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Improvement of heating uniformity in packaged acidified vegetables pasteurized with a 915 MHz continuous microwave system ☆

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ABSTRACT

Continuous microwave processing to produce shelf-stable acidified vegetables with moderate to high salt contents poses challenges in pasteurization due to reduced microwave penetration depths and non-uniform heating. Cups of sweetpotato, red bell pepper, and broccoli acidified to pH 3.8 with citric acid solution containing 0–1% NaCl were placed on a conveyor belt and passed through a microwave tunnel operating at 915 MHz and 4 kW with a 4 min residence time. The time–temperature profiles of vegetable pieces at 5 locations in the package were measured using fiber optic temperature sensors. Addition of 1% NaCl to the cover solution lowered microwave penetration into vegetable pieces and decreased the mean temperature in cups of acidified vegetables from 84 to 73 °C. Soaking blanched vegetables for 24 h in a solution with NaCl and citric acid prior to processing improved microwave heating. Heating was non-uniform in all packages with a cold spot of approximately 60 °C at a point in the container farthest from the incident microwaves. More uniform heating was achieved by implementation of a two-stage rotation apparatus to rotate vegetable cups 180° during processing. Rotating the cups resulted in more uniform heating and a temperature of 77 °C at the cold spot. This is above the industrial standard of 74 °C for in-pack pasteurization of acidified vegetables. The effective treatment involved blanching, soaking for 24 h in a NaCl and citric acid solution, and 180° rotation. This work has contributed to a better understanding of the influence of salt addition and distribution during dielectric heating of acidified vegetables using a 915 MHz continuous microwave system.

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1. Introduction

The use of microwave processing technology is rapidly becoming a viable method for pasteurization and sterilization of high and low-acid foods, respectively. Previous studies have utilized continuous flow microwave processing to aseptically process and package fruit and vegetable purees in large flexible containers (Coronel et al., 2005), as well as in-pack sterilization of prepared meals (Tang et al., 2008). High-quality retention of product color and antioxidant activities have been reported using 915 MHz microwaves (Coronel et al., 2005; Steed et al., 2008; Sun et al., 2007). The work of Sun et al. (2007) demonstrated improved antioxidant activity and green color retention of asparagus sterilized with a 915 MHz microwave-circulated water combination heating system, as compared to steam heating in a retort. These improvements in product quality have been attributed to the rapid come-up time due to volumetric heating provided by electromagnetic microwave energy. In addition, the adoption of microwave processes present potential energy savings, as well as opportunities to reduce water usage.

The use of continuous tunnel microwave processes is widely used in industry for drying processes (Meredith, 1998); however, it has received little attention on its potential applications to pasteurize packaged foods. Previous work by Burfoot et al. (1988) used a tunnel microwave system operating at 896 MHz to pasteurize spaghetti bolognaise trays, as well as trays of mashed potatoes (Burfoot et al., 1996). Uniform heating of the spaghetti bolognaise to at least 80 °C with a maximum temperature difference of 17 °C was achieved using 896 MHz microwaves, but not 2450 MHz microwaves (Burfoot et al., 1988). Processing of spaghetti bolognaise in trays at 2450 MHz yielded a maximum temperature difference of 36 °C. Rotation of the trays was not implemented in the study by Burfoot et al. (1988). The authors attributed the greater heating uniformity at 896 MHz to the greater penetration depth of microwaves.

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Microwave heating relies largely on the conversion of electromagnetic energy into heat via friction of dipolar molecules and ionic species which try to follow the oscillating electrical field, as opposed to conventional heating, which relies on heat transfer through conduction and convection (Thostenson and Chou, 1999). The manner and degree to which foods heat by exposure to microwave energy are largely affected by the dielectric properties of the food and the penetration depth of microwaves into the food (Sakai and Wang, 2004). Foods with moderate to high salt contents, such as acidified vegetables present difficulties in microwave heating due to dramatically reduced penetration depths. Fresh-pack acidified vegetables such as cucumbers and peppers are typically packed in salt brines to achieve equilibrated salt concentrations in the vegetable tissue from 2% to 5% (Potts et al., 1986; Daeschel et al., 1990; Passos et al., 2005). While industrial microwave processes utilize 915 MHz microwaves for their relatively high penetration depth, the addition of salt significantly reduces the penetration depth. This can present challenges in food processing. When the dimensions of a material exceed the penetration depth, the microwave energy is rapidly attenuated so the food material will not heat volumetrically and surface heating will predominate (Datta and Anantheswaran, 2001).

Only one study has examined the use of microwave-assisted pasteurization of acidified vegetables. Lau and Tang (2002) investigated heating uniformity and textural degradation kinetics of pickled asparagus packed in 1.8 kg (64 oz.) glass bottles when heated to 88 °C using a batch microwave system at 915 MHz. The authors were able to reduce heating time by 50% compared to heating in a water bath and reduced textural degradation (Lau and Tang, 2002). However, the asparagus was hot-filled with 80 °C brine and equilibrated to a temperature of 70 °C in a water bath before heating to 88 °C with 915 MHz microwaves.

In the case of food matrices containing solid and liquid phases, the differences in dielectric and thermophysical properties between these phases influence the heating characteristics. A study by Cha-um et al. (2009) examined microwave heating of a saturated porous medium consisting of 0.15 mm glass beads immersed in water. Inclusion of low loss glass beads increased penetration of microwaves into the water and bead mixture, resulting in higher temperatures at the bottom of the sample. In addition, it was observed that conduction was the predominant mode of heat transfer in the saturated porous medium, while convection prevailed when no beads were in the sample (Cha-um et al., 2009). This research suggests that the pairing of high and low loss materials could produce desirable heating patterns.

In the present study, the inclusion of liquid and solid phases presented the opportunity to manipulate the composition of these phases to improve microwave heating of high-salt, acidified vegetables. It was hypothesized that the absence of salt in the cover solution in which the vegetable pieces were submerged would promote a higher penetration depth of microwaves into the particles, resulting in higher heating rates of the vegetable particles. Conversely, the presence of 1% NaCl in the cover solution would preferentially heat the solution, and primarily transfer heat via convection to the vegetable particles. The objectives of the study were to: (1) compare the heating profiles of sweetpotato, red bell pepper, and broccoli, (2) determine the effects of salt and its distribution on heating, and (3) to improve heating uniformity of packaged acidified vegetables using a 915 MHz continuous microwave system.

2. Materials and methods

2.1. Sample preparation

Broccoli, red bell pepper, and orange-fleshed sweetpotato (cultivar *Covington*) were used in this study. Broccoli florets were prepared by cutting into pieces of 3 ± 1 cm in length, and 2 ± 1 cm in width. Red bell peppers were cored and sweetpotatoes were peeled prior to dicing into 1.2 cm cubes using a 3/8 inch slicer plate and 3/8 inch dicer plate of a Hobart food processor (Model FP150, Hobart, Troy, OH).

2.2. Acidification and salting

Three different treatments (Table 1) were designed to examine the level and distribution of salt within each vegetable system in order to best understand and optimize microwave heating uniformity. The vegetable to solution ratio was 50:50 for red bell pepper and sweetpotato cubes, and 33:67 for broccoli florets. Unblanched vegetables were combined with a solution containing 0.75% w/w citric acid and 0% NaCl (treatment 1) or 1% w/w NaCl (treatment 2). The blanch treatment (treatment 3) involved submersion of the vegetables in 95 °C water for 30 s, followed by immediate cooling in an ice-water bath for 2 min. A 2% w/w NaCl, 0.75% w/w citric acid soaking solution was then added to the vegetables in their respective vegetable to solution ratios, and allowed to equilibrate for 24 h at 20 ± 2 °C. Preliminary experiments monitored the dielectric properties of the vegetables after soaking for 4, 12, and 24 h. No changes in dielectric properties were observed between 12 and 24 h, therefore 24 h was selected for convenience. After 24 h, vegetables were removed from the soaking solution, placed in 109 mL polypropylene cups, covered with a 0.5% w/w citric acid solution and immediately put on the conveyor belt of a microwave system for pasteurization. The blanching and soaking of vegetables in a citric acid and salt solution served to increase the acidity and salt content of the vegetables. Treatment 1 evaluated time–temperature profiles of the vegetables during microwave heating when no salt was added to the system. Formulations without salt were tested to contrast any positive or negative influences of added salt in treatments 2 and 3. The net weight of each cup was 90 g.

2.3. Measurements of dielectric properties

Dielectric constants (ε') and loss factors (ε'') were measured at 915 MHz using a network analyzer (HP 8753C, Agilent Technologies, Palo Alto, CA) with an open-ended coaxial probe (HP 85070B, Agilent Technologies, Palo Alto, CA). Vegetable samples were mashed and placed into a pressurized test cell. The test cell was submerged in an oil bath (Model RTE111, Neslab Instruments Inc., Newington, NH) and the dielectric properties were measured at 15 °C intervals from 25 to 100 °C. The temperature of the oil bath was gradually increased such that the temperature difference between the sample and the oil bath was less than or equal to 10 °C. The dielectric constants and loss factors were used to calculate the penetration depth (d_p) of microwaves into the material with the following equation:

$$d_p = \frac{\lambda_0}{2\pi\sqrt{2\varepsilon'}}\left[\sqrt{1}+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2 - 1\right]^{\frac{-1}{2}}$$

where λ_0 is the wavelength of 915 MHz microwaves.

Table 1
Treatment key for acidified broccoli, red bell pepper, and sweetpotato.

Treatment	Unblanched (UB) or blanched (B)	Soaking solution[a]		Filling solution	
		Citric acid (% w/w)	NaCl (% w/w)	Citric acid (% w/w)	NaCl (% w/w)
1	UB	–	–	0.75	0
2	UB	–	–	0.75	1
3	B	0.75	2	0.50	0

[a] Blanched vegetables were placed in a soaking solution for 24 h at 20 ± 2 °C.

2.4. Continuous microwave system

A 5-kW microwave generator operating at 915 MHz transmitted microwaves through a traveling wave applicator by means of an aluminum waveguide (Model number P09Y5KA02, Industrial Microwave Systems, Morrisville, NC). A simplified schematic of the system is shown in Fig. 1. A microwave transparent conveyor belt (11 × 575 cm) traveled through the geometric center of the applicator (24.5 × 12.5 × 350 cm) at a rate of 0.711 m/min. The microwave generator was controlled through a computer interface (HP34970A, Agilent, Palo Alto, CA) with a program written in LabView (National Instruments Corp., Austin, TX). Power diodes (JWF 50D030+, JFW Industries, Inc., Indianapolis, IN) measured the transmitted power, reflected power, and lost forward at different points in the microwave system and were recorded using the LabView Data Acquisition Software. Generator power was set to 4 kW during microwave trials which examined compositional effects and 3.5 kW for cup rotation experiments. Residence time in the microwave cavity for all experiments was 4 min. The thermal treatment in this study was shorter in duration compared to the established process of heating to 74 °C and holding for 15 min (Etchells and Jones, 1942). The rationale of a shorter residence time was to rapidly heat the vegetable packs to temperatures greater than the required 74 °C, and then seal and hold the packs in an insulating mold to deliver a similar thermal treatment to the traditional method.

2.5. Food simulant

During continuous microwave processing, a constant mass flow rate must be maintained in the traveling wave applicator to minimize drastic changes in the electric field. In order to reduce the

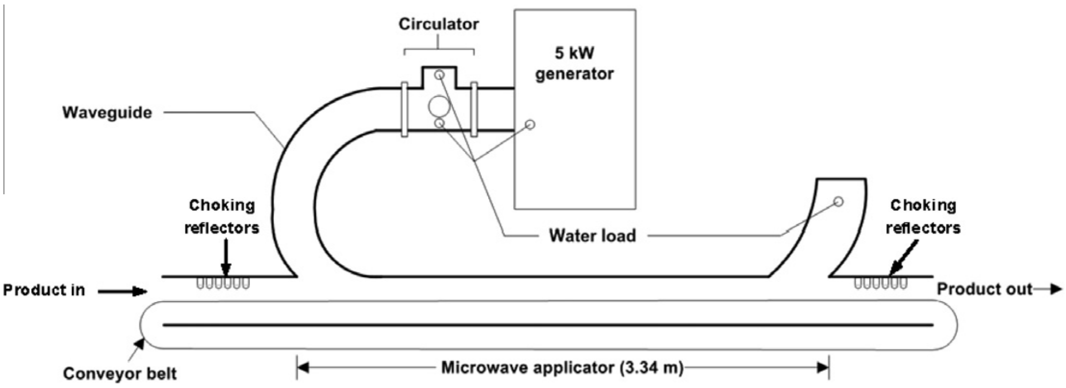

Fig. 1. Simplified schematic of 915 MHz, 5 kW continuous microwave processing tunnel.

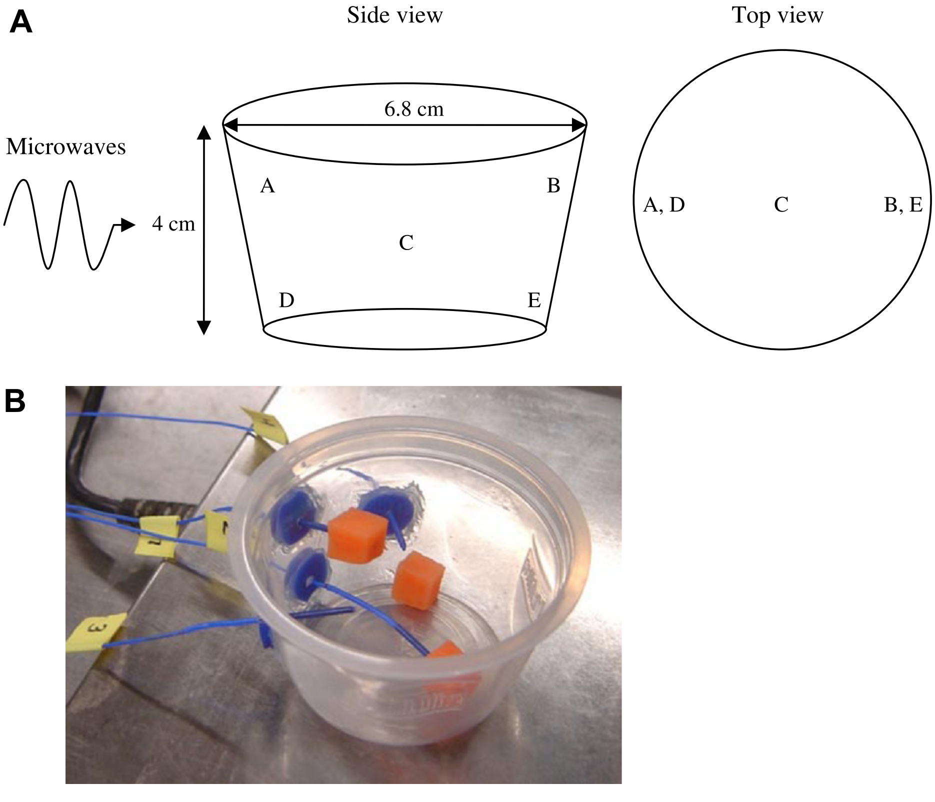

Fig. 2. Schematic representation of fiber optic temperature probe placement (A), and picture of fiber optic probe insertion (B). Microwave energy moves from left to right in (A).

amount of vegetable material used to obtain time–temperature heating profiles through the microwave system, a food simulant with similar dielectric properties to the acidified vegetables was developed. The dielectric properties of a solution consisting of 0.5% w/v pre-hydrated carboxymethylcellulose (CMC) (TIC Gums, White Marsh, MD) and 0.5% w/v NaCl were found to closely match those of the acidified and salted vegetables. CMC was included in the food simulant to increase the viscosity of the solution, such that spillage during handling of the cups would be minimized. Dummy cups were filled with 90 g of the food simulant and placed edge-to-edge to maintain a constant mass load in the microwave. Due to process limitations, cups were not sealed prior to microwave processing. For implementation of the two-stage rotation apparatus, cups were spaced 4 cm apart.

2.6. Fiber optic temperature sensor measurements

Vegetable and brine temperatures were continuously monitored during microwave processing at different locations within a cup by inserting precalibrated fiber optic temperature sensors (FOT-L/10 M, Fiso Technologies, Inc., Quebec, Canada) through the walls of the polypropylene cup. The sensing portion of the probe was inserted into the center of vegetable pieces as well as in the cover solution at the locations shown in Fig. 2. The fiber optic temperature sensors were connected to a 4-channel fiber optic signal conditioner (Model UMI 4, Fiso Technologies, Quebec, Canada) controlled by FISO Commander software (FISO Technologies, Quebec, Canada), and measured the temperature in 0.6 s intervals.

The cup with fiber optic temperature sensors was surrounded on both sides by cups that contained the food simulant. Upon start-up of the microwave system, dummy cups were run through the system until conditions were equilibrated in the microwave. Then the cup with fiber optic temperature sensors was placed on the conveyor belt, the cover solution added, and dummy cups placed on the belt until the fiber optic cup appeared at the end of the conveyor belt. At this point, microwave power was shut-off, and the cup was placed in an insulating mold made out of polyurethane.

2.7. Two-stage rotation apparatus

A two-stage rotation apparatus made of plaster and silicon beads was designed and implemented to rotate cups 180° and improve heating uniformity. Fig. 3 illustrates the two-stage rotation apparatus and movement of the cups through the applicator. Based on the experimental time–temperature heating profiles, it was shown that heating of the vegetables to their maximum temperature occurred within the first 30–60 s, or approximately 0.5 m into the microwave cavity. Therefore, it was determined that the two-stage rotation apparatus be placed 0.25 m from the beginning of the microwave applicator to maximize exposure of the entire cup to microwave energy. Beads of silicone provided a ribbed surface

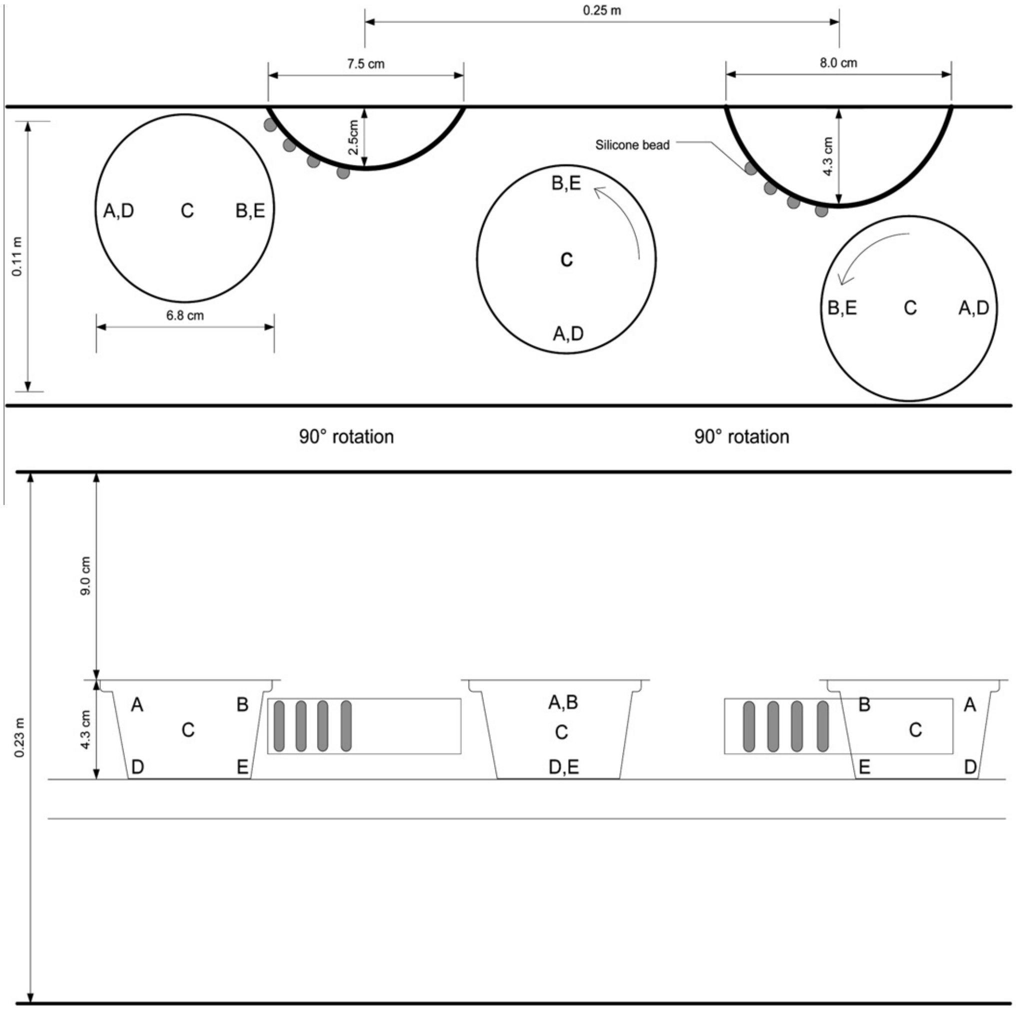

Fig. 3. Schematic of two-stage rotation apparatus: top view (top) and side view (bottom).

and added friction to the bumpers such that the cups consistently rotated 90° after each bumper, for a complete 180° rotation.

In order to successfully implement the rotation apparatus, other processing parameters had to be adjusted. Preliminary trials showed that when cups were placed side-by-side on the conveyor belt, forces applied to cups by trailing cups resulted in inconsistent and unpredictable rotation. Therefore, 4 cm spacing of the cups on the conveyor belt was necessary to consistently rotate the cups. Spacing the cups by 4 cm prevented cup-to-cup contact and produced reliable cup rotation. As a result of the spacing, the mass load in the microwave was reduced, thereby necessitating operation at a lower power level so that the cover solution would not boil. Heating profiles of red bell pepper (treatment 3) were obtained with rotation at 2, 3, 3.5, and 4 kW. The 3.5 kW was deemed an appropriate operating power level, so all subsequent trials with rotation were conducted at 3.5 kW. It should also be noted that the power density increased within the microwave cavity from 1010 W/kg in non-rotation experiments to 1350 W/kg in rotation experiments.

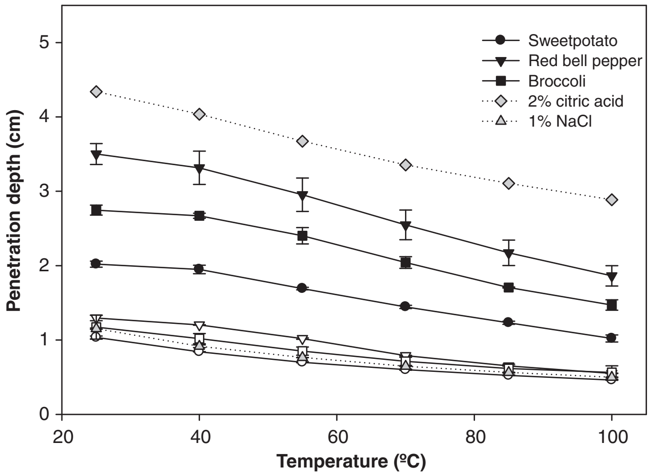

Fig. 4. Penetration depth of 915 MHz microwaves as a function of temperature for vegetables and cover solutions. Penetration depths calculated from measured dielectric properties. Closed symbols represent unblanched vegetables; open symbols represent blanched, equilibrated vegetables to 1% w/w NaCl.

3. Results and discussion

3.1. Dielectric properties and penetration depth

The effects of salt on the dielectric properties of foods have been widely documented (Ahmed et al., 2007). It is known that salt decreases the dielectric constant while simultaneously increasing the loss factor (Ryynänen, 1995). Therefore, the addition of solvated sodium and chloride ions to a food system decreases the penetration depth of microwaves as a consequence of increasing the conductivity component of the dielectric loss factor. Fig. 4 clearly illustrates this phenomenon. The unblanched samples had high penetration depths, 2.0–3.5 cm at 25 °C and 1.5–2.5 cm at 100 °C, which were significantly different ($p \leqslant 0.05$) among the vegetables. For the samples that were blanched and equilibrated to a salt content of 1%, the penetration depth was around 1 cm and not significantly different among the vegetables ($p \geqslant 0.05$). The penetration depths of the blanched, equilibrated vegetables were not significantly different than a 1% w/v NaCl solution. Previous work (Koskiniemi et al., 2011) showed that the highest concentration of citric acid that might be used in an acidified vegetable product was 2% due to its high degree of sourness, so penetration depths of a 2% citric acid solution were included in Fig. 4. The dielectric properties of vegetables were equalized by soaking in a salt solution. However, this equalization of dielectric properties among the vegetables resulted in reduced penetration depths, which is not always desirable for microwave processes. In order to overcome the disadvantage of low penetration depths of acidified vegetables with salt contents in the range of 0–1% w/w NaCl, different formulations were tested (Table 1).

3.2. Microwave heating profiles

A series of time–temperature heating profiles and contour plots are presented to illustrate the heating behavior of vegetable pieces in different locations in acidified vegetable packs. Fig. 2 shows the

Table 2
Maximum temperatures of vegetable particles and cover solutions at each measured location.

Treatment[a]	Rotation	Location[b]	Maximum temperature (°C)					
			Sweetpotato		Red bell pepper		Broccoli	
			Particle	Solution	Particle	Solution	Particle	Solution
Unblanched 0% NaCl solution	Non-rotating	A	100.0		76.8		96.9	
		B	96.9	87.0	78.4	86.5	100.0	92.3
		C	99.2	86.4	98.7	70.6	99.7	94.3
		D	79.2	73.7	64.9	65.4	86.5	86.1
		E	85.4		59.4		73.8	
Unblanched 1% NaCl solution	Non-rotating	A	85.0		82.3		90.2	
		B	79.9	80.2	68.6	73.7	76.7	70.2
		C	74.4	72.9	73.9	73.1	81.6	78.7
		D	70.3	67.4	59.6	58.4	65.8	64.5
		E	61.9		61.4		65.7	
Blanched (1% eq. NaCl) 0% NaCl solution	Non-rotating	A	96.3		99.4		100.0	
		B	80.6	77.8	83.4	83.4	84.0	74.4
		C	83.3	77.5	99.4	78.0	100.0	81.5
		D	82.2	65.4	83.7	67.6	68.1	65.9
		E	70.4		61.5		69.0	
Blanched (1% eq. NaCl) 0% NaCl solution	Rotating	A			90.3			
		B			89.5			
		C	97.9		94.6		99.2	
		D	80.6		85.5		79.8	
		E	81.5		77.1		83.2	

[a] Refer to Table 1 for complete treatment description.

[b] Refer to Fig. 2 for fiber optic temperature probe location diagram.

location of continuous temperature measurements during microwave processing. Five measurement locations were selected along the central vertical plane in the cups to best understand heating uniformity, and will be referred to as the cross-section. Time–temperature heating profile graphs are accompanied by contour plots to better visualize the cross-sectional temperature distribution. Contour plots were generated using the mean maximum temperatures of vegetable pieces (Table 2) at each of the five measurement locations as described in Fig. 2. Each vertex of the plot corresponds to the respective cross-sectional location and its maximum temperature (A = top-left; B = top-right; D = bottom-left; E = bottom-right). The measurement of location C is at the center of the contour plots. Contour plots show the maximum temperature reached during processing at each location, red being the hottest, and blue being the coldest spots (Figs. 5–7). All contour plots were generated using the same temperature scale.

Perhaps the most readily apparent question regarding the time–temperature heating profiles (Figs. 5–7) is the decrease in

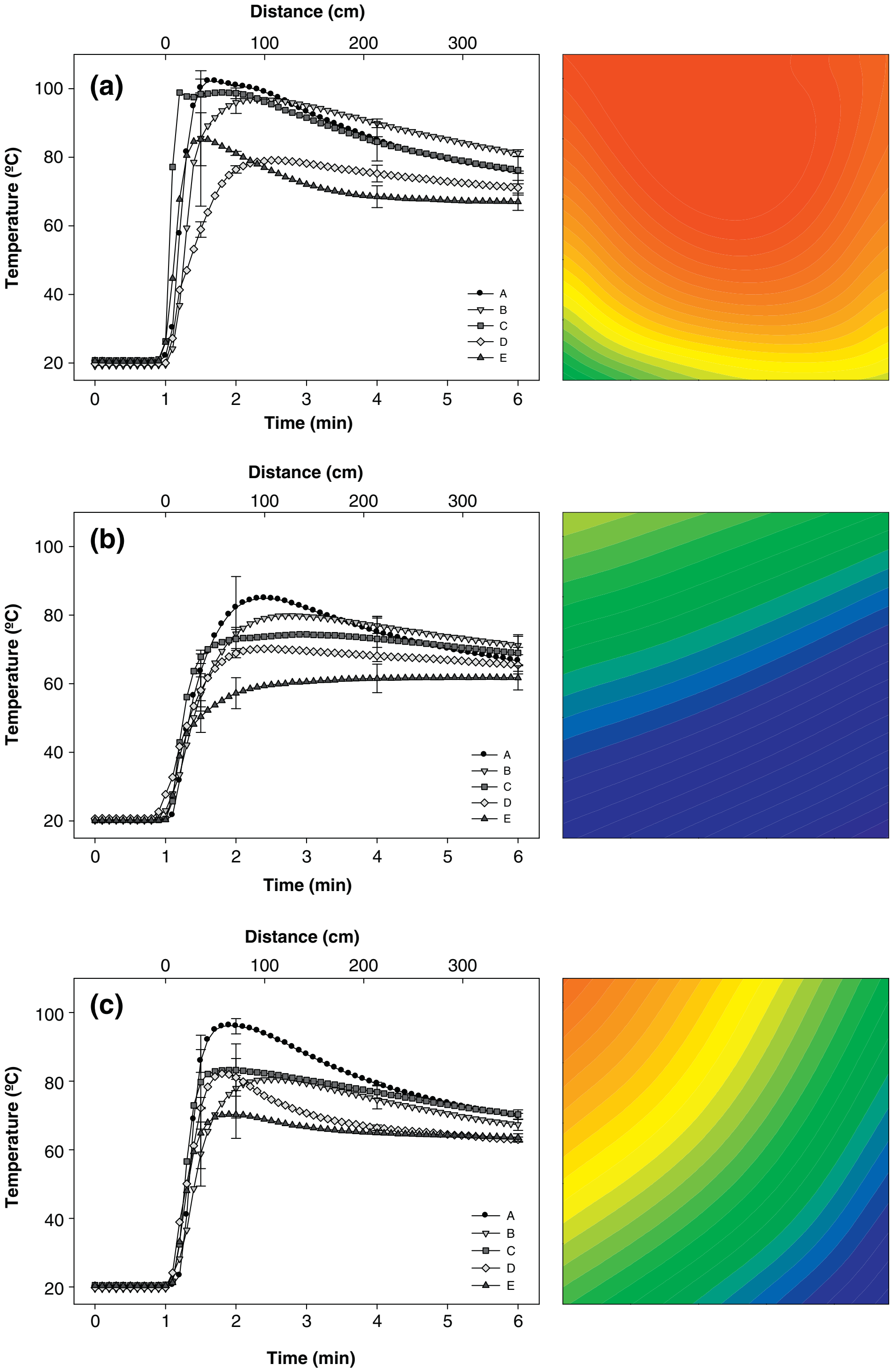

Fig. 5. Time–temperature heating profiles (left) and maximum temperature contour plots (right) during 915 MHz continuous microwave processing: (a) unblanched sweetpotato cubes in 0% NaCl cover solution, (b) unblanched cubes in 1% NaCl cover solution, and (c) blanched, 1% NaCl equilibrated cubes in 0% NaCl cover solution. Error bars represent 1 standard deviation ($n = 2$). Refer to Fig. 2 for locations of A–E.

temperature after reaching the maximum temperature. The high temperatures were not sustained because the vegetable cups were not sealed; rather, they were open to the atmosphere. As a result, evaporative cooling occurred and the overall temperature decreased. Preliminary experiments were conducted with sealed vegetable packs, but were unsuccessful. The inability to process sealed cups was caused by the generation of steam. This steam caused either seal failure, or bulging of the vegetable packs which did not allow passage through the exiting aperture of the microwave tunnel. With this limitation, the results and discussion will focus on the compositional and process modifications on heating uniformity. It is also important to keep in mind that the long-standing procedure for pasteurization of acidified vegetable products is heating to 74 °C and holding for 15 min (Etchells and Jones, 1942). The primary goal of the presented work was to rapidly reach temperatures greater than 74 °C in all measured locations using a continuous microwave system while improving heating uniformity.

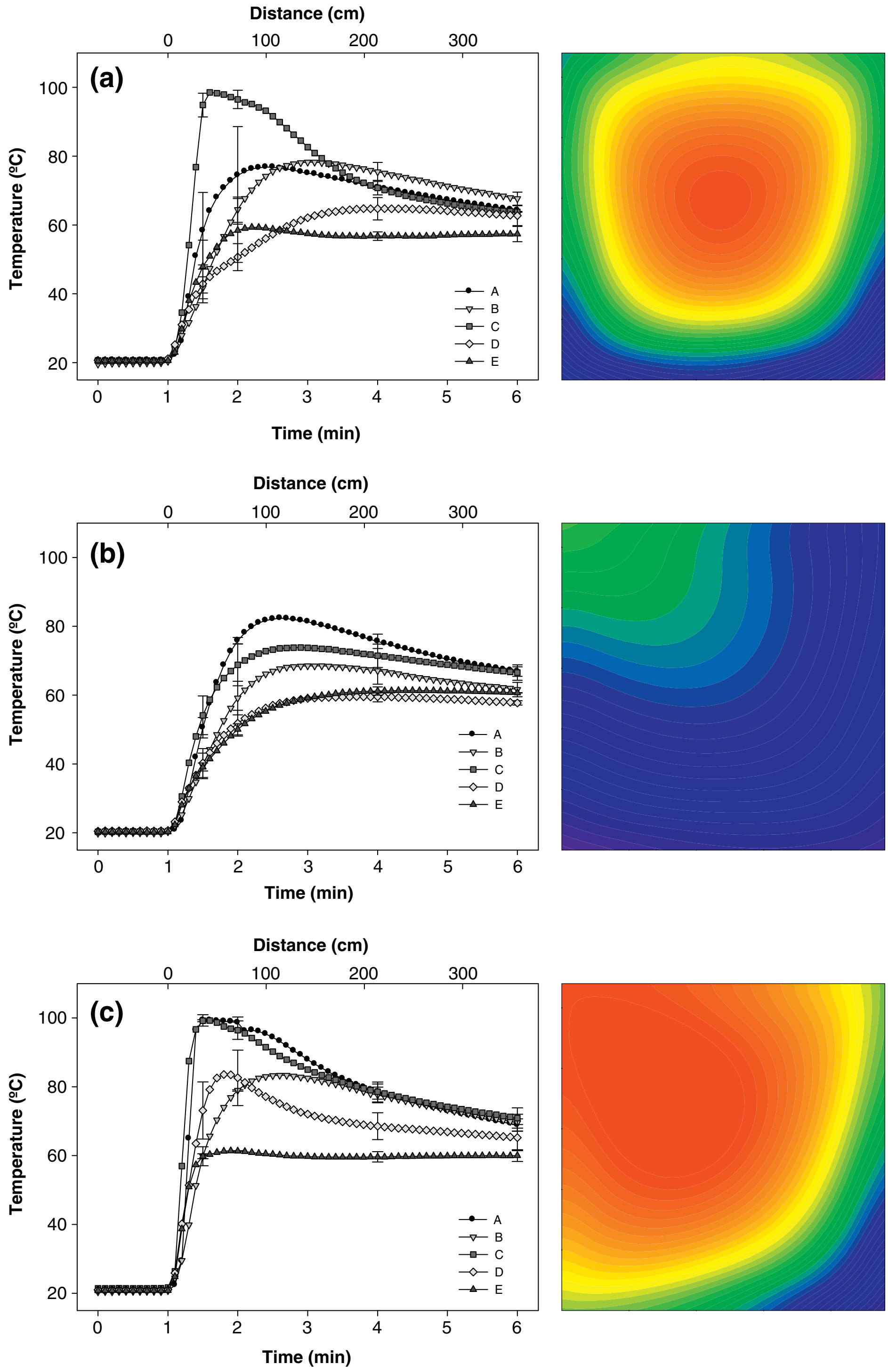

Fig. 6. Time–temperature heating profiles (left) and maximum temperature contour plots (right) during 915 MHz continuous microwave processing: (a) unblanched red bell pepper cubes in 0% NaCl cover solution, (b) unblanched cubes in 1% NaCl cover solution, and (c) blanched, 1% NaCl equilibrated cubes in 0% NaCl cover solution. Error bars represent 1 standard deviation ($n = 2$). Refer to Fig. 2 for locations of A–E.

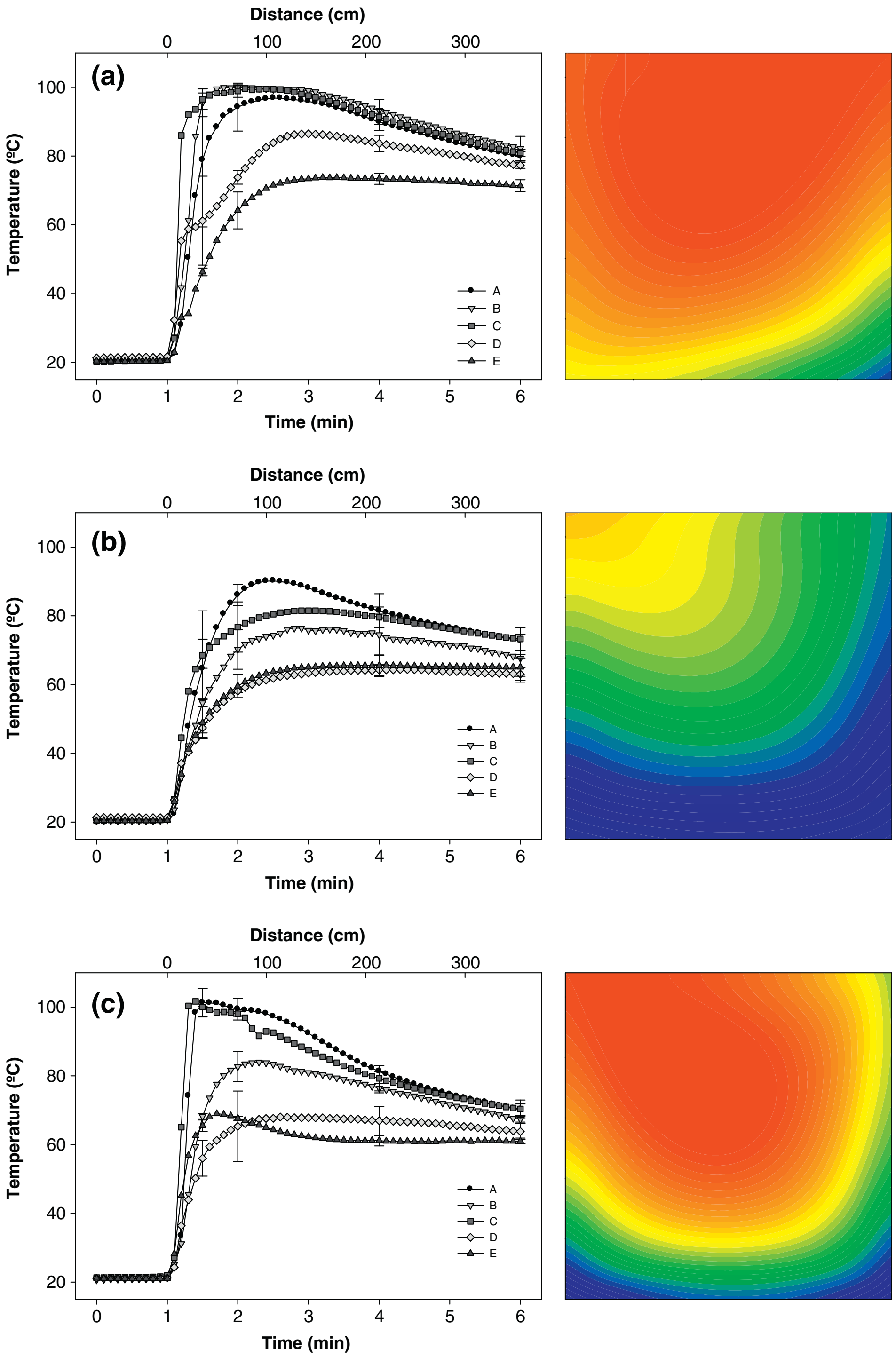

Fig. 7. Time–temperature heating profiles (left) and maximum temperature contour plots (right) during 915 MHz continuous microwave processing: (a) unblanched broccoli in 0% NaCl cover solution, (b) unblanched broccoli in 1% NaCl cover solution, and (c) blanched, 1% NaCl equilibrated broccoli in 0% NaCl cover solution. Error bars represent 1 standard deviation ($n = 2$). Refer to Fig. 2 for locations of A–E.

3.2.1. Treatment 1 – unblanched, 0% NaCl cover solution

Volumetric heating was readily apparent in the unblanched, 0% NaCl treatment for all vegetables. The penetration depth of the 0.75% citric acid cover solution with no salt was approximately equivalent to the measured penetration depth of the raw vegetable. The absence of salt effectively increased the penetration depth and created a heating profile where the center of the cup heated the fastest. This was evidenced by vegetable particles in the center of the cup reaching 100 °C (Figs. 5a, 6a, and 7a).

Compared to sweetpotato and broccoli, red bell pepper particles in the top half of the cup (locations A and B) were heated to a lesser extent. Red bell pepper particles at A and B reached maximum temperatures of 76.8 and 78.4 °C (Table 2, Fig. 6a), and maximum heating rates of 1.9 and 0.7 °C/s (Table 3), respectively. In comparison, the maximum temperatures of particles A and B of sweetpotato and broccoli ranged from 97 to 100 °C and the heating rates of particles A and B were at least 0.6 and 2.5 °C/s greater than those of red bell pepper, respectively.

Table 3
Heating rates of vegetable particles and cover solutions at each measured location.

Treatment[a]	Location[b]	Heating rate (°C/s)					
		Sweetpotato		Red bell pepper		Broccoli	
		Particle	Solution	Particle	Solution	Particle	Solution
Treatment 1	A	4.4		1.9		2.5	
Unblanched 0% NaCl solution	B	3.4	1.9	0.7	1.8	3.2	1.8
	C	9.8	1.2	3.5	1.2	10.2	1.6
	D	1.0	0.7	0.7	0.4	3.1	1.1
	E	3.4		1.1		0.9	
Treatment 2	A	1.7		1.4		2.2	
Unblanched 1% NaCl solution	B	1.1	1.7	0.8	1.5	1.4	1.8
	C	2.2	1.0	1.4	1.2	2.2	1.4
	D	0.9	0.7	0.7	0.7	0.9	0.8
	E	1.5		0.7		1.1	
Treatment 3	A	3.8		6.2		5.0	
Blanched (1% eq. NaCl) 0% NaCl solution	B	1.7	1.5	1.6	1.2	2.0	1.7
	C	3.0	1.3	4.3	1.0	6.8	1.5
	D	1.9	0.7	2.0	0.8	1.4	0.8
	E	2.0		1.7		1.9	

[a] Refer to Table 1 for complete treatment description.
[b] Refer to Fig. 2 for fiber optic temperature probe location diagram.

Locations D and E in the bottom of the cup showed different heating profiles compared to the center and upper locations. For all vegetables, locations D and E displayed the lowest maximum temperature. Red bell pepper showed the lowest maximum temperature at location E with a temperature of 59.4 °C (Table 3). Location E was also the cold spot for broccoli, and reached a maximum temperature of 73.8 °C during heating. For sweetpotato the cold spot was at location D and reached 79.2 °C.

The highest heating rates were measured in vegetable particles located in the center of the cup (location C) (Table 3). It is interesting to note that red bell pepper particles in the center (location C) exhibited the slowest heating rate of 3.5 °C/s, compared to sweetpotato and broccoli which achieved heating rates of 9.8 and 10.2 °C/s, respectively. These results were consistent with the dielectric properties of the unblanched vegetables (Fig. 4). Red bell pepper had the highest penetration depth and lowest loss tangent (Koskiniemi et al., 2011), indicating a slower rate of heating. Sweetpotato and broccoli were able to rapidly convert the microwave energy into heat due to their higher loss factors (Koskiniemi et al., 2011). This was also supported by comparing the heating rates (Table 3) and maximum temperatures (Fig. 5a, 6a, and 7a) achieved by the vegetable particles in locations A and B.

While heat must be delivered to the center of each particle, heating characteristics of the cover solution must also be taken into consideration. In general, heating of the 0% NaCl cover solution in treatment 1 followed the same trend as the vegetable particles. The cover solution in the upper half of the cups reached higher maximum temperatures for all vegetables (Table 2). A similar spatial heating pattern of water contained in cylinders was observed by Prosetya and Datta (1991). The observed heating effect can be the result of convective fluid flow from the rapidly heated, and less dense, center of the cup upwards due to buoyant forces, as well as the exposure of the unshielded cups to microwave energy. It followed that the cold spot was observed at the bottom of the cups due to a combination of insufficient microwave penetration and buoyancy-driven fluid flow.

The heating profile results showed that the vegetable particles were preferentially heated. This was evidenced by greater temperatures and heating rates, except for red bell pepper in location B (Tables 2 and 3). These results were also consistent with the measured dielectric properties. The temperature gradient between particles and solution was minimized in the bottom half of the cup due to less microwave exposure. Compared to the vegetable particles, heating was more uniform in the cover solution due to convection currents and higher penetration depth of microwaves into the citric acid cover solution.

These results indicated that when NaCl is not present, pasteurization temperatures of at least 74 °C could be achieved using continuous microwave processing for sweetpotato and broccoli. Red bell pepper presents challenges to microwave pasteurization because its dielectric properties are not as conducive to microwave heating as sweetpotato and broccoli.

3.2.2. Treatment 2 – unblanched, 1% NaCl cover solution

Volumetric heating was not efficient when unblanched vegetables were filled with a 1% w/v NaCl cover solution. The maximum temperature was achieved at location A for all vegetables. Location A is closest to the incident microwaves, so the microwave energy is rapidly absorbed and converted into heat in the 1% NaCl cover solution. Similar to treatment 1, higher particle temperatures were achieved in the upper half of the cup, although the maximum temperature achieved at any location in treatment 2 was lower than temperatures recorded in treatment 1 (Table 2). This may be explained by the rapid attenuation of microwaves in the 1% NaCl cover solution, rather than in the vegetable particles. As a result, the amount of electromagnetic energy converted into heat within the particle decreased and the amount of heat transferred to the particle by convection increased. This observation was supported by the small difference in temperatures between the cover solution and vegetable particles at the same measurement location (Table 2). This heating effect was different from treatment 1 in which the vegetable pieces were clearly heated preferentially to the surrounding solution, creating a large temperature gradient between the particle and solution at the same location. Overall, treatment 2 resulted in improved heating uniformity as seen by the decrease in range between maximum and minimum temperatures within the cup, but the average temperature within the cup was lower than treatment 1.

3.2.3. Treatment 3 – blanched, 1% NaCl equilibrated vegetables in 0% NaCl cover solution

It was hypothesized that increasing the dielectric loss by equilibrating the blanched vegetables to a 1% w/w NaCl content and placing them in a citric acid solution (0.5%) of lower dielectric loss would increase the maximum temperature of the vegetable particles during microwave processing. Blanching was used in order to facilitate the penetration of acid and salt into the vegetable material within 24 h as previously reported (Koskiniemi et al., 2011).

The vegetable pieces would be preferentially heated, and greater penetration of microwaves into the cup would occur. It was found that the hypothesis held true for each vegetable. The maximum temperatures for each vegetable particle in treatment 3 were greater than each of the corresponding pieces in treatment 2 (Table 2). Heating rates of the vegetables also increased, but the heating rates of the cover solution remained unchanged (Table 3). These results indicated that greater penetration of microwaves was achieved.

The equilibration of blanched vegetables with NaCl had the most significant effect on red bell pepper. Heating of red bell pepper particles A, B, C, and D showed significant improvement compared to treatment 2. The maximum temperature reached by particles A, B, C, and D increased by approximately 15 °C, compared to treatment 2. The compositional change did not improve heating of particle E for red bell pepper or broccoli, but increased the maximum temperature of sweetpotato in location E by 8 °C.

3.3. Comparison of compositional effects

Salt had a significant impact on the heating profiles of vegetable particles when added to the cover solution. The addition of salt to the cover solution clearly produced surface heating effects, as opposed to volumetric heating, which was observed when no salt was added to the cover solution. This finding was consistent with previous work on microwave heating of salt solutions in cylindrical containers (Anantheswaran and Swanderski, 2002). A remarkable feature of vegetables heated in a 0% NaCl solution was the rapid rise in temperature at the center of the cup. The cylindrical cup used in this study lent itself to favorable convergence of microwaves, which resulted in higher electric field intensity near the center of the cup. Focusing of microwaves only occurs if the radius of the cylinder does not exceed the penetration depth (Peyre et al., 1997). This explains why focusing was not observed in treatment 2. The penetration depth of the salted vegetables and 1% NaCl solution was approximately 1 cm (Fig. 4), and the radius of the cup was 3.4 cm, so microwaves could not reach the center of the cup to converge and produce a focusing effect.

For all product compositions, the coldest location during microwave processing was in the bottom part of the cup. This finding was consistent with previous works (Anantheswaran and Swanderski, 2002; Prosetya and Datta, 1991). Anantheswaran and Swanderski (2002) found that the cold spot of water and salt solutions was at the bottom of cylindrical containers during microwave heating at 2450 MHz in a domestic microwave oven. Surface heating near the top of 1% and 2% NaCl aqueous solutions was observed, whereas volumetric heating was apparent in distilled water during microwave heating.

3.4. Process design for improved heating uniformity

Regardless of compositional differences, a temperature greater than 60 °C could not be achieved in location E, farthest away from incident microwaves. Upon this finding, it was hypothesized that rotating the cups 180° during processing could increase the temperature at location E and improve heating uniformity. In order to accomplish 180° rotation, a two-stage rotation apparatus (Fig. 3) was designed and implemented as described above.

Installation of the two-stage rotation apparatus into the microwave applicator improved heating uniformity and increased the mean temperature at the exit of the microwave as seen in Fig. 8. Comparing the bottom cup locations (D and E) of sweetpotato and red bell pepper clearly showed two-stage heating curves corresponding to the 180° rotation of the cup. Prior to rotation (stage 1: 0–20 cm), vegetable particles at location D heated more rapidly due to its closer proximity to incident microwaves. A transitional stage occurred from approximately 20–40 cm in the applicator, during which the cup rotated. After 180° rotation (stage 2: 40 cm onward), a marked increase in the heating rate of location E was observed due to its increased exposure to microwave energy, since locations D and E have reversed. Interestingly, the heating profiles

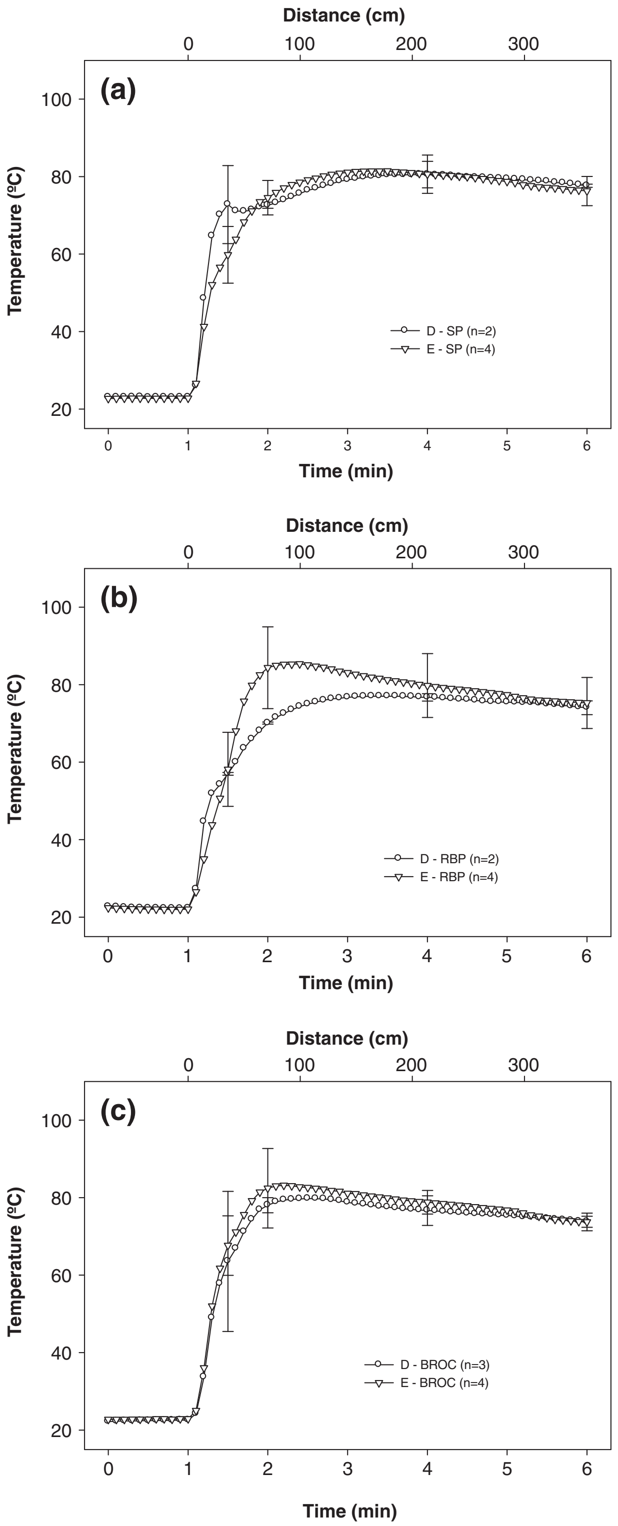

Fig. 8. Time–temperature heating profiles of bottom locations (D and E) as affected by cup rotation during 915 MHz continuous microwave processing of blanched, 1% NaCl equilibrated vegetables in 0% NaCl cover solution at 3.5 kW: (a) sweetpotato, (b) red bell pepper, and (c) broccoli. Error bars represent 1 standard deviation of at least two replicates. Refer to Fig. 2 for locations of D and E.

at location E were similar to the findings of Geedipalli et al. (2007). Geedipalli et al. (2007) investigated the heating uniformity contributed by a rotating turntable in microwave ovens at 2450 MHz and observed a stepwise-like increase in temperatures corresponding to the angle of rotation. The temperature of the hot spot would rise rapidly, then slowly, corresponding to each 180° turn of the food, indicating the uneven electrical field distribution in the microwave cavity.

While a crossover in temperatures and heating rates was observed at locations D and E for sweetpotato and red bell pepper, the same was not observed for broccoli. A two-stage heating curve was also observed for broccoli, although not as pronounced. This may be a result of the different vegetable:solution ratio (30 g broccoli, 60 g cover solution) for broccoli, compared to the other vegetables (45 g vegetable, 45 g cover solution). As a result, inclusion of a higher amount of a low-loss citric acid cover solution enabled greater microwave penetration into the broccoli pieces, as well as more convection in the cup.

As a final measure of the overall improvement in heating uniformity, time–temperature heating profiles of red bell pepper (treatment 3) were measured at each measurement location while processing at 3.5 kW with 4 cm spacing and rotation. Compared to microwave processing at 4 kW with no rotation (Fig. 6c), the process modifications with rotation dramatically improved heating uniformity and effectively heated the cold spot (Fig. 9). The range in maximum temperatures at the hot and cold spots decreased from 37.9 to 17.5 °C, and a temperature of 77 °C was achieved at the cold spot in the cup to meet the required pasteurization temperature of 74 °C. In addition to the marked effect of rotation, the change in power density cannot be overlooked. When cups were placed adjacently and processed at 4 kW, the power density, or power per kg of product within the microwave cavity was calculated to be 1010 W/kg. When cups were spaced 4 cm apart to facilitate rotation, the power density in the microwave cavity increased to 1350 W/kg, and so aided in exceeding pasteurization temperatures. These results showed that the addition of rotation and other process modifications significantly improved microwave heating characteristics of acidified vegetable packs.

3.5. Effects of process modification on microwave power

An important aspect of any thermal process is the efficiency of energy transfer, or energy conversion, especially in the case of microwaves. To this end, forward and reflected microwave power was also recorded. Table 4 shows the forward, reflected, and lost forward power during microwave processing at 4 and 3.5 kW. Forward power is the total amount of energy transmitted into the waveguide, reflected power is that which was directed back towards the circulator, and the lost forward power was the amount of microwave energy not absorbed by the product at the end of the microwave cavity. By looking at the reflected and lost forward power as a percentage of forward power, one can compare the effects of product arrangement in the microwave applicator. The results showed that reflections were greater when vegetable packs were spaced apart, as opposed to being placed adjacent to one another. Furthermore, the fluctuations in reflected power recorded during the experiments were much greater when cups were spaced apart than when adjacent (data not shown). It appeared that cup spacing and lateral movement involved during rotation of the cups increased the relative amount of reflected power. While these reflections did not impede the heating process, energy conversion could be optimized through tuning of the microwave system.

Table 4
Effect of cup arrangement on microwave power efficiency during processing.

	Mean power[a] (kW)		% of forward power[b]	
	Adjacent[c]	Spaced[d]	Adjacent	Spaced
Forward power transmitted	4.04	3.70	–	–
Reflected (reverse) power	0.07	0.12	1.66	3.34
Lost forward power	0.02	0.03	0.54	0.78
Net power absorbed	3.96	3.55	97.80	95.88

[a] Means are the process means of at least 8 runs.
[b] Percentages of forward power lost were significantly different ($p < 0.05$) between adjacent and spaced treatments.
[c] Adjacent cups (no rotation) were processed at a nominal power level of 4 kW.
[d] Spaced cups (with rotation) were processed at a nominal power level of 3.5 kW.

4. Conclusions

The level and distribution of salt in acidified vegetable packs was found to play a significant role in microwave heating. When no salt was added, a pronounced focusing effect was observed for all vegetables. Addition of salt to the cover solution lowered microwave penetration into vegetable pieces and resulted in lower

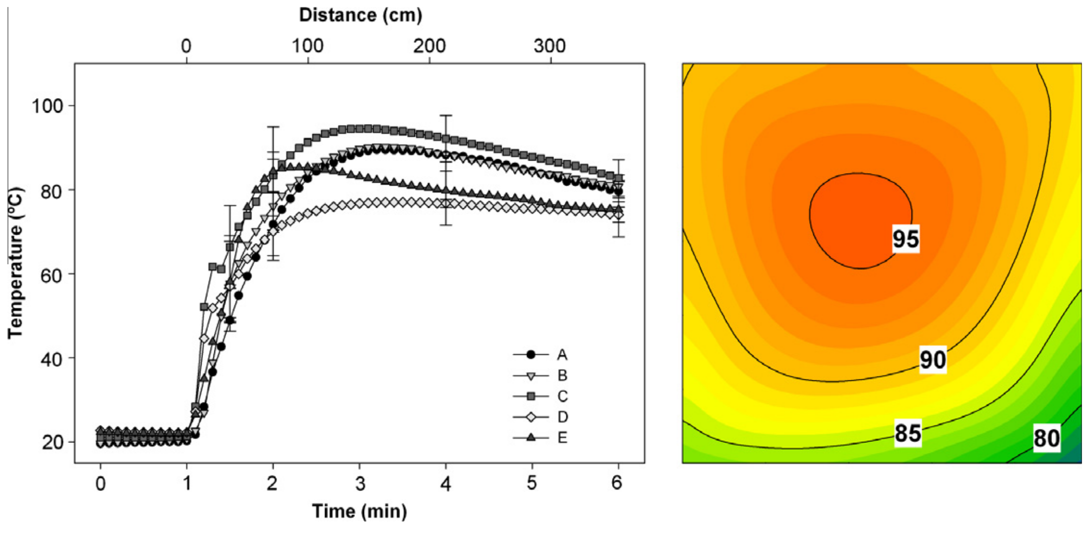

Fig. 9. Time–temperature heating profile (left) and contour plot (right) of pre-equilibrated red bell pepper to 1% NaCl in 0% NaCl cover solution. Error bars represent 1 standard deviation of at least 2 replicates. Refer to Fig. 2 for locations of A, B, C, D, and E.

temperatures during processing. Pre-equilibrating vegetable pieces to 1% NaCl improved microwave heating due to increased dielectric properties, and, coupled with a low loss cover solution increased microwave penetration into the vegetable packs.

Rotation of vegetable packs by 180° during continuous microwave processing was shown to reliably and significantly improve microwave heating by increasing exposure of the packs to incident microwaves. The effective treatment involved blanching, soaking for 24 h in a NaCl and citric acid solution, and 180° rotation. This work has contributed to a better understanding of the influence of salt addition and distribution during dielectric heating of acidified vegetables using 915 MHz continuous microwave system.

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