	58.2 ± 0.3	55.5 ± 0.7	54.3 ± 0.4	51.1 ± 1.3	48.7 ± 1.1	46.1 ± 0.1
		ε''	4.7 ± 0.4	5.4 ± 0.4	6.4 ± 0.4	7.8 ± 0.3	9.7 ± 0.2	12.2 ± 0.1	14.4 ± 0.3
	915	ε'	46.0 ± 0.1	47.7 ± 0.5	48.0 ± 0.6	48.3 ± 0.8	47.5 ± 1.3	45.6 ± 1.3	44.6 ± 0.1
		ε''	14.8 ± 0.1	12.8 ± 0.0	10.8 ± 0.3	9.0 ± 0.3	7.5 ± 0.3	5.9 ± 0.3	4.8 ± 0.4
	2450	ε'	33.8 ± 0.1	36.9 ± 0.5	38.9 ± 0.4	41.0 ± 0.6	41.8 ± 1.2	41.7 ± 1.1	41.5 ± 0.0
		ε''	17.6 ± 0.1	16.9 ± 0.1	15.6 ± 0.2	14.1 ± 0.2	12.4 ± 0.3	10.2 ± 0.3	8.4 ± 0.6
	4500	ε'	25.8 ± 0.2	29.0 ± 0.3	31.4 ± 0.1	34.3 ± 0.3	35.8 ± 0.8	37.1 ± 0.7	37.5 ± 0.0
		ε''	17.3 ± 0.0	17.6 ± 0.1	17.2 ± 0.2	16.6 ± 0.2	15.4 ± 0.4	13.6 ± 0.4	11.7 ± 0.7

Table 2
Dielectric properties (mean ± standard deviation) of pure jujube honey (17.6%) and its solutions with seven water contents at seven temperatures and five selected frequencies.

Water content (%)	Frequency (MHz)		Temperature (°C)						
			20	30	40	50	60	70	80
17.6	10	ε'	35.8 ± 1.1	36.6 ± 1.2	37.5 ± 1.8	39.8 ± 1.3	40.7 ± 1.4	38.9 ± 3.7	39.1 ± 2.3
		ε''	7.3 ± 0.8	6.9 ± 0.5	5.8 ± 0.4	5.0 ± 0.7	4.4 ± 0.5	3.6 ± 0.8	6.2 ± 1.4
	27	ε'	30.2 ± 0.8	31.1 ± 0.8	32.1 ± 1.2	35.2 ± 1.1	37.4 ± 1.3	37.3 ± 3.5	38.3 ± 2.1
		ε''	8.4 ± 0.5	8.3 ± 0.4	8.0 ± 0.6	7.4 ± 0.4	6.2 ± 0.1	4.2 ± 0.4	4.2 ± 0.4
	915	ε'	11.9 ± 0.2	12.3 ± 0.2	12.8 ± 0.4	14.6 ± 0.4	17.1 ± 0.9	20.9 ± 2.4	25.7 ± 2.5
		ε''	5.2 ± 0.1	5.4 ± 0.1	5.7 ± 0.1	6.8 ± 0.2	7.9 ± 0.4	8.9 ± 1.0	9.3 ± 0.4
	2450	ε'	9.2 ± 0.2	9.5 ± 0.2	9.8 ± 0.3	10.9 ± 0.3	12.4 ± 0.6	15.1 ± 1.6	18.9 ± 2.0
		ε''	3.7 ± 0.1	3.8 ± 0.1	4.1 ± 0.1	5.0 ± 0.2	6.1 ± 0.4	7.7 ± 0.9	9.3 ± 0.8
	4500	ε'	8.3 ± 0.2	8.4 ± 0.2	8.6 ± 0.3	9.4 ± 0.3	10.4 ± 0.5	12.2 ± 1.3	15.1 ± 1.6
		ε''	3.1 ± 0.0	3.2 ± 0.1	3.5 ± 0.1	4.3 ± 0.1	5.2 ± 0.3	6.7 ± 0.8	8.6 ± 0.8
22.1	10	ε'	45.1 ± 2.5	46.1 ± 2.1	46.4 ± 1.8	45.0 ± 1.0	43.5 ± 0.5	41.0 ± 0.8	38.6 ± 1.6
		ε''	6.1 ± 0.4	5.8 ± 0.4	5.7 ± 0.4	5.2 ± 0.7	6.8 ± 1.4	9.7 ± 2.3	14.1 ± 2.1
	27	ε'	40.8 ± 2.2	42.3 ± 2.0	43.4 ± 2.0	42.9 ± 0.9	42.3 ± 0.6	40.4 ± 0.8	38.1 ± 1.7
		ε''	8.1 ± 0.4	7.9 ± 0.2	7.2 ± 0.2	5.9 ± 0.2	5.2 ± 0.1	5.4 ± 0.4	6.3 ± 0.4
	915	ε'	16.8 ± 0.8	18.0 ± 1.0	19.8 ± 1.7	22.3 ± 0.5	25.7 ± 0.1	28.8 ± 0.1	30.2 ± 1.0
		ε''	8.8 ± 0.6	9.3 ± 0.7	10.1 ± 0.9	10.6 ± 0.4	10.9 ± 0.3	10.2 ± 0.5	9.0 ± 0.7
	2450	ε'	12.0 ± 0.1	12.7 ± 0.6	13.8 ± 1.0	15.6 ± 0.3	18.2 ± 0.1	21.2 ± 0.2	23.2 ± 0.5
		ε''	6.4 ± 0.4	6.9 ± 0.5	7.8 ± 0.9	8.8 ± 0.3	9.9 ± 0.2	10.6 ± 0.2	10.5 ± 0.5
	4500	ε'	9.9 ± 0.1	10.5 ± 0.5	11.2 ± 0.8	12.4 ± 0.3	14.3 ± 0.1	16.7 ± 0.1	18.6 ± 0.5
		ε''	5.2 ± 0.3	5.6 ± 0.4	6.4 ± 0.7	7.4 ± 0.2	8.7 ± 0.1	9.9 ± 0.1	10.3 ± 0.3
26.2	10	ε'	51.7 ± 0.2	51.6 ± 0.1	50.5 ± 0.2	48.1 ± 0.7	45.7 ± 1.4	44.0 ± 1.7	42.1 ± 1.6
		ε''	6.1 ± 1.1	5.4 ± 1.1	5.0 ± 1.2	7.2 ± 1.4	10.1 ± 1.6	14.6 ± 1.1	20.0 ± 1.0
	27	ε'	48.5 ± 0.3	48.8 ± 0.1	48.5 ± 0.1	47.1 ± 0.7	45.1 ± 1.2	43.5 ± 1.4	41.5 ± 1.3
		ε''	7.5 ± 0.2	6.9 ± 0.3	6.0 ± 0.5	5.5 ± 0.5	5.7 ± 0.5	6.8 ± 0.4	8.5 ± 0.3
	915	ε'	22.4 ± 0.2	23.6 ± 0.1	26.2 ± 0.3	29.6 ± 0.3	32.5 ± 0.0	34.5 ± 0.5	35.4 ± 0.5
		ε''	11.6 ± 0.1	12.0 ± 0.1	12.4 ± 0.2	12.2 ± 0.2	11.3 ± 0.1	10.2 ± 0.1	8.9 ± 0.1
	2450	ε'	15.4 ± 0.2	16.2 ± 0.1	18.0 ± 0.3	20.9 ± 0.3	32.9 ± 0.0	26.5 ± 0.4	28.4 ± 0.5
		ε''	9.0 ± 0.1	9.5 ± 0.1	10.5 ± 0.1	11.5 ± 0.1	12.0 ± 0.2	12.0 ± 0.1	11.5 ± 0.1
	4500	ε'	12.4 ± 0.1	12.9 ± 0.2	14.2 ± 0.4	16.4 ± 0.4	18.9 ± 0.2	21.2 ± 0.6	23.1 ± 0.7
		ε''	7.4 ± 0.2	7.9 ± 0.1	8.9 ± 0.0	10.3 ± 0.1	11.3 ± 0.2	11.9 ± 0.0	12.0 ± 0.0
30.3	10	ε'	56.2 ± 1.0	55.5 ± 1.5	53.2 ± 2.0	51.4 ± 2.4	48.7 ± 2.7	44.1 ± 5.4	38.6 ± 0.9
		ε''	6.3 ± 0.5	6.4 ± 1.1	8.7 ± 1.5	12.4 ± 1.9	17.6 ± 2.2	23.0 ± 3.7	28.8 ± 4.1
	27	ε'	54.2 ± 0.9	53.8 ± 1.2	52.0 ± 1.8	50.3 ± 2.2	47.7 ± 2.7	43.0 ± 5.3	37.4 ± 6.9
		ε''	5.7 ± 0.1	5.5 ± 0.2	5.5 ± 0.3	6.3 ± 0.5	7.6 ± 0.7	9.2 ± 1.3	11.1 ± 1.5
	915	ε'	31.3 ± 0.6	32.3 ± 0.9	34.9 ± 1.8	37.2 ± 1.8	38.3 ± 2.3	36.7 ± 4.3	37.6 ± 5.6
		ε''	14.2 ± 0.2	14.0 ± 0.2	13.1 ± 0.3	11.9 ± 0.3	10.3 ± 0.5	8.2 ± 1.1	6.2 ± 1.4
	2450	ε'	21.3 ± 0.4	22.3 ± 0.6	24.9 ± 1.4	27.7 ± 1.4	29.9 ± 1.8	30.1 ± 3.3	29.0 ± 4.4
		ε''	12.8 ± 0.2	13.1 ± 0.3	13.5 ± 0.6	13.6 ± 0.6	13.0 ± 0.7	11.4 ± 1.4	9.3 ± 1.9
	4500	ε'	16.4 ± 0.3	17.1 ± 0.5	19.2 ± 1.1	21.7 ± 1.2	23.9 ± 1.4	24.7 ± 2.5	24.6 ± 3.4
		ε''	11.1 ± 0.3	11.5 ± 0.4	12.5 ± 0.7	13.3 ± 0.7	13.5 ± 0.8	12.6 ± 1.5	11.1 ± 2.0
34.4	10	ε'	56.9 ± 1.7	56.4 ± 1.3	54.3 ± 0.9	51.9 ± 1.1	48.9 ± 1.7	45.1 ± 1.4	41.4 ± 3.1
		ε''	7.1 ± 0.6	8.9 ± 0.4	12.1 ± 0.9	17.2 ± 0.5	23.2 ± 1.4	29.8 ± 1.3	42.7 ± 0.7
	27	ε'	55.5 ± 1.7	55.1 ± 1.3	53.4 ± 0.9	51.1 ± 1.5	48.0 ± 1.8	44.1 ± 1.5	40.2 ± 1.0
		ε''	5.6 ± 0.1	5.7 ± 0.2	6.2 ± 0.3	7.5 ± 0.3	9.3 ± 0.6	11.6 ± 0.6	16.0 ± 1.6
	915	ε'	34.5 ± 1.8	37.2 ± 1.2	39.1 ± 1.0	40.6 ± 0.9	40.6 ± 1.5	39.3 ± 1.3	37.9 ± 2.5
		ε''	14.7 ± 0.5	14.1 ± 0.4	12.9 ± 0.2	11.2 ± 0.4	9.3 ± 0.5	7.4 ± 0.4	5.8 ± 0.3
	2450	ε'	23.8 ± 1.3	26.5 ± 0.8	29.0 ± 0.7	31.6 ± 0.6	33.2 ± 1.0	33.7 ± 0.9	34.1 ± 2.2
		ε''	14.0 ± 0.8	14.5 ± 0.6	14.4 ± 0.4	13.9 ± 0.5	12.7 ± 0.7	11.0 ± 0.6	9.1 ± 0.7
	4500	ε'	18.1 ± 0.9	20.3 ± 0.5	22.6 ± 0.4	25.2 ± 0.2	27.1 ± 0.5	28.4 ± 0.4	29.8 ± 1.7
		ε''	12.2 ± 0.7	13.2 ± 0.5	13.8 ± 0.4	14.2 ± 0.4	13.8 ± 0.7	12.8 ± 0.6	11.5 ± 0.9
38.5	10	ε'	56.8 ± 1.8	55.5 ± 1.4	53.8 ± 0.4	50.3 ± 0.5	46.8 ± 0.5	43.6 ± 0.7	40.6 ± 0.6
		ε''	9.8 ± 0.6	13.6 ± 0.2	17.8 ± 0.5	24.1 ± 0.9	31.8 ± 1.3	41.0 ± 0.5	50.6 ± 0.5
	27	ε'	55.8 ± 1.6	54.8 ± 1.1	53.1 ± 0.4	49.9 ± 0.5	46.3 ± 0.4	43.0 ± 0.6	39.7 ± 0.3
		ε''	6.0 ± 0.1	6.8 ± 0.1	7.9 ± 0.3	9.9 ± 0.4	12.5 ± 0.5	15.6 ± 0.2	18.9 ± 0.3
	915	ε'	38.1 ± 0.6	40.4 ± 1.1	42.1 ± 0.6	42.5 ± 0.7	41.6 ± 0.9	40.2 ± 1.1	38.3 ± 1.0
		ε''	14.5 ± 0.7	13.4 ± 0.4	12.0 ± 0.3	10.1 ± 0.4	8.2 ± 0.4	6.6 ± 0.5	5.5 ± 0.4
	2450	ε'	26.8 ± 0.2	29.6 ± 0.8	32.2 ± 0.4	34.1 ± 0.5	35.1 ± 0.6	35.3 ± 0.7	34.7 ± 0.8
		ε''	15.1 ± 0.4	15.1 ± 0.4	14.8 ± 0.3	13.7 ± 0.4	12.0 ± 0.4	10.3 ± 0.6	8.7 ± 0.5
	4500	ε'	20.5 ± 0.1	23.1 ± 0.7	25.6 ± 0.3	27.8 ± 0.3	29.5 ± 0.4	30.6 ± 0.3	30.9 ± 0.4
		ε''	13.8 ± 0.2	14.6 ± 0.4	15.0 ± 0.2	14.7 ± 0.2	13.8 ± 0.3	12.6 ± 0.4	11.2 ± 0.4
42.6	10	ε'	61.1 ± 0.5	59.7 ± 0.6	57.6 ± 1.1	55.7 ± 1.1	53.0 ± 1.0	50.2 ± 0.7	46.9 ± 0.4
		ε''	15.5 ± 0.9	19.7 ± 1.0	25.9 ± 1.2	33.8 ± 1.1	43.6 ± 2.0	55.0 ± 1.8	67.0 ± 3.0
	27	ε'	60.2 ± 0.3	58.8 ± 0.3	56.6 ± 0.8	54.5 ± 0.6	51.7 ± 0.6	48.7 ± 0.2	45.3 ± 0.3
		ε''	7.3 ± 0.3	8.5 ± 0.3	10.4 ± 0.4	13.1 ± 0.4	16.6 ± 0.8	20.6 ± 0.7	24.9 ± 1.0
	915	ε'	45.2 ± 0.4	47.0 ± 0.2	47.9 ± 0.2	48.1 ± 0.1	47.1 ± 0.2	45.7 ± 0.6	43.3 ± 1.1
		ε''	14.6 ± 0.2	12.9 ± 0.3	11.1 ± 0.3	9.2 ± 0.4	7.6 ± 0.4	6.3 ± 0.6	5.2 ± 0.6
	2450	ε'	33.3 ± 0.1	36.2 ± 0.2	38.7 ± 0.6	40.7 ± 0.6	41.4 ± 0.3	41.4 ± 0.1	40.2 ± 0.4
		ε''	17.1 ± 0.5	16.5 ± 0.5	15.4 ± 0.5	13.8 ± 0.6	11.9 ± 0.6	10.1 ± 0.8	8.3 ± 0.9
	4500	ε'	25.5 ± 0.5	28.5 ± 0.8	31.3 ± 1.3	30.1 ± 1.4	35.8 ± 1.2	36.8 ± 1.1	36.6 ± 0.8
		ε''	16.3 ± 0.2	16.6 ± 0.2	16.4 ± 0.1	15.6 ± 0.2	14.3 ± 0.3	12.7 ± 0.5	10.9 ± 0.7

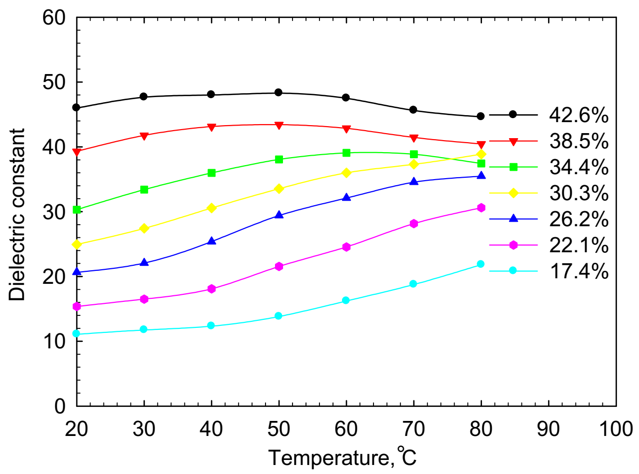

Fig. 3. Effect of temperature on the dielectric constant of yellow-locust honey solutions with indicated water contents at 915 MHz.

3.3. Penetration depth

The calculated penetration depths of yellow-locust honey solutions with 17.4% and 30.3% water contents at 20, 40, 60 and 80 °C from 10 to 4500 MHz are shown in Fig. 6. It shows that penetration depth decreased with increasing frequency at a given temperature. For 17.4% honey, the penetration depth was reasonably linear with frequency in the log–log plot at a given temperature (Fig. 6(a)). It can be described by:

$$\log D_p = a \log f + b \quad (1)$$

where a is the slope of the regression line, and b is the intercept at $\log D_p = 0$. The regression constants and coefficients of determination (R^2) for 17.4% honey at various temperatures are listed in Table 5. Penetration depth increased with increasing temperature at lower frequencies, but it decreased with temperature at the higher frequencies. However, the linear relationship between pen-

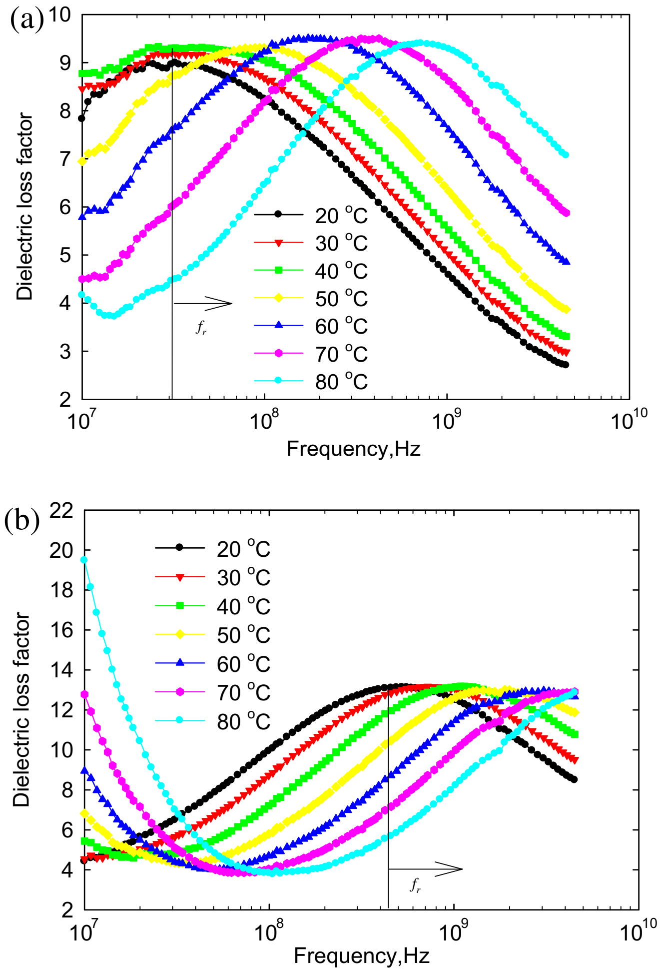

Fig. 4. The measured dielectric loss factors and the relaxation frequency (f_r) of yellow-locust honey solutions with 17.4% (a) and 30.3% (b) water contents at indicated temperatures as a function of frequency.

Table 3
The relaxation frequencies and maximum loss factor values for yellow-locust honey solutions with various water contents at 20–80 °C over the frequency range from 10 to 4500 MHz.

Water content (%)	Relaxation frequency (MHz)							Maximum loss factor values						
	20 °C	30 °C	40 °C	50 °C	60 °C	70 °C	80 °C	20 °C	30 °C	40 °C	50 °C	60 °C	70 °C	80 °C
17.4	32.4	36.8	45.4	99.4	202	424	720	9.00	9.17	9.32	9.31	9.50	9.49	9.40
22.1	110	144	230	490	780	1265	2443	10.60	10.68	10.75	10.75	10.85	10.89	10.73
26.2	337	424	588	1144	1884	3060	–[a]	12.50	12.51	12.53	12.41	12.28	–	–
30.3	522	720	1083	1438	2443	–	–	13.13	13.18	13.18	12.98	12.93	–	–
34.4	780	1023	1326	1884	2854	–	–	15.97	15.68	15.11	14.38	13.48	–	–
38.5	2108	2443	4089	–	–	–	–	16.05	16.14	15.93	–	–	–	–
42.6	2443	–	–	–	–	–	–	17.62	–	–	–	–	–	–

[a] Dashes in the table indicate that the relaxation frequency is outside the frequency range of the measurement.

Table 4
The relaxation frequencies and maximums of loss factor for jujube honey solutions with various water contents at 20–80 °C over the frequency range from 10 to 4500 MHz.

Water content (%)	Relaxation frequency (MHz)							Maximum of loss factor						
	20 °C	30 °C	40 °C	50 °C	60 °C	70 °C	80 °C	20 °C	30 °C	40 °C	50 °C	60 °C	70 °C	80 °C
17.6	48.2	59.7	67.8	125	248	654	1205	8.58	8.59	8.60	8.86	9.04	8.99	9.55
22.1	202	248	301	424	1023	1438	3060	10.63	10.87	11.08	10.89	10.88	10.67	10.50
26.2	391	424	654	1023	1996	3060	–[a]	12.49	12.55	12.51	12.32	12.12	12.04	–
30.3	962	1265	1996	2443	–	–	–	14.15	13.97	13.68	13.57	–	–	–
34.4	1084	1996	2443	4294	–	–	–	14.81	14.66	14.43	14.19	–	–	–
38.5	1996	2331	3471	–	–	–	–	15.27	15.18	15.04	–	–	–	–
42.6	2443	3266	–	–	–	–	–	17.09	16.70	–	–	–	–	–

[a] Dashes in the table indicate that the relaxation frequency is outside the frequency range of the measurement.

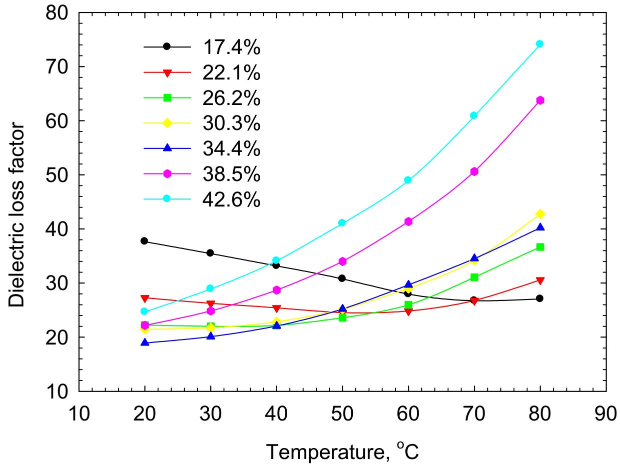

Fig. 5. The dielectric loss factor as a function of temperature of yellow-locust honey solutions with indicated water contents at 915 MHz.

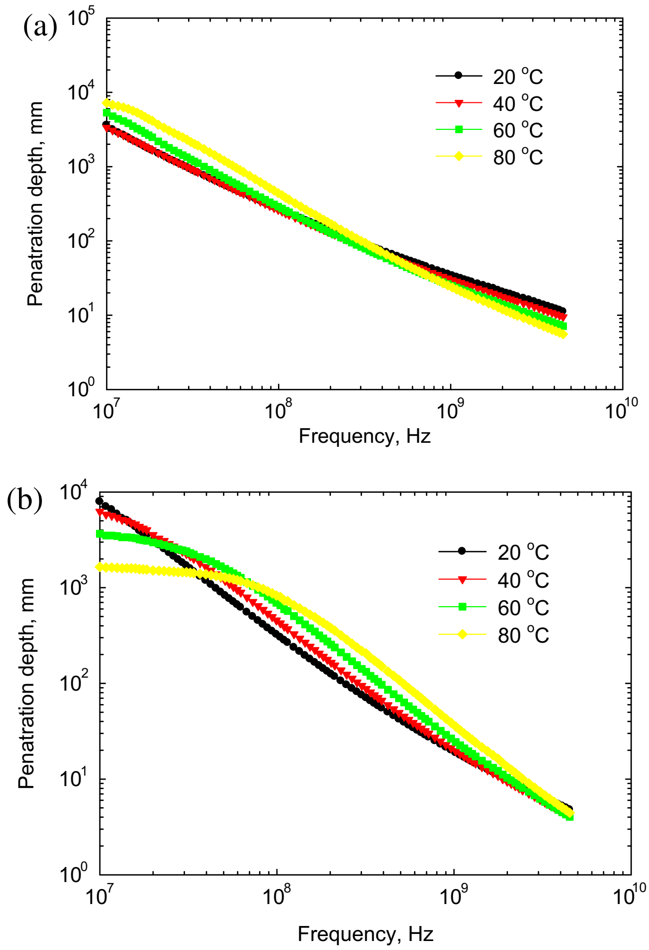

Fig. 6. The calculated penetration depths of yellow-locust honey solutions with 17.4% (a) and 30.3% (b) water contents at indicated temperatures as a function of frequency.

etration depth and frequency in the log–log plot only existed at 20 °C for 30.3% honey solution, and penetration depth decreased slowly at lower frequencies and higher temperatures (Fig. 6(b)). Moreover, temperature reduced the penetration depth below 30 MHz but raised it at about 200 MHz for 30.3% honey solution.

Table 5
The regression constants and coefficients of determination in Eq. (1) for pure yellow-locust honey at various temperatures.

Temperature (°C)	*a*	*b*	R^2
20	−0.926	9.888	0.994
30	−0.944	10.024	0.994
40	−0.961	10.152	0.995
50	−1.017	10.619	0.993
60	−1.089	11.234	0.994
70	−1.166	11.910	0.995
80	−1.236	12.544	0.997

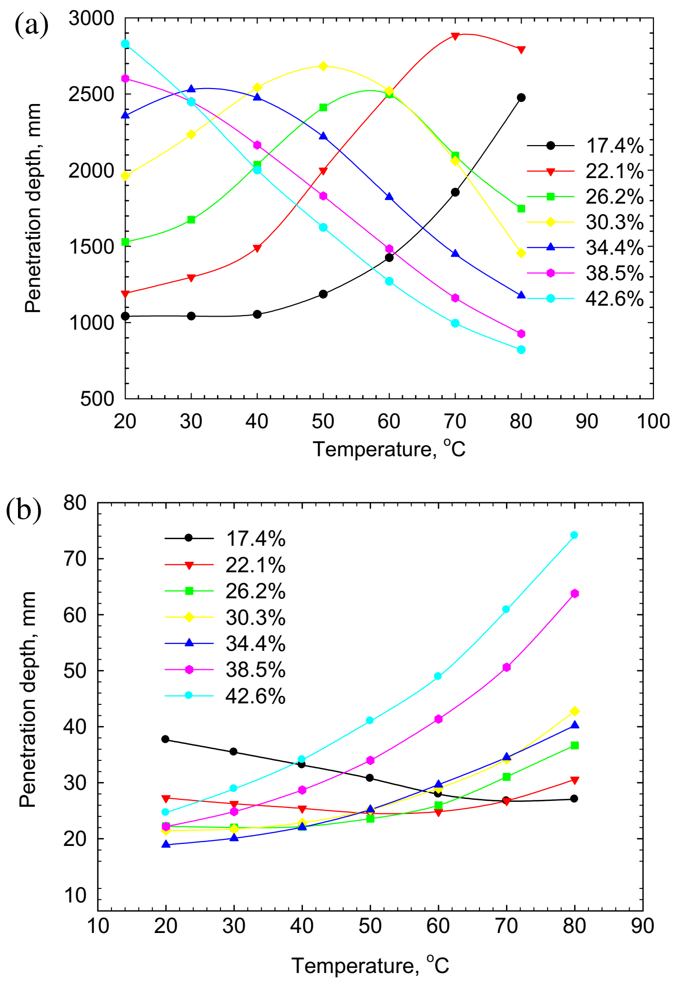

Fig. 7. Penetration depths of yellow-locust honey solutions with indicated water contents as a function of temperature from 20 to 80 °C at 27 MHz (a) and 915 MHz (b).

Fig. 7 shows the effect of temperature on penetration depth with various water contents of yellow-locust honey samples at 27 MHz (a) and 915 MHz (b). No general trends were observed between penetration depth and temperature. Fig. 7(a) illustrates that, at 27 MHz, the penetration depth in honey with 17.4% water content increased with temperature, and increased greatly at higher temperatures. The maximal penetration depths were at 70, 60, 50 and 30 °C for the honey samples with 22.1%, 26.2%, 30.3% and 34.4% water contents, respectively. The depth decreased with increasing temperature at 38.5% and 42.6%. It also shows that the lowest penetration depth at room temperature (20 °C), 1040 mm, was found in pure honey. However, the lowest at 80 °C, 820 mm, was found in the highest water content (42.6%). At 915 MHz, except for 17.4% and 22.1% water contents, the penetration depth at any given water content increased with increasing temperature (Fig. 7(b)). For example, it increased from 18.9 to 40.2 mm and from 24.7 to 74.1 mm at 34.4% and 42.6% water contents when temperature increased from 20 to 80 °C, respectively. At 20 °C, the greatest penetration depth, 37.6 mm, existed in pure honey (17.4% water content), but it appeared in 42.6% honey sample at 80 °C. The smallest penetration depth for pure honey at 80 °C was 27 mm. Similar frequency- and temperature-dependent penetration depths were found for jujube honey.

For uniform pasteurization with dielectric heating, the thickness of food material should not be more than two or three times the penetration depth (Schiffmann, 1995). Thus, considering penetration depths for pure honey, thickness for dielectric heating would be between 2 and 3 m at 27 MHz and between 54 and 81 mm at 915 MHz.

4. Conclusions

Frequency, water content, and temperature affect the dielectric properties of yellow-locust and jujube honey. For pure honey with no more than 18.0% water content, the dielectric constant increased with increasing temperature at 20–80 °C over the frequency range from about 40 to 4500 MHz. For honey diluted with water, the dielectric constant decreased with increasing temperature at lower frequencies and increased with temperature at higher frequencies. For diluted honey, prominent dielectric relaxations were noted in the 10–4500 MHz range, which shifted to higher frequencies with increasing temperature. Maximum values of loss factor showed little change with temperature. Ionic conduction played a dominant role at higher temperatures and higher water contents. There was strong negative linear correlation between penetration depth and frequency in log–log plots for pure honey at 20–80 °C from 10 to 4500 MHz. In diluted honey, the penetration depth decreased with temperature below 30 MHz, but at about 200 MHz, it increased with temperature. An appropriate thickness for heating honey at 915 MHz would be about 54–81 mm. The research will be helpful in honey pasteurization processing by radio-frequency and microwave dielectric heating.

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