Innovative Food Science and Emerging Technologies 74 (2021) 102837

Contents lists available at ScienceDirect

Innovative Food Science and Emerging Technologies

journal homepage: www.elsevier.com/locate/ifset

Dielectric properties of water relevant to microwave assisted thermal pasteurization and sterilization of packaged foods

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ARTICLE INFO

Keywords:
Dielectric properties
Microwave heating
Pasteurization
Purified water
Sterilization
Tap water

ABSTRACT

Microwave assisted thermal sterilization and pasteurization systems, as emerging thermal processing technologies, use circulation water to reduce edge heating of the food packages in the microwave heating sections. Yet, the influence of the circulation water on microwave heating efficiency for food is unknown. This research studied the dielectric properties of purified water from a reverse osmosis unit and tap water over microwave frequencies of 150–2500 MHz at 23–120 °C and evaluated microwave loses in the circulation water. The values of the dielectric constant of purified and tap water decreased ($P < 0.05$) with increasing temperature and slightly decreased with increasing frequency. The value of the loss factor of purified water also decreased with temperature ($P < 0.05$) but increased with frequency. The trend was more complicated for the loss factor of tap water. The penetration depth of 915 MHz microwave power in purified water was 399 and 457 mm at 90 and 120 °C, respectively, it was reduced to 161 and 136 mm in tap water. The microwave power loss in the 18–30 mm deep purified water, depending on the thickness of the food packages, was 4–7%, compared to 11–20% in tap water. Thus, using purified circulation water in microwave assisted thermal sterilization (MATS) and pasteurization systems (MAPS) can significantly improve the efficiency of microwave heating of packaged foods.

Industrial relevance: The information from this research are highly relevant to industrial operations of microwave-assisted thermal sterilization and pasteurization systems of pre-packaged foods. The dielectric property data will contribute to the literature related to the physical properties of water in microwave heating.

1. Introduction

Microwave assisted thermal sterilization (MATS) system and microwave assisted pasteurization system (MAPS) are emerging technologies recently developed for commercial production of high quality pre-packaged ready-to-eat meals with extended shelf life at room temperature or in refrigeration (Tang, 2015; Tang, Hong, Inanoglu, & Liu, 2018). In both MATS systems and MAPS, low ionic conductive circulation hot water is used to reduce edge heating in food packages in the 915 MHz single-mode microwave cavities. Furthermore, the circulation water broadens the bandwidth of the resonant frequency (reduces Q factor) of the microwave cavities, as an important design consideration to enhance system performance (Tang, 2015). The knowledge of the dielectric properties of water having different ionic conductivities as functions of temperature and frequency would help process developers to estimate microwave penetration through circulation water to reach the packaged foods in MATS systems and MAPS. Additionally, dielectric properties will allow the selection of appropriate circulation water to ensure that the systems meet performance requirements.

Materials dielectric properties can be described by the complex relative permittivity (ε^*) as:

$$\varepsilon^* = \varepsilon' – j\varepsilon'' \tag{1}$$

where j is $\sqrt{-1}$, ε' is the dielectric constant that represents the ability of the material to store electric energy, and ε'' is the dielectric loss factor which describes the ability to convert microwave energy to thermal energy (Nelson, 1973; Tang, 2005). Both dipole rotation of water molecules and migration of ions in the material play a major role in the conversion of microwave energy into thermal energy. The dielectric loss

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https://doi.org/10.1016/j.ifset.2021.102837
Received 17 April 2021; Received in revised form 11 August 2021; Accepted 19 September 2021

factor reflects the summation of both dipole (ε''_d) and conductivity (ε''_σ) effects, as shown in (Ryynänen, 1995):

$$\varepsilon'' = \varepsilon''_d + \varepsilon''_\sigma = \varepsilon''_d + \frac{\sigma}{2\pi f \varepsilon_o} \tag{2}$$

where σ is ionic conductivity (S/m); ε_o is dielectric permittivity of vacuum (8.85×10^{-12} F/m), and f is frequency (Hz). Water molecules are the main contributor to the dipole effects, while dissolved salts contribute to ionic conductivity (Tang, 2015).

In a pure liquid with ideal spherical molecules, the relaxation time (τ), which is the time required by the molecules for reorientation of the dipolar moments in the electric field direction, is related to the viscosity and temperature of the liquid as the result of Brownian motion (Eq. (3)) (von Hippel, 1954). Based on the Arrhenius approach, the inverse relationship between fluid viscosity and temperature can be expressed according to Eq. (4) (Tang, 2005):

$$\tau = V\frac{3\eta}{kT} \tag{3}$$

$$\eta = \eta_o e^{E_a/\left(R_g T\right)} \tag{4}$$

In Eq. (3) τ (*sec*) is relaxation time, V (m^3) is the volume of a molecule, η (kg/(m.s)) is viscosity, k (1.38×10^{-23} J/K) is the Boltzmann constant, and T (K) is absolute temperature. In Eq. (4), η_o is the initial viscosity, E_a (J/mol) is the activation energy, and R_g (8.3145 J/(K.mol)) is the universal gas constant. The critical frequency f_c (Hz), at which the dielectric loss factor reaches its maximum value, is related to the relaxation time (τ) as follow (Nelson, 1973):

$$f_c = \frac{1}{2\pi\tau} \tag{5}$$

In the USA, the Federal Communications Commission (FCC) has allocated a limited number of microwave frequency bands for Industrial, Scientific, and Medical (ISM) applications to avoid interference with radar and wireless communications. Both 915 ± 13 and 2450 ± 50 MHz are used for industrial microwave food processing (Tang, 2015). The MATS systems and MAPS use 915 MHz microwaves because of the relatively long wavelength and availability of high-power commercial microwave generators at this frequency (Tang, 2015). Both systems have four main sections: preheating, heating, holding and cooling. The four sections are filled with circulation water at controlled temperatures. The temperature of circulation water in the microwave heating and holding sections is about 120 °C in a MATS system and about 90 °C in a MAPS. In the microwave heating section, pre-packaged foods are heated by both the circulation water and microwaves (Tang, 2015; Tang et al., 2018). The circulation water mitigates the fringing microwave fields that could cause edge heating of pre-packed foods. Both the MATS systems and MAPS sharply shorten the exposure time of food products to the elevated temperatures needed for pathogen control compared to conventional heating methods, resulting in better product quality (Barnett et al., 2020; Tang, 2015). Questions arise as to how much microwave energy is absorbed by the circulation water before reaching the foods in a a MATS system or MAPS, and what are the benefits of using 915 MHz instead of 2450 MHz microwaves in terms of energy efficiency.

In industrial operations, food plants may use local tap water, purified water generated from reverse osmosis units, or mixtures of both, as the circulation water. Thus, tap water and purified water represent the two extremes for commercial operations of MATS systems and MAPS. There has been no reported systematic study on the dielectric properties of purified and tap waters over the temperature range (23–120 °C) that is relevant to the operation of MATS systems and MAPS. Information on temperature dependent dielectric properties of water at 2450 MHz also provides useful insights into heating in domestic microwave ovens. The objectives of this research were to study the dielectric properties of purified and tap waters in the frequency range of 150–2500 MHz from room temperature (23 °C) to 120 °C and to investigate the effects of frequency and temperature on the penetration of microwaves through purified and tap water.

2. Materials and methods

2.1. Sample preparation

Purified water was collected from a 00SRO730 Reverse Osmosis filtration system with the R22–2521 membrane (AmeriWater, Dayton, OH, USA). Tap water was collected from the laboratory (Washington State University (WSU), Pullman, WA, USA) after running the water for 5 min.

2.2. Dielectric property measurement

The dielectric properties of purified and tap water samples were measured using an Agilent E5071C Network Analyzer and 85070E Open-End Coaxial Dielectric Probe (Agilent Technologies, Santa Clara, CA, USA) as shown in Fig. 1A. The measurements were conducted over the frequency range 150–2500 MHz and the temperature range 23–120 °C. To prevent the water samples from boiling during the measurement at and above 100 °C, they were held in a custom-built temperature-controlled test cell, as shown in Fig. 1B. The test cell was built from 2 coaxial stainless steel sanitary tubes and two stainless sanitary caps that were fastened together using stainless sanitary cramps (not shown). The jacket formed between the two coaxial tubes of the test cell allowed a circulating fluid to heat the sample in the inner tube. Under the compression of the cramps, silicon gaskets between the caps and the flanges welded to the top and bottom of the coaxial tubes provided a tight seal while the sample was heated by the external fluid. This test cell was used in dielectric property measurement over a temperature range of up to 120 °C for several materials related to microwave assisted thermal sterilization (Auksornsri, Tang, Tang, Lin, & Songsermpong, 2018; Guan, Cheng, Wang, & Tang, 2004; Luan et al., 2015).

Before measurement, the network analyzer and the probe were calibrated using an open circuit (air), a short circuit (gold-plated precision shorting block), and a known load (25 °C Milli-Q water). After calibration, the test cell was filled with a water sample. The dielectric property measurement probe, which was installed tightly through a sanitary cap, was then placed on top of the loaded test cell and kept in contact with the sample during the measurement. A programmable AP07R-20-A11B circulating bath (PolyScience Products, Niles, IL, USA) pumped the heating/cooling fluid through the test cell jacket, allowing the sample to be heated/cooled. The circulator was capable of providing the fluid at stable temperatures from −20 to 200 °C during measurements. A thermocouple probe was mounted through the bottom cap to measure sample temperature. Dielectric properties data of the samples were collected at 10 °C increments when the sample temperature was equilibrated with that of the fluid. The measurements were made in triplicate.

2.3. Ionic conductivity measurement

The ionic conductivity of the purified and tap water samples was measured using an Orion 3 Star conductivity meter (Thermo Scientific, Waltham, MA, USA). Conductivity probes of 013016MD and 013005MD were used for the purified and tap water samples, respectively. Calibration of these probes was performed by setting the respective cell constant number of the probes and using a 100 μS conductivity standard (Orion Application Solution). Conductivities were measured according to Thermo Fisher Scientific (2010) in triplicate from 23 to 90 °C.

2.4. Calculated dielectric properties

The values of the dielectric constant and loss factors of pure water

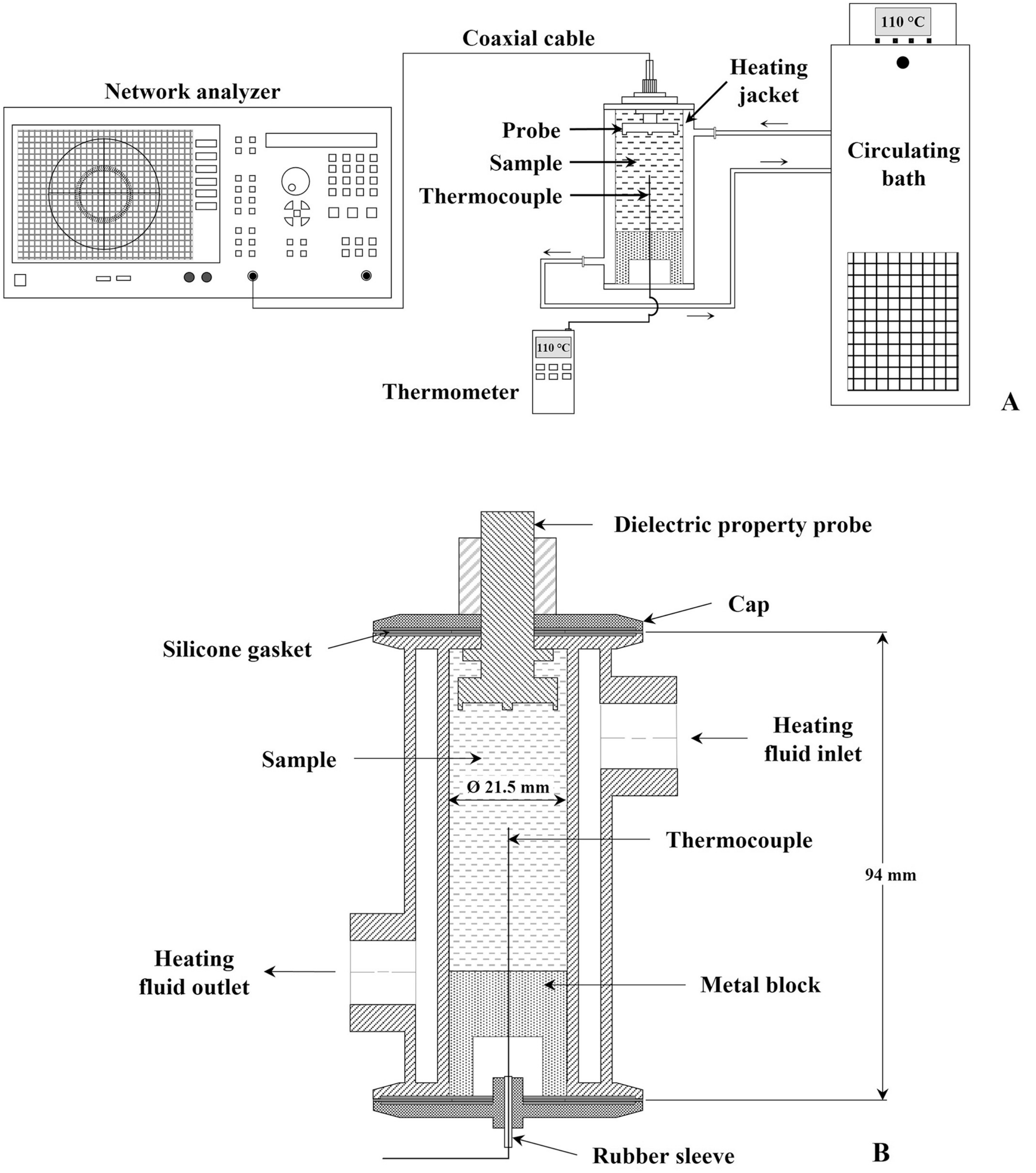

Fig. 1. Schematic diagram: (A) the experimental setup for dielectric property measurement (not to scale) and (B) a custom-built temperature-controlled test cell (adapted from Wang, Wig, Tang, & Hallberg, 2003).

samples at varying frequencies were calculated and interpreted using the Debye model (Nelson, 1973):

$$\varepsilon' = \varepsilon_\infty + \frac{(\varepsilon_s - \varepsilon_\infty)}{1 + \omega^2\tau^2} \tag{6}$$

$$\varepsilon'' = \frac{(\varepsilon_s - \varepsilon_\infty)\omega\tau}{1 + \omega^2\tau^2} \tag{7}$$

where ε_∞ is the relative permittivity (high-frequency permittivity), ε_s is the static dielectric constant (low-frequency permittivity), ω ($2\pi f$) is the angular frequency.

The complex permittivity of tap water samples can be expressed similarly to saline water based on the model described by Ulaby, Moore, and Fung (1986). The loss factor can be expressed as follow (Eves & Yakovlev, 2002):

$$\varepsilon'' = \frac{(\varepsilon_s - \varepsilon_\infty)\omega\tau}{1+\omega^2\tau^2} + \frac{\sigma}{2\pi f \varepsilon_o} \tag{8}$$

The constant parameters in Eqs. (6) to (8) can be predicted with the following empirical equations, which were developed based on experimental permittivity data measured over the temperature range from −4.1 to 60 °C, below 100 GHz and at atmospheric pressure (Kaatze, 1989):

$$\varepsilon_s = 10^{(1.94404 - 0.001991\times(T-273.15))} \tag{9}$$

$$\varepsilon_\infty = 5.77 - 0.0274 \times (T - 273.15) \tag{10}$$

$$\tau = 3.745\times10^{-15}\left(1 + \left(7\times10^{-5}\right)\times(T-300.65)^2 \times e^{\left(\frac{2295.7}{T}\right)}\right) \tag{11}$$

where T (K) is the absolute temperature.

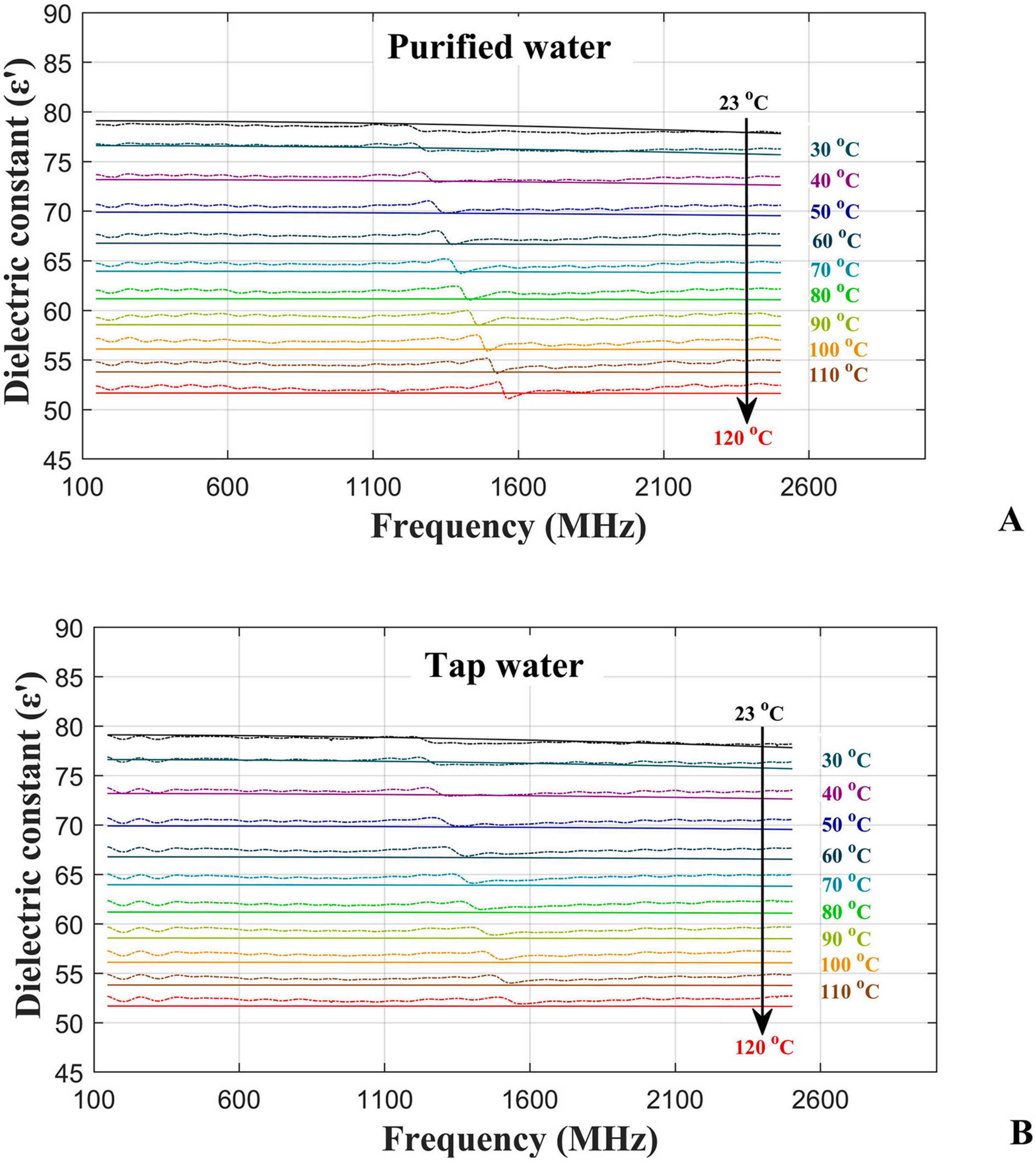

Fig. 2. Dielectric constants at various temperatures and frequencies. Continuous curves (—) were obtained from the Debye model (Eq. (6)), scattered dots (—.) were average of measurements ($n = 3$): (A) purified and (B) tap water.

2.5. Penetration depth determination

The penetration depth (d_p) is defined as thet distance over which 63% of microwave power is dissipated or the depth where the entering microwave power is reduced by a factor of $1/e$ ($e = 2.718$) (von Hippel, 1954). The penetration depth was calculated with the following equation:

$$d_p = \frac{c}{2\pi f\sqrt{2\varepsilon'\left[\left(\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2}\right)-1\right]}} \tag{12}$$

where c is the speed of light in free space ($\sim 3 \times 10^8$ m/s). The decay of the microwave power as it propagates through the circulation water was calculated using Eq. (13) (von Hippel, 1954):

$$P(z) = P_o e^{-2\alpha z} \tag{13}$$

where $P(z)$ (W/m^2) is microwave power in the circulation water at distance z from the surface of the water, P_o is the initial microwave power, and α (Np/m) is the attenuation constant, which causes the microwave amplitude to decrease along with propagation (Balanis, 2012):

$$\alpha = \frac{2\pi f}{c}\sqrt{\frac{\varepsilon'}{2}\left(\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2}-1\right)} \tag{14}$$

2.6. Statistical data analysis

The statistical and ANOVA analyses of purified and tap water dielectric properties were carried out using MATLAB with Statistics Toolbox software version 2020b (Natick, MA, USA). A comparison between means ($n = 3$) was performed at a significant level of $P \leq 0.05$, using the Tukey HSD test.

3. Results and discussion

3.1. Dielectric constant of water

3.1.1. Effect of frequency

Fig. 2A shows the experimental and calculated dielectric constant values of purified water in the 150–2500 MHz frequency range as influenced by temperature. The calculated dielectric constant values were obtained using the constant parameters from Table 1 and the Debye model (Eq. (6)). The experimental data matched well with the calculated values, the maximum difference between the values was less than 3%. A slight decline of the dielectric constant of purified water with increasing frequency can be explained according to the Debye model (Eq. (6)) that at a certain temperature, the increase of frequency reduces values of the dielectric constant (Kaatze, 1989; Kaatze & Uhlendorf, 1981; Tang, 2005).

A similar decline in dielectric constant with increasing frequency was observed in tap water (Fig. 2B). Although the Debye model was originally developed to describe the dielectric properties of pure water, the experimental dielectric constant values of the tap water fit well with the calculated values (Fig. 2B). This suggests that the dissolved ions in tap water did not influence the value of its dielectric constant.

Minor ripples were observed in the measured dielectric constants of purified and tap water samples in the range 1200–1600 MHz, as shown in Fig. 2. These were the artifacts of measurements caused by the resonance frequency of the sample testing cell (diameter: 21.5 mm). As the temperature increased from 23 to 120 °C, the phase velocity increased for the electromagnetic waves in the test tube, resulting in the shifting of the ripples to higher frequencies (Balanis, 2012). Since the artifacts occurred in the frequency range that is far from the two allocated frequencies (915 and 2450 MHz) for food processing, they did not cause notable errors in the measured dielectric properties at these two frequencies.

Table 1
The Debye model constant parameters (values obtained with Eqs. (9)–(11) and curve fitting).

Temperature (°C)	ε_S	ε_∞	τ (Sec 10^{-12})
23	79.11	5.14	8.50
30	76.61	4.95	7.29
40	73.18	4.67	5.78
50	69.90	4.40	4.72
60	66.77	4.13	3.95
70	63.95	3.85	3.20
80	61.18	3.58	2.70
90	58.56	3.30	2.20
100	56.11	3.03	2.10
110	53.81	2.76	1.90
120	51.68	2.48	1.70

3.1.2. Effect of temperature

Increasing the temperature from 23 to 120 °C caused a significant ($P < 0.05$) decrease in the dielectric constant in both purified and tap water samples (Fig. 2). As presented in Eq. (9), the increased Brownian motion with increasing temperature reduced the static dielectric constant (ε_s) (Tang, 2005; von Hippel, 1954). According to Eq. (6), the reduction in ε_s, in turn, reduced the dielectric constant. A similar decline in pure water dielectric constant with increasing temperature was also observed by Fernández-Prini, Corti, and Japas (1991) and Mudgett (1985).

As shown in Fig. 3, the dielectric constants of purified and tap water were not significantly different ($P < 0.05$) at both 915 and 2450 MHz and in the temperature range 23–120 °C.

At 915 MHz and 23 °C, the dielectric constant of purified water was 78.5 ± 0.05 (Fig. 3 (A)). This value was 0.5% less than the experimental data reported in Ikediala, Hansen, Tang, Drake, and Wang (2002) for pure water at 915 MHz and room temperature (22 °C). Tang, Hao, and Lau (2002) also reported a dielectric constant of 79.5 for pure water at 915 MHz and 20 °C. Additionally, Tang et al. (2002) reported 78.0 for pure water at 915 MHz and 25 °C. The dielectric constant of 78.0 ± 0.01 obtained for the purified water at 2450 MHz and 23 °C (Fig. 3 (B)) was also in agreement with the reported value (78.2) by Mudgett (1985) for pure water at 20 °C. The dielectric constant values calculated for purified water based on the Debye model also agree well with the experimental results obtained over the entire temperature range in this study (Fig. 3). The maximum difference between the experimental observations and calculated values was 1.5% at 915 MHz and 2.3% at 2450 MHz.

For the tap water collected from Pullman, WA, USA, Komarov and Tang (2004) determined the dielectric constant at 915 MHz and reported 74 and 56 at 40 and 121 °C, respectively. These values are slightly higher ($P < 0.05$) than the values obtained in this study for 40 °C (73.3 ± 0.3) and 120 °C (52.0 ± 0.1). The differences might have been caused by seasonal variations in the hardness of the local tap water. The local water used in this study was to illustrate the influence of the different dielectric characters of tap water, as compared to purified water, on microwave penetration in circulation water. It should be pointed out that the overall ions content and composition in tap water vary with the season in each plant location. Azoulay, Garzon, and Eisenberg (2001) and Patterson, Pehrsson, and Perry (2013) reported the presence of Cu, Ca, Mg, and Na in the USA tap water, where compositions of Mg and Ca show seasonal variability. The influence of ions and concentrations on the dielectric properties of water is reflected by ionic conductivity, as discussed in Tang (2015) and Peng, Tang, Jiao, Bohnet, and Barrett (2013).

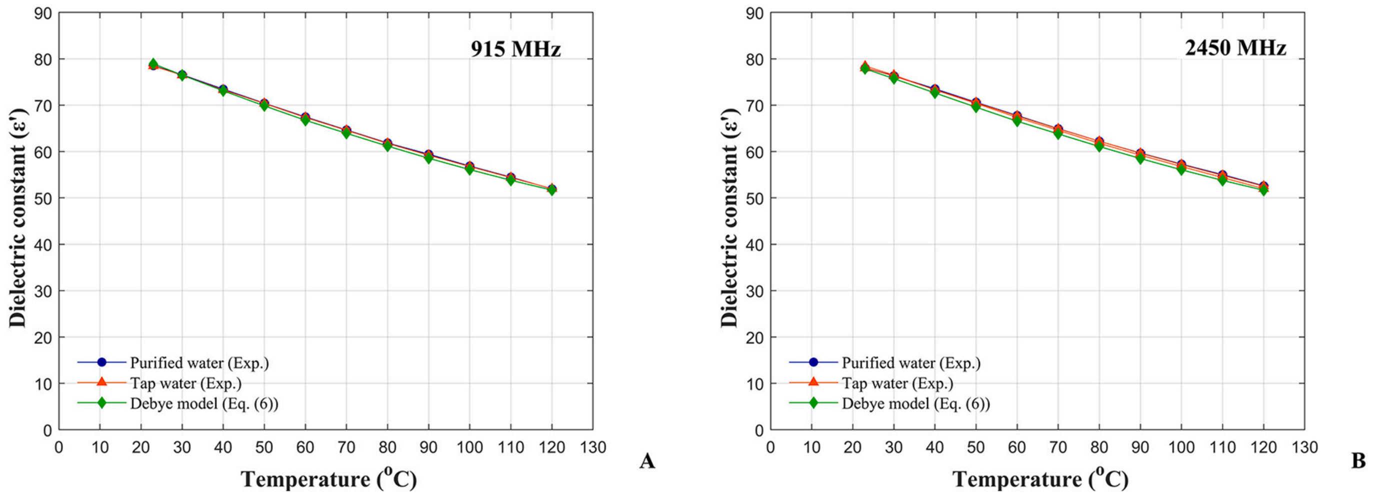

Fig. 3. Dielectric constant for purified and tap waters at (A) 915 MHz and (B) 2450 MHz; data are average values ($n = 3$).

3.2. *Dielectric loss factor of water*

3.2.1. *Effect of frequency*

Fig. 4A shows the experimental and calculated dielectric loss factors of purified water from 150 to 2500 MHz as influenced by temperature. The calculated results were obtained from the Ulaby model (Eq. (8)) using the ionic conductivity data in Table 1. As presented in the figure, the dielectric loss factors of purified water increased significantly ($P < 0.05$) with increasing frequency. This was expected as frequency approached the resonant frequency of pure water, which is around 20,000 MHz at room temperature (Tang, 2015). Additionally, Fig. 4A depicts a decline in loss factor with increasing temperature; this phenomenon was due to the shifting of the resonant frequency of pure water with increasing temperature (Eqs. (3, 5)) (Tang, 2005). The minor peaks in the frequency range 1200–1600 MHz were measurement artifacts caused by the resonance frequency of electromagnetic waves in the testing tube, as explained in Section 3.1.1.

The loss factor values of the tap water samples displayed two different responses over the measured frequency range, as shown in Fig. 4B. From 150 to 600 MHz, the dielectric loss factor was inversely related to frequency, while for frequencies beyond 600 MHz dielectric loss factor increased proportionally with frequency at temperatures up to 90°C. These two types of loss factor response for tap water resulted from ionic conductivity and water dipole rotation (İcier & Baysal, 2004; Ryynänen, 1995). Contribution of ionic conduction dominated at lower frequencies (<600 MHz). Such influence decreased with increasing frequency, according to Eq. (2). The decrease in the influence of ionic conductivity at higher frequencies reduced Eqs. (8) to (7), which caused the loss factor of tap water to behave similarly to purified water. Hence, at frequencies beyond 600 MHz, the loss factor of tap water was similar to that of the purified water. The increase in the loss factor value with increasing frequency was due to dipole rotation of water molecules, which dominated at higher frequencies (Calay, Newborough, Probert, &

Table 2
Measured conductivity of purified and tap waters; data are average values ($n = 3$).

Temperature (°C)	Ionic conductivity (μS/cm)	
	Purified water	Tap water
23	1.89 ± 0.00	318 ± 0
30	2.15 ± 0.00	371 ± 0
40	2.58 ± 0.00	441 ± 1
50	3.05 ± 0.01	519 ± 1
60	3.57 ± 0.01	609 ± 1
70	4.12 ± 0.01	700 ± 2
80	4.83 ± 0.01	809 ± 1
90	5.76 ± 0.00	943 ± 2

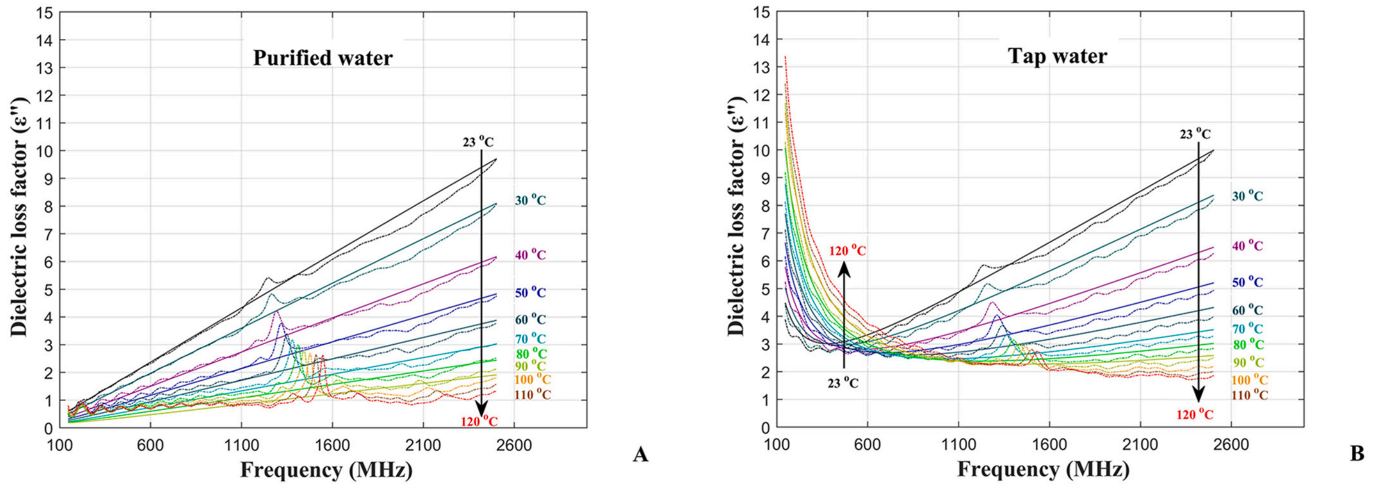

Fig. 4. Dielectric loss factors at various temperatures and frequencies. Continuous curves (—) obtained from the Ulaby model (Eq. (8)), scattered dots (—.) were average of measurements ($n = 3$): (A) purified and (B) tap water.

Calay, 1995; Tang & Resurreccion Jr, 2009). Similar observations were also reported by Roebuck, Goldblith, and Westphal (1972) for their carbohydrate-water mixtures.

3.2.2. *Effect of temperature*

The increase in temperature from 23 to 120 °C at a given frequency resulted in a significant ($P < 0.05$) reduction in the loss factor of the purified water (Fig. 4A). This was likely caused by increased Brownian motions at elevated temperatures. According to Eqs. (3, 4), increasing temperature reduced relaxation time (τ) of water molecules and the viscosity (η) of water samples. The reduction in τ shifted the critical frequency (f_c) to higher frequencies according to Eq. (5), resulting in reduced loss factors of purified water in the measured frequency range of this study (Fig. 4A). Tang et al. (2002) also reported a decrease in loss factor due to shifts in the critical frequency to a higher value with temperature increase. Higher temperatures increase Brownian motion, which in turn reduces the static dielectric constant. The decrease in static dielectric constant resulted in a declining loss factor, as mathmatically expressed in Eq. (7) for pure water (Kaatze & Uhlendorf, 1981; Tang, 2005).

In the lower frequency range (150–600 MHz), a rise in temperature from 23 to 120 °C significantly ($P < 0.05$) increased the loss factors for tap water (Fig. 4B). This was due to the rise in ionic conductivity of tap water with increasing temperature (Table 2), which increased the contribution of ionic conduction to the loss factor as expressed in Eq. (8). Similar observations were also reported by İcier and Baysal (2004) and Stogryn (1971). The direct relationship between temperature and loss factor was limited to lower frequencies, where ionic conduction dominated. For higher frequencies (600–2500 MHz), there was an inverse relationship between temperature and loss factor where dipole rotation dominated. This is the result of the shifting of the critical frequency of water moleculestoward higher frequency bands, similar to purified water behavior (Ryynänen, 1995; Tang, 2005; Tang & Resurreccion Jr, 2009).

At 915 MHz, the loss factors for tap water were significantly ($P <$ 0.05) higher than for purified water over the measured temperature range (Fig. 5A). The higher loss factor for tap water was due to higher ionic conductivity, as depicted in (Eq. 8). Since the contribution of ionic conductivity was higher at lower frequencies, a higher loss factor for tap water was observed at 915 MHz compared to 2450 MHz (Tang, 2005). The rise of loss factor values of tap water after 70 °C was due to higher ionic conductivity. At 2450 MHz, the difference in loss factor between purified and tap waters became small; insignificant ($P < 0.05$) difference was observed for temperatures less than 40 °C. This agrees with the fact that the dipole rotation became more significant than ionic conduction at higher frequencies above 1000 MHz (Ryynänen, 1995).

As shown in Fig. 5, loss factor values from the Debye and Ulaby models for purified water were similar for both frequencies. This is because the lower ionic conductivity of the purified water diminished the contribution of the ionic conduction; thus reducing Eqs. (8) to (7) (İcier & Baysal, 2004). Fig. 5 A shows that a temperature increases from 23 to 70 °C caused a significant ($P < 0.05$) reduction in the loss factor of tap waters at 915MHz. But this trend was reversed at above 70^{o}C. The difference in the loss factor between the purified and tap water at 915 MHz increased with increasing temperature, particularly at above 70^{o}C. This was caused by the two phenomena associated with increasing temperature: i) the shift of the resonance frequency (critical frequency) of water to a higher frequency band (Ryynänen, 1995; Tang, 2015) and ii) an increase of the ionic conductivity (İcier & Baysal, 2004; Peng et al., 2013). In purified water, an increase in temperature will only cause the former phenomenon to reduce the loss factor. But in tap water, both phenomena occurred because of the presence of ions. That is, in tap water, the decrease of the loss factor caused by the shift of the resonance frequency was compensated by the increase of the ionic conduction. Furthermore, the effect of the contribution of ionic conduction to the loss factor increased with temperature was larger than the effect of the resonance frequency shift. This might be the reason to observe the wider loss factor difference between the purified and tap water as temperature increases.

Interestingly, at 2450 MHz where dipole rotation dominates over ionic conduction, the differences in the values of the loss factor of between purified and tap waters were much smaller than that at 915 MHz (Fig. 5B). The loss factors at 2450 MHz decreased steadly with increasing temperature (Fig. 5B). This reduction was due to the shift of the resonant frequency toward higher bands with temperature rise. A similar observation was also reported by Ryynänen (1995).

The measured loss factor of purified water in this study compared very well with literaure values. As shown in Fig. 5A, a loss factor of 3.5 ± 0.03 for purified water was measured at 915 MHz and 23 °C. Mudgett (1985) reported a loss factor of 3.8 at 915 MHz and 20 °C for pure water. Ikediala et al. (2002) reported a loss factor of 3.7 ± 0.1 for pure water at 915 MHz and room temperature. Fig. 5B shows a loss factor of 9.3 ± 0.12 at 2450 MHz and 23 °C for the purified water. Mudgett (1985) measured a loss factor of 10.3 for pure water at 2450 MHz and 20 °C. The experimental results obtained for purified water also agreed with calculated loss factors (Fig. 5) that were obtained based on the Ulaby model (Eq. 8).

In this study, a loss factor of 4.1 ± 0.0 was measured with tap water at 915 MHz and 23 °C, the value is significantly different ($P < 0.05$) from the result (4.5) reported in Ikediala et al. (2002) for tap water collected

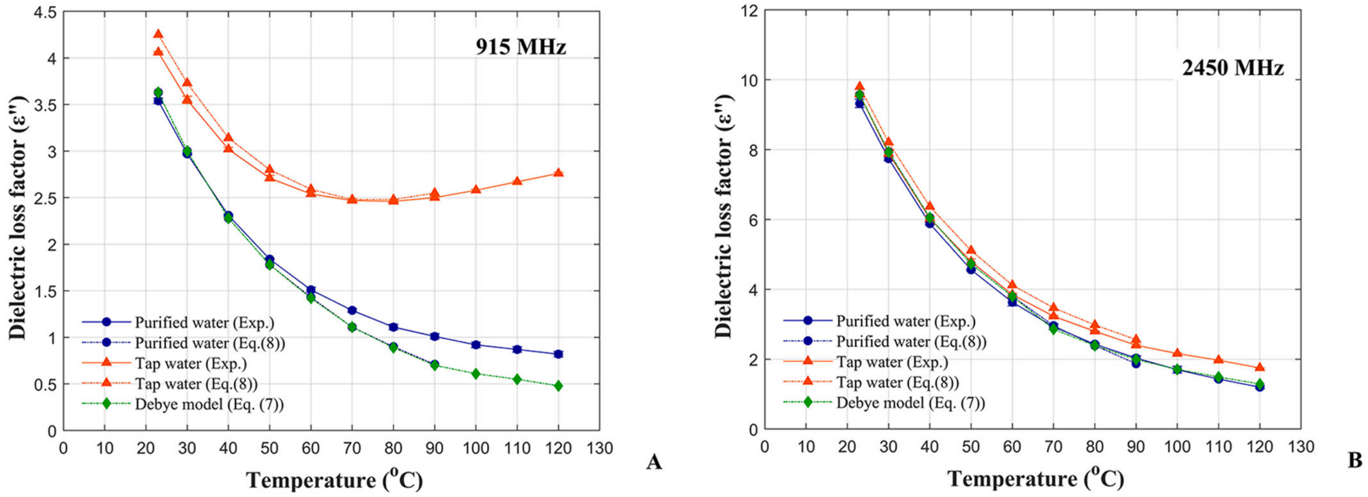

Fig. 5. Dielectric loss factor for purified and tap waters at (A) 915 MHz and (B) 2450 MHz; data are average values ($n = 3$).

from Pullman, WA, USA at 915 MHz and measured at room temperature. Komarov and Tang (2004) measured the loss factor of tap water (Pullman, WA, USA) at 915 MHz and 40 °C, where a value of 3.2 was found. This value was close to the experimental result of the tap water (3.0 ± 0.0) measured at 40 °C in this study. Their value obtained at 121 °C (2.8) was also not different ($P < 0.05$) from the experimental observation made at 120 °C (2.8 ± 0.0). Additionally, the measured loss factors of tap water agreed with the Ulaby model (Eq. (8)), as shown in Fig. 5. In the temperature range 23–90 °C, the maximum differences between the experimental and calculated values were 4.5% at 915 MHz and 9.3% at 2450 MHz.

3.3. *Microwave penetration depths in water*

3.3.1. *Effect of frequency*

Fig. 6 presents the calculated microwave power penetration depths (using the measured dielectric property data) in purified and tap waters at 915 and 2450 MHz from 23 to 120 °C. At both frequencies, higher penetrations were found in purified water than in tap water. This was due to differences in the dielectric properties of purified *versus* tap water (Eq. (12)).

3.3.2. *Effect of temperature*

Microwave power penetration depths in purified water increased with increasing water temperature at 915 and 2450 MHz (Fig. 6). Specifically, at 915 MHz, the penetration depth increased from 131 to 457 mm when the temperature rose from 23 to 120 °C. This observation supports the statement in Tang (2015) that water becomes nearly transparent to 915 MHz microwaves at higher temperatures. The penetration depth of 915 MHz microwaves in tap water peaked at 70^{o}C and decreaded to 140 mm, less than 1/3 of that in purified water, at 120 ^{o}C. The ions in tap water reduced the penetration depth of 915 MHz microwaves, particularly at high temperatures.

Compared to 915 MHz, microwaves at 2450 MHz had much shallower penetration depths in both purified and tap waters. Microwave power penetration depth at 2450 MHz in purified water changed from 19 to 118 mm when the temperature increased from 23 to 120 °C. It is interesting to note that the ions in the tap water did not have a large effect on the penetration of 2450 MHz microwave power, in particular at less than 70^{o}C. The depth increased from 18 to 81 mm when the temperature increased from 23 to 120 °C.

Microwave penetration depth in circulation water directly influences the amount of microwave energy that reaches packaged foods in MATS systems and MAPS. As shown in Fig. 7, the depth of the circulation water is the distance separating the microwave window and the top or the bottom of food packages in a MATS system or MAPS. Since the dimensions of the microwave heating cavities are fixed, the depth of the circulation water on top or bottom of a food package in MATS systems or MAPS depends on the thickness of the processed package. For example, when 6-lb US military group ration trays (40 mm thick) are processed, the depth of the circulation water would be 18 mm. On the other hand, when 8-oz single-meal pouches (16 mm thick) are processed, the water circulation depth would be 30 mm. The rectangular area in Fig. 6 represents the range of circulation water depth (18–30 mm) in the 915 MHz single-mode microwave heating cavity of MATS systems and MAPS developed at WSU.

As shown in Fig. 6, penetration depths of 915 MHz microwaves in both purified and tap waters were much larger than the depth of the circulation water in the microwave heating cavities of MAPS and MATS systems. But using purified water could sharply increases microwave penetration, in particular at temperatures between 90 and 120 °C. For example, at 90 °C (the circulation water temperature typically used in the MAPS), 915 MHz microwave power penetration depth in purified water (399 mm) was 1.5 times that in tap water (161 mm). In the 915

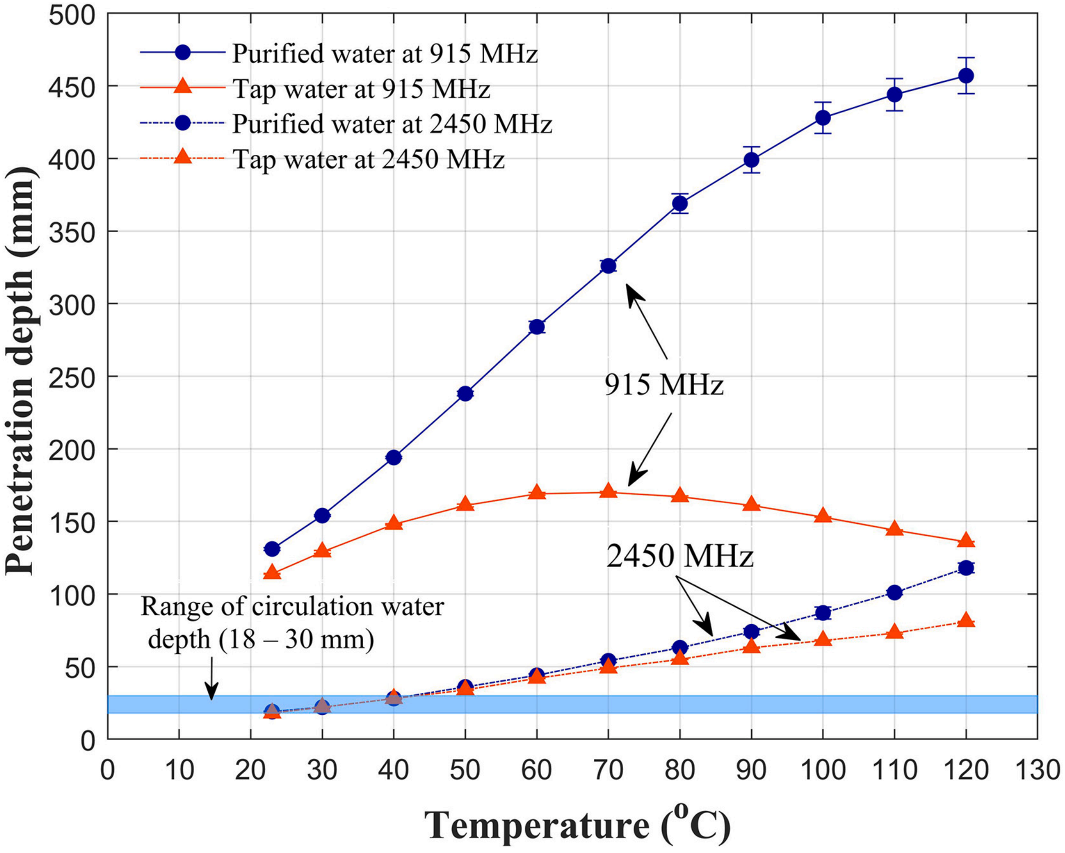

Fig. 6. The penetration depth of microwave power in purified and tap waters; data are average values ($n = 3$).

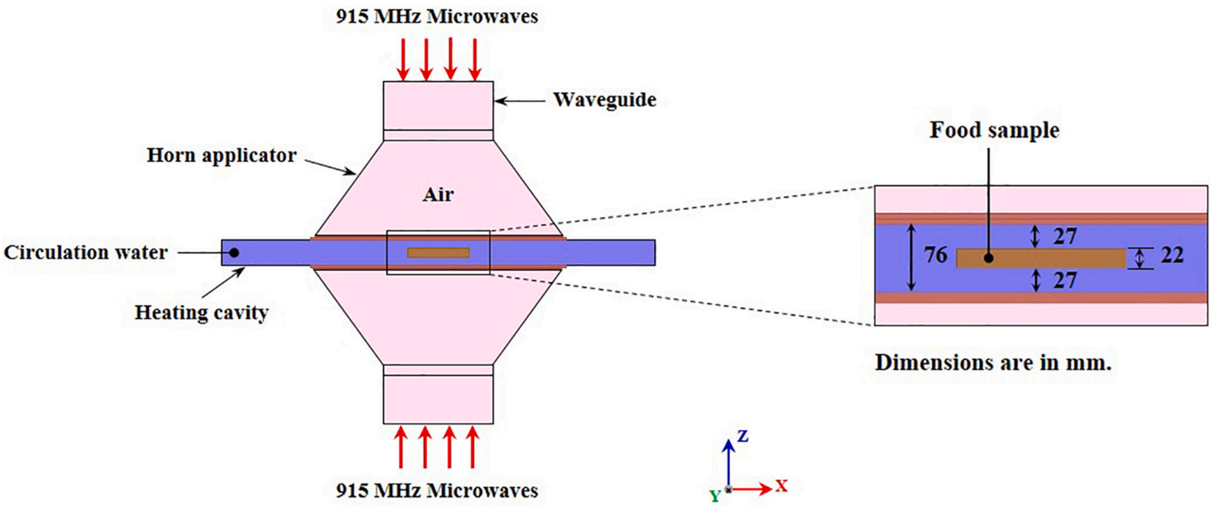

Fig. 7. Single-mode microwave heating cavity with 22 mm thick food sample and 27 mm circulation water depth.

MHz MATS system where circulation water is often slightly above 120 °C, using purified water instead of tap water would increase microwave penetration depth by 2.4 times, from 136 mm to 457 mm.

The strategy of water immersion may not work well for microwave systems operating at 2450 MHz, as the microwave penetration depths are very small (Fig.6) Using purified water only slightly improves microwave energy efficiency. For instance, at 90 °C (for pasteurization in MAPS), changing from tap water to purified water only increased penetration depth by 17.5%, from 63 to 74 mm. At 2450 MHz and 120 °C, using purified water increased penetration depth by 46% from 81 to 118 mm, compared to using tap water.

Fig. 8 depicts the change in microwave energy as it travels through different circulation waters at 915 and 2450 MHz, as calculated using Eq. (13). As presented in Fig. 7, in processing 10-oz (22 mm) packaged foods, the circulation water depth will be 27 mm. When 915 MHz microwaves propagate through purified circulation water in MAPS operations (90 °C), 93% of the initial microwave power will reach the packaged foods (Fig. 8A). If tap water is used as the circulation water in the same setup, only 85% of the initial microwave power will reach the packaged foods. Hence, using purified water in MAPS processes will reduce the microwave power loses by about 50% compared to using tap water. In the MATS system process for 10 oz. packages, 94% of the initial microwave power will reach food packages in purified circulation water at 120 °C *vs.* 82% when in tap circulation water at the same temperature (Fig. 8B). Therefore, the use of purified water can save 12% more microwave power (or reduce microwave power loss by 67%) in MATS system operations.

Table 3 summarizes the percentage of microwave power that reaches the food surface after traveling through the circulation water. As the depth of the circulation water increases from 18 to 30 mm, the microwave power reaching the food samples is reduced in all cases. Overall, we estimated 4–7% microwave power loss in purified circulation water and 11–20% losses in tap water in the MATS system (120 °C) and MAPS (90 °C) operations using 915 MHz microwaves. But between 14-38% microwave energy will be lost in the circulation water when using microwaves at 2450 MHz. It needs to be pointed out that the microwave power loss in the circulating water should not be considered as complete energy waste in the MATS system and MAPS. The conversion of the microwave energy into thermal energy in the circulation water compensates partially, if not all, of the convective heat transfer from the circulation water to the packaged foods.

As shown in Table 3, increasing circulation water temperature from 90 to 120 °C reduces microwave power loss in purified water. That is, pure water becomes more transparent at a higher temperature (Tang, 2015). But tap water at 915 MHz, on the other hand, causes higher microwave power decay at 120 °C than at 90 °C. This is because of the increases in loss factor at a higher temperature, due to the increased ionic conductivity, above 70 °C as presented in Fig. 5A.

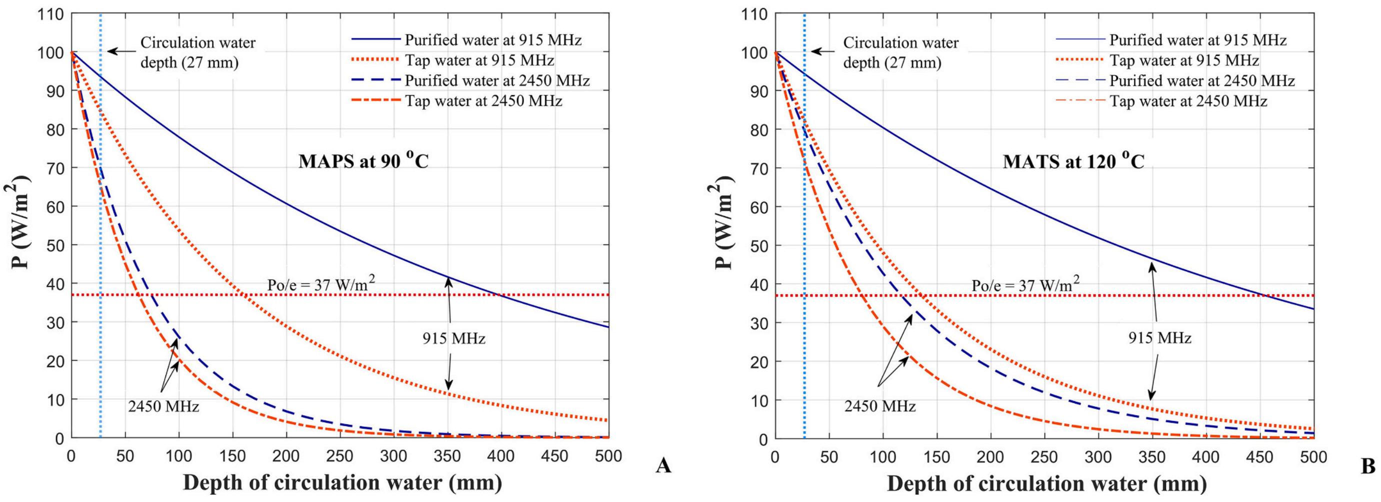

Fig. 8. Microwave power decay (W/m^2) in the circulation water (A) in the MAPS at 90 °C and (B) in the MATS system at 120 °C.

Table 3
The percentage microwave power reaching packaged foods after propagating through different depths of circulation water in pasteurization (90 °C) and sterilization (120 °C) systems.

Circulation water depth (mm)	Microwave power (%), calculated using Eq. (13).							
	915 MHz				2450 MHz			
	90 °C		120 °C		90 °C		120 °C	
	Purified water	Tap water	Purified water	Tap Water	Purified Water	Tap water	Purified water	Tap Water
18	96	89	96	88	78	75	86	80
19	95	89	96	87	77	74	85	79
20	95	88	96	86	76	73	84	78
21	95	88	96	86	75	72	84	77
22	95	87	95	85	74	70	83	76
23	94	87	95	84	73	69	82	75
24	94	86	95	84	72	68	82	74
25	94	86	95	83	71	67	81	73
26	94	85	94	83	70	66	80	72
27	93	85	94	82	70	65	79	72
28	93	84	94	81	69	64	79	71
29	93	83	94	81	68	63	78	70
30	93	83	94	80	67	62	77	69

4. Conclusions

Dielectric properties of purified and tap waters were measured in the frequency range of 150 to 2500 MHz and the temperature range of 23 to 120 °C. In both purified and tap waters, dielectric constants decreased with increasing frequency and temperature. The dielectric loss factors of purified water increased proportionally with frequency. The dielectric loss factor of tap water responded differently at frequencies between 150 and 600 MHz and above 600 MHz. The penetration depth of 915 MHz microwave power in purified water (399 mm) was 1.5 times the value in tap water (161 mm) at 90 °C which is the typical temperature of the circulation water in MAPS for in-package pasteurization. In the MATS system for in-package sterilization with 120 °C circulation water, using purified water instead of tap water increased 915 MHz microwave penetration depth by 2.4 times, from 136 to 457mm. In comparison with tap water, purified water (27 mm deep) reduces 915 MHz microwave power loss by about 50% and 70 % at 90 and 120 °C, respectively. Thus, microwave energy efficiency and production rate can be improved significantly by using purified water in the MATS system and MAPS operating at 915 MHz. Microwaves at 2450 MHz, on the other hand, have much less penetation in water (compared to at 915 MHz), and using puried circulation water does not significantly reduce microwave loses at this frequency.

Declaration of Competing Interest

None

Acknowledgments

The authors would like to acknowledge the support of the USDA National Institute of Food and Agriculture [grant numbers 2016-68003-24840] and the Washington State University Agricultural Research Center.

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