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Overcoming issues associated with the scale-up of a continuous flow microwave system for aseptic processing of vegetable purees ☆

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Abstract

Continuous flow microwave heating is a promising alternative to conventional heating for aseptic processing of low-acid vegetable purees. However, non-uniform temperature distribution and control of processing parameters are the major hurdles in the implementation of continuous flow microwave heating. This study was undertaken to overcome issues associated with the scale-up of a continuous flow microwave system from pilot plant scale to industrial scale and to conduct extended run times of 8 h based on the procedure developed. Dielectric properties and cross-sectional temperature profiles were measured during processing of green pea puree and carrot puree from 20 to 130 °C in a 5-kW continuous flow microwave system. During processing of green peas, cross-sectional temperature differences of 8.6 and 5 °C were observed at the outlet for center temperatures of 50 and 130 °C respectively. These temperature differences were 32.9 and 3.6 °C for carrot puree. For process scale-up, green pea puree and carrot puree were processed in a 60-kW microwave system with the objective of successful operation for at least 8 h. Static mixers, installed at the exit of each of the microwave applicators, improved temperature uniformity for both purees. Successful completion of processing the purees for 8 h in the 60-kW microwave system showed the potential for the scale-up of a continuous flow microwave system from pilot plant scale to industrial scale.

Keywords: Aseptic processing; Microwave heating; Vegetable purees; Scale-up

1. Introduction

Vegetable purees are used as ingredients in various food products such as baby foods, soups, and beverages. Preservation of vegetable purees involves initial processing of vegetables into purees followed by subsequent refrigeration, freezing, canning, or aseptic processing. Preservation by freezing requires a considerable investment in frozen distribution and storage as well as space, energy, and time-consuming defrosting treatment before use. Preservation by canning usually involves excessive thermal treatment of the product because heat transfer from the wall of the can to the center of the can for these very viscous products is mainly by conduction. The slow rate of heat transfer from the wall to the center of the can limits the maximum size of the can. This is a major hurdle for more widespread use of vegetable purees as ingredients in the food industry. Excessive thermal treatment of the product also results in degradation of color, flavor, texture, and nutrients.

Aseptic processing is considered as a potential alternative to conventional canning to meet the demand for convenient and high quality foods. As opposed to conventional

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canning, the use of high temperature for a short period of time in aseptic processing can be designed to yield a higher quality product with equal or better level of microbiological safety as that in a conventional canning system. In addition, it is also possible to aseptically fill the finished product into packages of different sizes and shapes (David, Graves, & Carlson, 1996). In aseptic processing, scraped-surface heat exchangers (SSHEs) have been used for highly viscous products such as low-acid vegetable purees. However, high maintenance costs, complex and time consuming cleaning operation limit the use of SSHEs. These limitations of SSHEs have contributed to a need for alternative heating technologies for processing highly viscous products such as vegetable purees.

Continuous flow microwave heating is an emerging technology in the food industry. The rapid and uniform heating associated with microwaves should be ideal for aseptic processing. Heating of food products using continuous flow microwave systems have been shown to provide improved color, flavor, texture, and nutrient retention (Coronel, Simunovic, & Sandeep, 2003; Gentry & Roberts, 2005; Giese, 1992; Nikdel, Chen, Parish, Mackellar, & Friedrich, 1993; Tajchakavit, Ramaswamy, & Fustier, 1998; Villamiel, Lopez-Fandino, & Olano, 1996). Recently, aseptic processing of sweetpotato puree using a continuous flow microwave system has been reported (Coronel, Truong, Simunovic, Sandeep, & Cartwright, 2005). However, prior to commercialization, there is a need to better understand and overcome the issues associated with the scale-up of the continuous flow microwave system.

Extended run times of a process at industrial scale using conventional heating systems are associated with issues such as fouling. Similarly, scale-up of a continuous flow microwave system is associated with certain issues. One of the major issues in implementing an aseptic process for vegetable purees using microwaves on an industrial scale is the possibility of having a non-uniform temperature distribution within the product. Factors responsible for non-uniform temperature distribution include differences in dielectric and thermophysical properties, non-uniform distribution of electromagnetic field, and the magnitude of the diameter of the applicator tube. Additional issues associated with the scale-up of a microwave process to industrial scale include control of processing parameters such as microwave power, flow rate, temperature, and pressure. Specially designed focused microwave applicators (Drozd & Joines, 2001) have been shown to yield a relatively uniform temperature distribution for dairy products (Coronel et al., 2003). This study was a beginning towards the commercialization of continuous flow microwave technology, but issues related to scale-up and extended run times still need to be addressed.

The present study utilized two different continuous flow microwave systems with specially designed focused applicators to overcome operational issues associated with the scale-up from pilot plant scale to industrial scale. Two vegetable purees (green pea and carrot) were processed for an extended run time of 8 h (typical duration of plant operation in industries) in the industrial scale system based on the procedures developed.

2. Materials and methods

2.1. Test material

Frozen green pea puree and carrot puree were purchased from Stahlbush Island Farm Inc. (Corvallis, OR). The composition of the frozen purees as given by the supplier has been given in Table 1. These purees were thawed at room temperature for several hours prior to processing.

2.2. Measurement of dielectric properties

Dielectric properties (dielectric constant, ε' and dielectric loss factor, ε'') of green pea puree and carrot puree were measured in triplicate using an open-ended coaxial probe (Model HP 85070E, Agilent Technologies, Palo Alto, CA) connected to a network analyzer (Model HP 8753C, Agilent Technologies, Palo Alto, CA). Dielectric properties were measured under continuous flow conditions because the measurement by the conventional approach (under static conditions) measures dielectric properties of only a portion of the material in contact with the probe. Thus, measurement by conventional approach may not be representative of the dielectric properties of the bulk. The food product was continuously pumped across the dielectric probe in measurement under continuous flow conditions. This approach gives a better representation of the dielectric properties of the bulk of the food product because different parts of the food product are in contact with the probe at different times. The instrument was calibrated by leaving the tip of the probe in contact with air, metal, and 25 °C de-ionized water and measuring the dielectric properties. The dielectric properties were measured at 20, 75, 90, 100, 110, 120, 125, and 130 °C and at frequencies from 300 to 3000 MHz with an increment of 5 MHz. A variable step size for temperature increment (with a smaller step size at higher temperatures) was used because this study involved determining the dielectric properties at sterilization temperatures. HP 85070E is a small diameter probe with an outer diameter (OD) of 2.2 mm which was inserted in the tube using a smart gasket (Rubber-Fab, Newton, NJ). A schematic representation of the experimental system to measure dielectric properties during continuous flow

Table 1
Composition of frozen green pea puree and carrot puree

	Green pea puree	Carrot puree
Water (%)	79.93	90.04
Protein (%)	5.21	0.78
Carbohydrate (%)	13.71	7.9
Fat (%)	0.37	0.46
Dietary fiber (%)	4.20	3.3

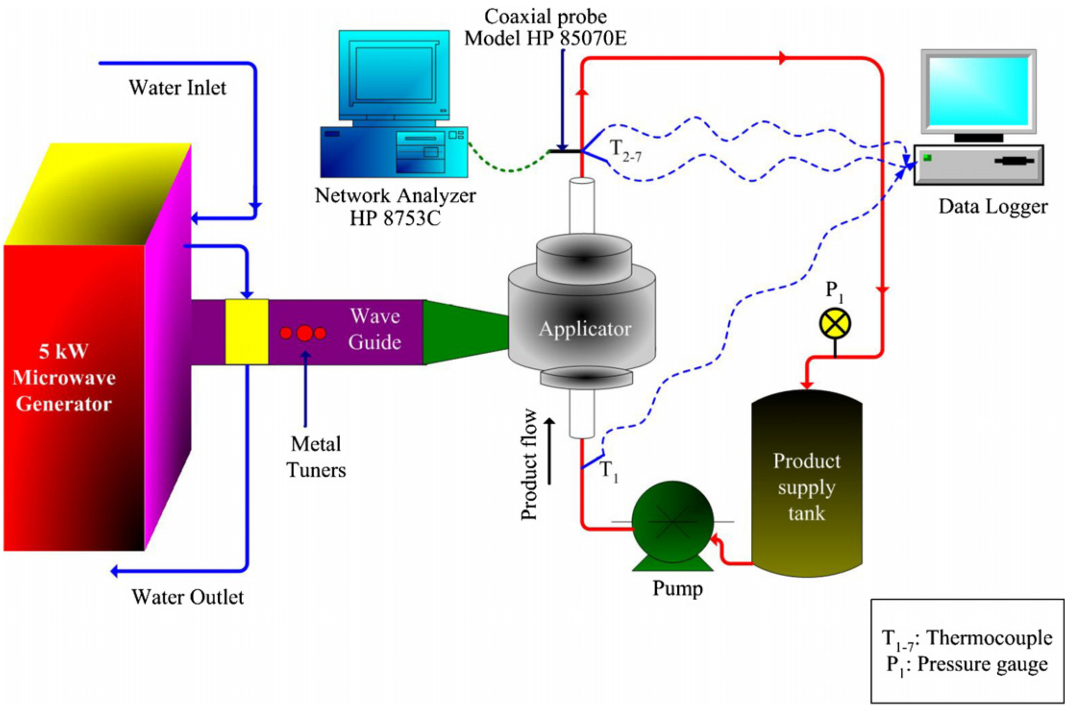

Fig. 1. Schematic representation of the 5-kW microwave system to measure dielectric properties.

microwave heating is shown in Fig. 1. The product was heated using a 5-kW microwave system which is described below.

2.3. 5-kW microwave system

The 5-kW microwave system, shown in Fig. 1, consists of a 5-kW microwave generator (Industrial Microwave Systems, Morrisville, NC) operating at 915 MHz, a waveguide of rectangular cross-section, and a specially designed focused applicator (Drozd & Joines, 2001). A tube of 1.5 in. nominal diameter (0.038 m ID) made of Polytetrafluoroethylene (PTFE or Teflon®) was placed at the center of the applicator through which the product was pumped using a positive displacement pump (Model MD012, Seepex GmbH+ Co., Bottrop, Germany). The length of applicator tube exposed to microwaves was 0.28 m. The average residence time of the product in the applicator for a flow rate of 0.9 L/min was 21.1 s. The temperatures at the inlet and outlet of the applicator were recorded using thermocouples and a datalogging system (Model DAS-16, Keithley Metrabyte Inc., Taunton, MA). The dielectric probe (HP 85070E) was inserted at the outlet of the applicator in one of the three ports of a smart gasket (Coronel et al., 2003) as shown in Fig. 1.

2.4. 60-kW microwave system

The 60-kW microwave system, shown in Fig. 2, consisted of a 60-kW microwave generator (Industrial Microwave Systems, Morrisville, NC) operating at 915 MHz, a waveguide of rectangular cross-section split into two sections, and two specially designed focused applicators (Drozd & Joines, 2001). A PTFE tube (0.038 m ID) was placed at the center of each applicator through which the product was pumped with a positive displacement pump (Model A7000, Marlen Research Corp., Overland Park, KS). The length of applicator tube exposed to microwaves was 0.45 m in each applicator. The average residence time of the product in each of the applicators for a flow rate of 3.78 L/min was 8.2 s. Temperatures were measured at the inlet of the system, the inlet and exit of each applicator, and at the exit of the holding tube using thermocouples and a datalogging system (HP 3497A, Agilent Technologies, Palo Alto, CA).

2.5. Statistical analysis

All the experiments were performed in triplicates. Student's two-tailed t test at 95% ($p < 0.05$) confidence interval was used to determine if the means of dielectric properties of green pea and carrot puree were significantly different. Statistical data analysis toolbar of MS Excel was used for statistical analysis (Microsoft Corporation, Redmond, WA).

3. Results and discussion

3.1. Dielectric properties

The dielectric properties of green pea puree and carrot puree at 915 MHz measured under continuous flow condi-

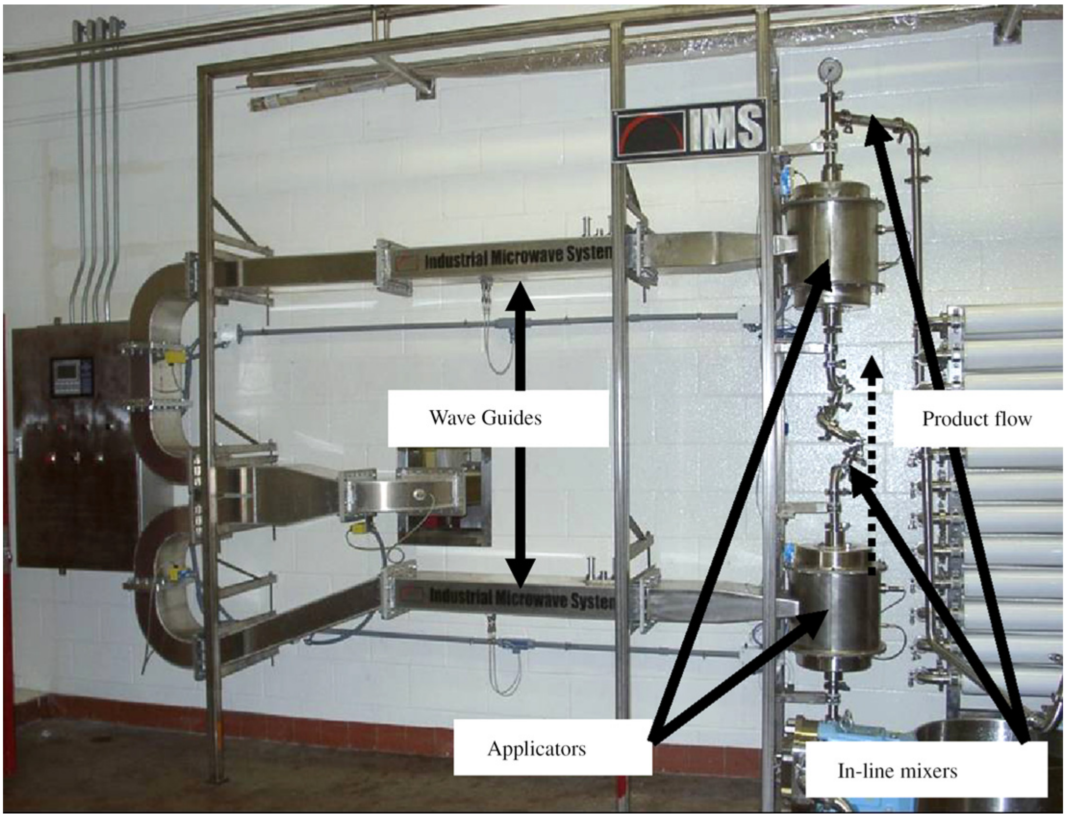

Fig. 2. 60-kW microwave system.

tions in the temperature range of 20–130 °C are shown in Fig. 3. For both the purees, dielectric constant decreased with an increase in temperature and the dielectric loss factor increased with an increase in temperature. This observation is in accordance with the observations of Datta, Barringer, and Morgan (1997) for food products with moisture content greater than 60%. Dielectric constant and dielectric loss factor of green pea puree were significantly different from those of carrot puree. Second-order polynomial correlations for the dependence of dielectric properties of both purees on temperature at 915 MHz were developed and are shown in Table 2.

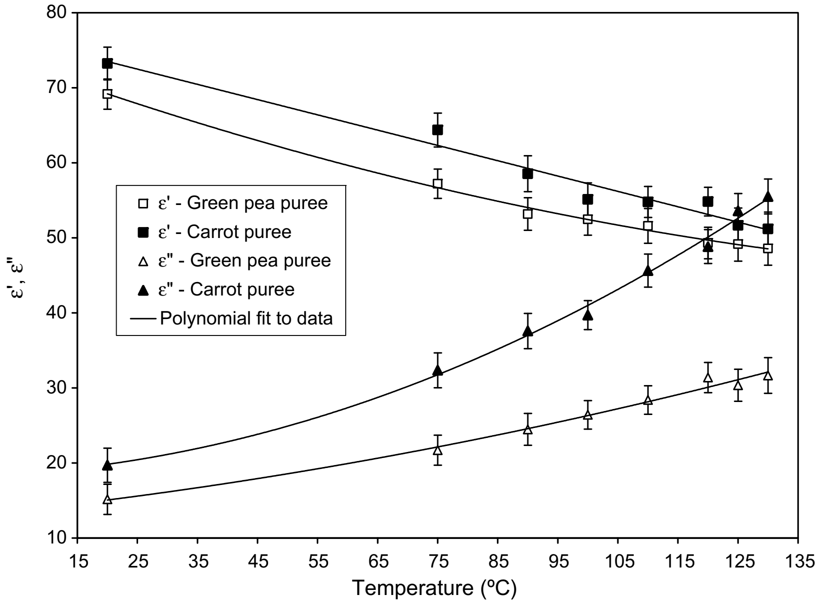

Fig. 3. Dielectric constant (ε') and dielectric loss factor (ε'') of green pea puree and carrot puree at 915 MHz.

Table 2
Dielectric properties of green pea puree and carrot puree as a function of temperature at 915 MHz

Sample	Correlations (T in °C)	r^2	Standard error of estimate
Green pea puree	$\varepsilon' = 74.8 - 0.2957\ T + 0.0007\ T^2$	0.994	0.75
	$\varepsilon'' = 13.2 + 0.0829\ T + 0.0005\ T^2$	0.986	0.72
Carrot puree	$\varepsilon' = 77.5 - 0.2022\ T - 0.00001\ T^2$	0.969	1.44
	$\varepsilon'' = 18.4 + 0.0359\ T + 0.0019\ T^2$	0.995	0.92

The conventional method of sterilization of the processing system by hot water cannot be applied to continuous flow microwave heating systems because the dielectric properties of the food product and water are different. As a result, transition from water to food product could result in under- or over-heating, depending on the dielectric properties of the food product. A method was developed by Coronel (2005) to prepare model solutions by matching the dielectric properties of the solutions prepared from table salt, sugar, and CMC to those of the food product to be processed. Thus, the correlations for dielectric properties were used to prepare the model solution to be used as a sterilization solution prior to processing in the 60-kW microwave system.

3.2. Processing in the 5-kW microwave system

The purees were processed by recirculating in the 5-kW microwave system with a microwave power output of 3 kW and at a flow rate of 0.9 L/min. Temperatures at the inlet and outlet of the applicator tube during processing of green pea puree and carrot puree are shown in Figs. 4 and 5 respectively. For green pea puree, cross-sectional temperature differences of 8.6 and 5.0 °C at the outlet were observed for the center temperatures of 50 and 130 °C respectively. These temperature differences for carrot puree were 32.9 and 3.6 °C respectively. From Figs. 4 and 5, it can be seen that the temperature differences between the center and the wall of the applicator tube at the outlet became smaller as the outlet temperature increased from 20 to 100 °C. This might be due to better absorption of microwave energy by the purees at higher temperature as their loss tangent increases with an increase in temperature. The faster dissipation of heat within the purees due to a decrease in viscosity at higher temperature might also have contributed to this narrowing of temperature profile. The cross-sectional temperature differences in the 5-kW microwave system suggested the use of static mixers in a scale-up operation.

Processing in the 5-kW microwave system prior to processing in the 60-kW microwave systems has several advantages. Processing in the 5-kW system establishes the compatibility of the product for continuous flow microwave heating. If a product does not reach the required temperatures for sterilization or pasteurization, it is concluded that continuous flow microwave heating will not be suitable for that particular product in its present form. Processing in the 5-kW system also helps in understanding the behavior of the food products with respect to fat melting, starch gelatinization, or protein denaturation. For products containing fine powder (Chocolate milk containing cocoa powder), the extent of fouling in the applicator tube during processing in the 5-kW system can be used to

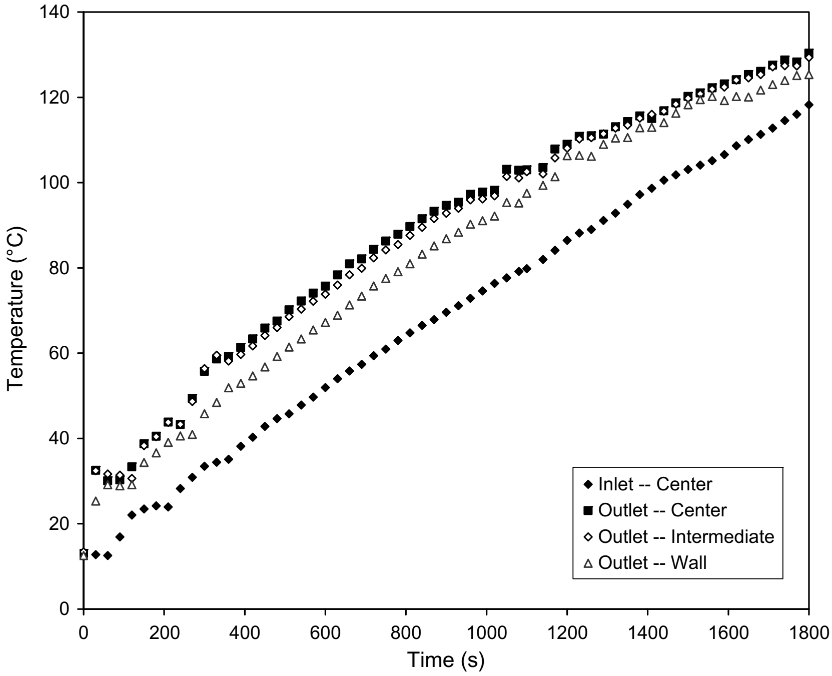

Fig. 4. Temperature profile during processing of green pea puree in the 5-kW microwave system.

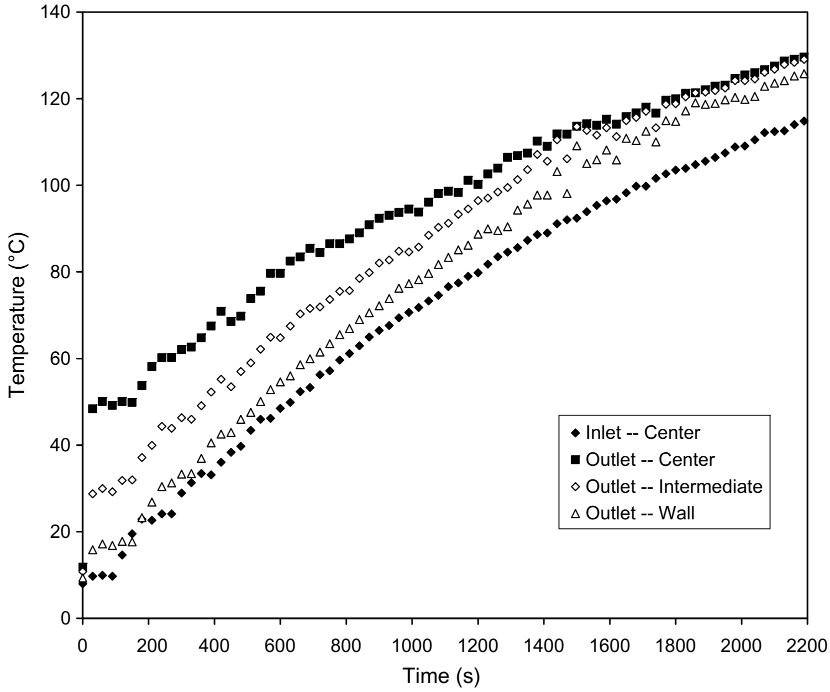

Fig. 5. Temperature profile during processing of carrot puree in the 5-kW microwave system.

decide if processing in the 60-kW microwave system would possibly result in failure of the applicator tube due to overheating of the deposits on the tube surface. Dielectric properties measured during processing in the 5-kW system are used to prepare the sterilization solution to be used during processing in the 60-kW microwave system. Thus, processing in the 5-kW microwave system determines the feasibility for any product to be processed using a continuous flow microwave system on an industrial scale.

3.3. Processing in the 60-kW microwave system

For process scale-up, green pea puree and carrot puree were processed using the 60-kW microwave system with the objective of successful operation for at least 8 h. Prior to introduction of the product, sterilization solutions were prepared by matching the dielectric properties of the solutions prepared by using table salt and sugar to those of the food product and these were recirculated at 130 °C for 30 min to sterilize the system prior to all processing runs. This sterilization method was found to provide good transition from sterilization solution to the puree.

Processing of products in the 60-kW microwave system resulted in failure of the applicator tube made from PTFE. This failure of the applicator tube might have been due to deposit formation on the internal surface of the tube and localized overheating of the deposits, cold shock upon sudden power off of the microwave generator, or stress fractures due to time–temperature–pressure combination. A new applicator tube, made from high purity alumina coated PTFE, with high temperature and pressure resistance was used for subsequent processing. In order to avoid failure of applicator tubes, a temperature monitoring system (at the inlet and exit of each of the microwave applicators) and a pressure gauge (at the inlet and exit of microwave applicators) were installed. An excessive pressure or temperature build-up at the exit of the heating section might be an early warning against a potential failure of the applicator tube.

Due to the non-uniformity in temperature distribution for purees in 5-kW microwave runs, static mixers (Admixer™, Admix Inc., Manchester, NH) were installed at the exit of each of the microwave applicators to decrease any temperature differences within the product at the outlet of the applicator tubes. Green pea puree and carrot puree were processed for 8 h using the 60-kW microwave system with a microwave power output of 30–40 kW and at a flow rate of 3.78 L/min. Mixing by the static mixers at the exit of applicators improved temperature uniformity. Temperature distributions at the exit of first applicator (A) and at the exit of second static mixer (B) for green pea puree and carrot puree are shown in Figs. 6 and 7 respectively. From Fig. 6A, it can be seen that there is a substantial temperature difference without static mixers at the exit of first applicator. If the material with this temperature distribution were to enter the second applicator, there would be a possibility of developing an extreme temperature and pressure condition in the tube of second applicator, leading to tube failure and possible damage of the microwave processing system. From Fig. 6B, it can be seen that the temperature difference is significantly reduced by the installation of static mixers. With static mixers, maximum value of the temperature differences between the center and the wall was reduced from 38.2 °C at the exit of first

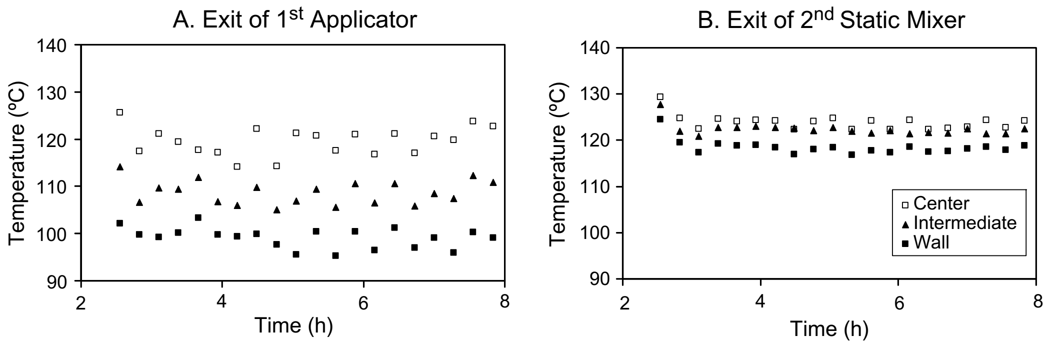

Fig. 6. Temperature profile during processing of green pea puree in the 60-kW microwave system.

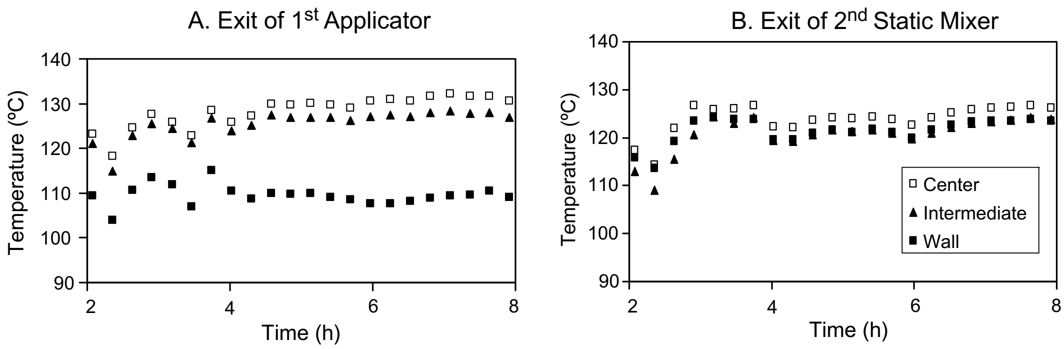

Fig. 7. Temperature profile during processing of carrot puree in the 60-kW microwave system.

applicator to 15.4 °C at the exit of second static mixer for green pea puree. The average value of the temperature differences between the center and the wall was reduced from 17.2 °C at the exit of first applicator to 5.2 °C at the exit of second static mixer for green pea puree. For carrot puree, maximum value of the temperature differences between the center and the wall was reduced from 54.5 °C at the exit of first applicator to 11.6 °C at the exit of second static mixer for green pea puree. The average value of the temperature differences between the center and the wall was reduced from 18 °C at the exit of first applicator to 2.3 °C at the exit of second static mixer. Thus, these results illustrate the effectiveness of temperature equalization to eliminate temperature differences in the cross-sectional area. Successful completion of processing the purees for 8 h in the 60-kW microwave system showed the potential for the scale-up procedures developed in this study for continuous flow microwave heating from pilot plant scale to industrial scale.

4. Conclusions

Results of dielectric property measurements during continuous flow microwave heating were used to prepare a model solution to be used as a sterilization solution prior to processing in the 60-kW microwave system. During processing of green peas in the 5-kW microwave system, cross-sectional temperature differences of 8.6 and 5 °C were observed at the outlet for center temperatures of 50 and 130 °C respectively. These temperature differences were 32.9 and 3.6 °C for carrot puree. Processing in the 5-kW system established that green pea puree and carrot puree are compatible for continuous flow microwave heating. Temperature distribution during processing of both the purees in the 60-kW microwave system showed the efficiency of static mixers as a means of temperature equalization. A new applicator tube, made from high purity alumina coated PTFE, with high temperature and pressure resistance was found to be less prone to failures. Successful completion of processing the purees for 8 h in the 60-kW microwave system showed the potential for the scale-up procedures developed in this study for continuous flow microwave heating from pilot plant scale to industrial scale.

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