

# Aseptic Processing of Sweetpotato Purees Using a Continuous Flow Microwave System

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**ABSTRACT:** Sweetpotato purees (SPP) were aseptically processed using a continuous flow microwave system to obtain a shelf-stable product. The dielectric properties of SPP were measured, and the dielectric constant and loss factor were within the range of the published values for fruits and vegetables. Small-scale tests were conducted in a 5-kW microwave unit to determine changes in color and viscosity with different thermal treatments. The results of these tests showed that color values ( $L^*$ ,  $a^*$ ) and viscosity did not change significantly compared with the untreated control. Pilot-scale tests were then conducted in a 60-kW microwave unit where the product was heated to 135 °C and held at that temperature for 30 s. The pilot-scale test produced a shelf-stable product with no detectable microbial count during a 90-d storage period at room temperature. This is the 1st report of aseptically packaged vegetable puree processed by a continuous flow microwave heating system.

**Keywords:** sweetpotato, aseptic processing, continuous-flow-microwave

## Introduction

The use of sweetpotatoes in the food industry often involves processing of the roots into purees that can be subsequently frozen or canned for year-round availability of the produce. Sweetpotato purees (SPP) can be used as an ingredient in various products, including baby food, casseroles, puddings, pies, cakes, bread, restructured fries, patties, soups, and beverages (Truong 1992; Woolfe 1992; Truong and others 1995; Walter and others 2001).

Preservation of SPP by freezing is a well-established method, but the frozen puree requires considerable investment in frozen distribution and storage, as well as a lengthy and poorly controlled defrosting treatment before use. Canned purees typically receive excessive thermal treatment, especially when processed in institutional-size packages, which provide poor use of storage space and presents a difficulty in handling, opening, and dispensing of the product and disposing of the empty packages. Due to the poor heat penetration characteristic of the purees, canned vegetable purees such as sweetpotatoes, pumpkin, or squash are retorted for over 165 min at 121 °C for a can size of 603 × 700 (Lopez 1987), and the product quality within a can varies drastically from the can center to the wall edges where the product is severely over-processed with dark color and burnt flavor. The can size is, therefore, limited at size nr 10, and this size limitation is a major obstruction to the wider applications of canned sweetpotato purees in the food-processing industry. Other thermal processing technologies, such as scraped surface heat exchangers or flash sterilization treatment, also have limitations because of the low thermal diffusivity of SPP (Smith and others 1982). Fasina and others (2003) reported that SPP has a thermal diffusivity in the order of  $3 \times 10^{-7}$  m<sup>2</sup>/s and a thermal conductivity of 0.54 W/m K. The low thermal diffusivity and high viscosity of SPP leads to very long periods of heating by conventional thermal processing methods to achieve the required ster-

ilization levels, which in turn causes degradation of the nutrients in SPP and poor product quality.

Continuous flow microwave heating is one of the emerging technologies in food processing, offering fast and efficient heating. Heating of dairy products using this technology proved to be uniform in previous tests (Coronel and others 2003). The heating of food products using microwaves is governed by the dielectric properties of the material. The dielectric properties of SPP, as reported by Fasina and others (2003), are in the range of products that have been identified as promising to be processed using continuous flow microwave heating systems. Therefore, this study was undertaken to determine the technical feasibility of producing shelf-stable SPP using continuous flow microwave heating systems operating at 915 MHz. To the best of our knowledge, this is the 1st report of an aseptically packaged and shelf-stable vegetable puree processed by a continuous flow microwave heating system.

## Materials and Methods

### Preparation of sweetpotato purees (SPP)

Purees from Beauregard cultivar sweetpotatoes were prepared in the Fruit and Vegetable Pilot Plant of the N.C. State Univ. Dept. of Food Science for testing in 5-kW microwave unit and measurement of dielectric properties, color, and viscosity. The roots were cured at 30 °C, 85% to 90% relative humidity for 7 d and stored at 13 °C to 16 °C, 80% to 90% relative humidity. The purees were prepared as previously described (Truong and others 1995). Roots were washed, lye-peeled in a boiling solution (104 °C) of 5.5% NaOH for 4 min, and thoroughly washed in a rotary-reel sprayed washer to remove separated tissue and lye residue. Peeled roots were hand-trimmed and cut into slices (0.95-cm thick; Louis Allis Co. Slicer, Milwaukee, Wis., U.S.A.). The slices were steam-cooked for 20 min in a thermoscrew cooker (Rietz Manufacturing Co., Santa Rosa, Calif., U.S.A.) and comminuted in a hammer mill (Model D, Fitzpatrick Co., Chicago, Ill., U.S.A.) fitted with a 0.15-cm screen. The puree was placed in polyethylene bags, frozen, and stored at -20 °C until used. For test runs in a 60-kW microwave unit, which required a large quantity of the material, frozen sweetpotato puree

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from Beauregard cultivar were purchased from the Bright Harvest Sweetpotato Co., Inc. (Clarksville, Ark., U.S.A.). All the puree samples used in the study had moisture contents of 80% to 82%.

### Measurement of dielectric properties

An open coaxial dielectric probe (HP 85070B, Agilent Technologies, Palo Alto, Calif., U.S.A.) and an automated network analyzer (HP 8753C, Agilent) were used to measure the dielectric properties of the samples. The dielectric properties were measured in the 300 to 3000 MHz frequency range, with 541 intermediate frequencies. The system was calibrated using the calibration sequence following the instruction manual provided by the manufacturer (Agilent 1998). The samples (<100 g) were heated in an oil bath (Model RTE111, Neslab Instruments Inc, Newington, N.H., U.S.A.) until the desired temperatures (10 °C to 145 °C in 5 °C intervals) were attained, the samples were then placed in an insulating block to measure the dielectric properties. The temperature was measured again after the dielectric properties were read to ensure that the temperature was within 2 °C of the set-point. Three repetitive measurements were performed for each duplicated samples.

### Rheological tests

Constant rate measurement of sweetpotato puree viscosity as a function of shear rate was performed at 25 °C with a StressTech rheometer (Reologica Instruments AB, Lund, Sweden) using a cone and plate geometry (C40 4). Apparent viscosity was recorded as shear rates were ramped from 0.1/s to 300/s. Two repeated measurements were performed on each of the duplicated samples.

### Color analysis

Objective color of the samples was measured with a Hunter colorimeter (Hunter Associates Laboratory Inc., Reston, Va., U.S.A.). Results were expressed as tri-stimulus values,  $L^*$  (lightness, 0 for black, 100 for white),  $a^*$  ( $-a^*$  = greenness,  $+a^*$  = redness), and  $b^*$  ( $-b^*$  = blueness,  $+b^*$  = yellowness). The instrument (45°/0° geometry, D25 optical sensor) was calibrated against a standard white reference tile ( $L^* = 92.75$ ,  $a^* = -0.76$ ,  $b^* = -0.07$ ). The puree samples were filled into a 60 × 15-mm covered Petri dishes (Becton Dickinson Labware, Franklin Lakes, N.J., U.S.A.). Six measurements were performed for each sample, and average values were used in the analysis.

### Tests in a 5-kW microwave unit

A continuous flow microwave heating unit (Industrial Microwave Systems, Morrisville, N.C., U.S.A.) was used for processing SPP. The microwave system described herein was designed for the continuous processing operation that is different from other microwave units such as the microwave-circulated water combination heating system for batch production of pouches and trays reported by Guan and others (2003). The unit consisted of a 5-kW microwave generator operating at 915 MHz, a waveguide of rectangular cross-section in which a directional coupler was attached and a specially designed applicator. A tube of 1.5 inch nominal diameter (0.038-m inner dia) made of Polytetrafluoroethylene (PTFE or Teflon®) was placed at the center of the applicator. The exposure region to the microwaves was 0.125 m long. The power delivered by the microwave generator and the power reflected back were measured using diodes located in the directional coupler and LabView software (Natl. Instruments Corp, Austin, Tex., U.S.A.). This software also controls the amount of power the generator delivers to the product.

A positive displacement pump (Model MD012, Seepex GmbH+Co, Bottrop, Germany) was used to pump SPP at a rate of 0.5 L/min. Temperatures at 9 radial locations were measured using a thermo-

couple arrangement described by Coronel and others (2003) and recorded using a datalogger (model DAS-16, Keithley Metrabyte Inc, Taunton, Mass., U.S.A.). The power of the generator was adjusted using the control software to ensure that the product attained the required centerline temperature at the exit of the applicator. The product was then cooled in an ice-water bath, and samples were taken for further analysis.

### Tests in the a 60-kW microwave unit

Based on the results obtained in the tests in the 5 kW, processing conditions were established for a test in a 60-kW continuous flow microwave heating unit (Industrial Microwave Systems) operating at 915 MHz. The power delivered from the generator was monitored using a control panel supplied by the manufacturer. The microwaves were delivered to the product by a waveguide of rectangular cross-section, which were split into 2 sections and geared toward 2 specially designed applicators, with a directional coupler in each as seen in Figure 1. A PTFE tube (0.038-m inner dia) was placed at the center of each applicator, and the exposure region was 0.2 m long in each applicator.

A positive displacement pump (Model A7000, Marlen Research Corp., Overland Park, Kans., U.S.A.) was used to pump the product through the system. Temperatures were measured at the inlet of the system, the inlet and exit of each applicator, and at the holding tube exit. Arrangements of the thermocouples were described by Coronel and others (2003). The temperatures were recorded in 4-s intervals using a Datalogging system (HP 3497A, Agilent Technologies, Palo Alto, Calif., U.S.A.). The temperature at the exit of the system was achieved by controlling the power generated by the microwave system.

The system was 1st sterilized using an aqueous solution of NaCl and sugar, which was heated to 130 °C and recirculated for 30 min. The product was heated to 135 °C to 145 °C, held for 30 s, rapidly cooled in a tubular heat exchanger, and then aseptically packaged in aluminum-polyethylene laminated bags (Scholle Corp, Chicago, Ill., U.S.A.) using a bag-in-box unit (Model PT.A.F, Astepo, Parma, Italy). The puree bags were stored at ambient temperature (22 °C), and 2 bags were randomly taken for microbiological analysis after 1, 15, and 90 d. Standard plate count assay was used to enumerate total aerobic bacteria in the sweetpotato puree samples. Samples (50 g) were aseptically transferred to sterile filter bags (Spiral Biotech, Bethesda, Md., U.S.A.) containing 50 mL of sterile physiological saline solution (0.85% NaCl), and the bags were macerated with a Tekmar stomacher (Model TR5T, Tekmar Co., Cincinnati, Ohio, U.S.A.) on a high speed for 160 s. Appropriate dilutions of the stomacher filtrate were made using sterile physiological saline solution and spread onto duplicate PCA agar plates using the Spiral Biotech Autoplate 4000 spiral plater. The PCA plates were inoculated at 37 °C for 48 h for total aerobic bacterial counts. Sample dilutions were also spread onto plates of yeast/mold agar plates and inoculated for enumeration of yeast and mold colonies. Medium preparation was carried out following the standard procedures (Difco Laboratories 1998).

### Statistical analysis

Data were subjected to the analysis of variance (SAS Inst. 1996). Statistical testing was performed at the 95% ( $P < 0.05$ ) confidence level.

## Results and Discussion

### Dielectric properties

The dielectric properties of the sweetpotato purees measured at 915 and 2450 MHz and temperatures of 10 °C to 145 °C are shown

in Figure 2. The values for dielectric constant and loss factors were similar with those reported by Fasina and others (2003) for Beaugard sweetpotato puree, and they are within the ranges that have been reported for other food materials (Nelson and Datta 2001). For example, at 20 °C, the values of  $\epsilon'$  were 73.0 and 66.1, and  $\epsilon''$  values were 17.9 and 17.3 at 915 MHz and 2450 MHz, respectively (Figure 2). Nelson and others (1994) reported an  $\epsilon'$  range of 47 to 75 at 915 MHz and 45 to 73 at 2450 MHz,  $\epsilon''$  of 8 to 22 at 915 MHz and 10 to 18 at 2450 MHz for 24 common fresh fruits and vegetables at 23 °C. A sweetpotato sample was also among the tested materials and the reported  $\epsilon'$  and  $\epsilon''$  values were about 20% to 25% lower than the results obtained in our study. The differences can be attributed to moisture and compositional variations commonly observed in agricultural products. Sipahioglu and Barringer (2003) reported that

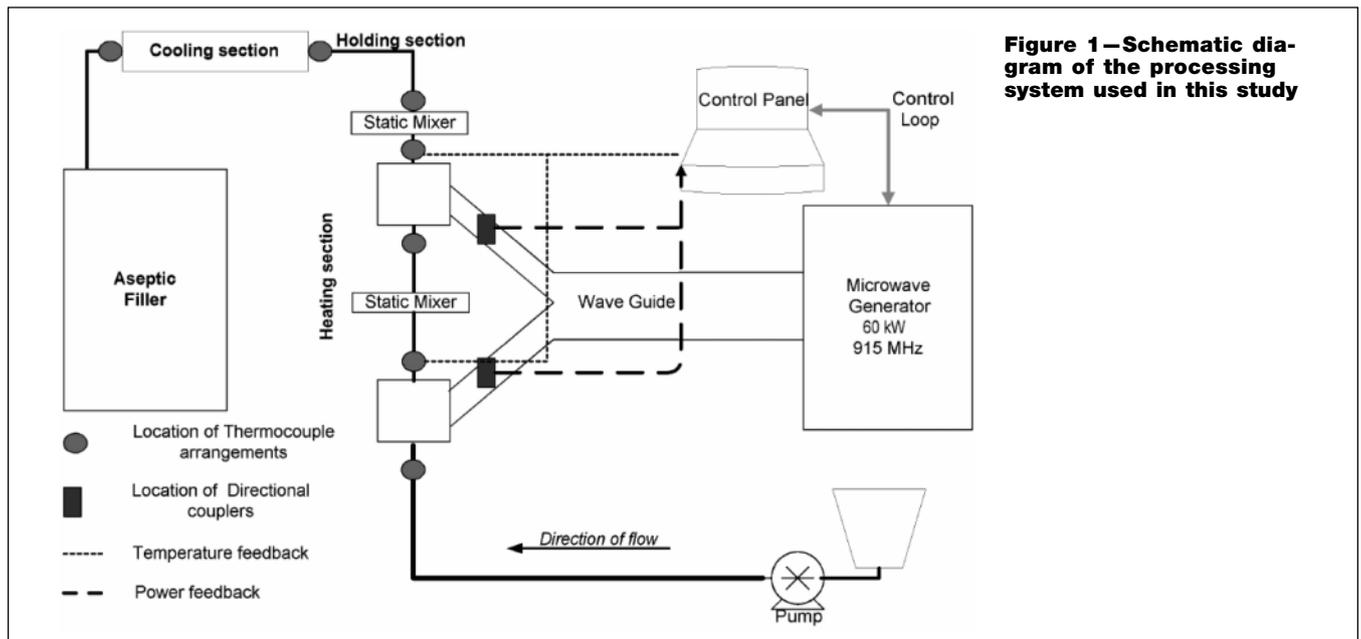
variation in the contents of moisture, ash, and high-molecular-weight carbohydrates affects the dielectric properties of various fruits and vegetables.

The obtained data fitted well using the predictive equations reported by Fasina and others (2003) for the dielectric constant ( $R^2 = 0.87$ ) and loss factor ( $R^2 = 0.89$ ) as a function of temperature (T) and frequency (f), as indicated by the dotted lines in Figure 2:

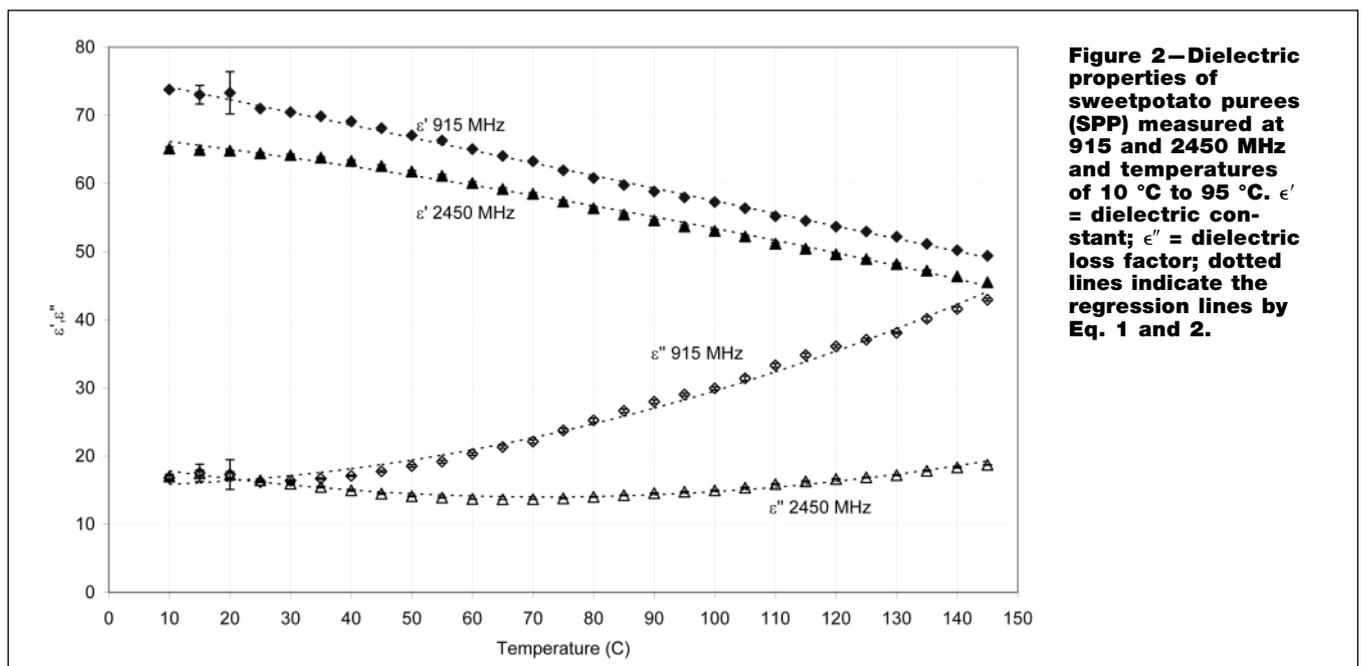
$$\epsilon' = 74.84 - 0.113T - 0.00214f \quad (1)$$

$$\epsilon'' = 29.76 + 0.125T - 0.0144f - 8.60 \times 10^{-5}fT + 4.11 \times 10^{-6}f^2 + 7.64 \times 10^{-4}T^2 \quad (2)$$

The effect of temperature on the dielectric constant was similar for



**Figure 1—Schematic diagram of the processing system used in this study**



**Figure 2—Dielectric properties of sweetpotato purees (SPP) measured at 915 and 2450 MHz and temperatures of 10 °C to 95 °C.  $\epsilon'$  = dielectric constant;  $\epsilon''$  = dielectric loss factor; dotted lines indicate the regression lines by Eq. 1 and 2.**

both 915 and 2450 MHz,  $\epsilon'$  decreasing with an increase in temperature, with values of 71.5 at 10 °C and 49.4 at 145 °C for 915 MHz and 67.1 at 10 °C and 45.5 at 145 °C for 2450 MHz (Figure 2). The loss factor ( $\epsilon''$ ) increased with increasing temperature, with values of 17.3 at 10 °C and 42.9 at 145 °C for 915 MHz. Elevated temperature reduced the puree viscosity and resulted in increased mobility of ions and higher electric conductivity (Herve and others 1998). However, at 2450 MHz,  $\epsilon''$  decreased with increasing temperature with values of 17.5 at 10 °C and 13.6 at 70 °C. Ohlsson (1989) attributed this phenomenon to the predominance of the dispersion resulting from dipole rotation of water molecules at 2450 MHz, and at high temperatures, fewer hydrogen bonds are formed and reformed, causing a decrease in  $\epsilon''$  values. Apparently, the effect of this dipole rotation at 2450 MHz was more pronounced than the increased in mobility of water molecules contributed by reduction of puree viscosity up to 70 °C. Above 80 °C, the temperature dependency of  $\epsilon''$  followed an upward trend, and increased to 18.7 at 145 °C (Figure 2).

The maximum operating diameter (MOD) of the tube to be used in the applicator was calculated using a method developed in our laboratory which involves a solution of the microwave energy penetration equation (Helmholtz equation) in cylindrical coordinates and a calculation of a theoretical temperature profile (Coronel and others 2004). MOD is defined as the largest diameter that can be used in continuous microwave flow processing to obtain a theoretical uniform temperature distribution across the cross-sectional area, and it is a function of dielectric properties at different temperatures. As shown in Figure 3, MOD decreases with increasing temperature, values of 0.060 m at 10 °C and 0.033 m at 145 °C for 915 MHz. The increase in the loss factor with temperature makes the energy conversion into heat more efficient in the outside of the tube, thus decreasing the penetration depth and, hence, MOD. MOD compared favorably to the diameter of the tube used in this experiments (39 mm), thus indicating that the processing of SPP in the existing system was possible.

### Tests in a 5-kW microwave unit

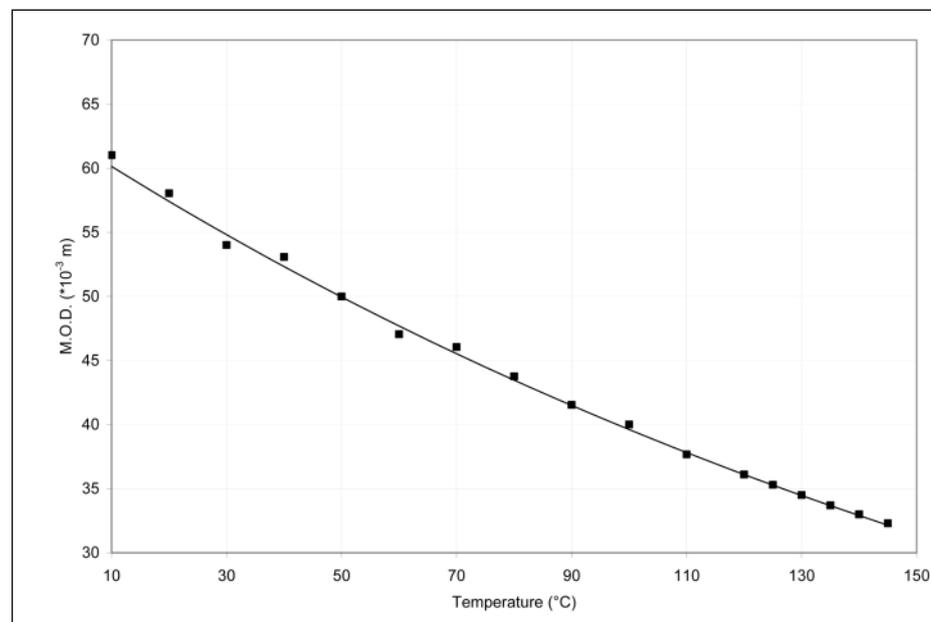
The product was processed using the 5-kW microwave unit, keeping a constant holding time and changing the centerline exit temperature. The desired centerline exit temperatures were 110 °C,

130 °C, and 140 °C with an exposure time in the heating section of 17 s and a holding time of 90 s.

Large temperature differences were observed between the walls and the center of the applicator tube. The differences between the maxima and minima were of 35 °C, 40 °C, and 43 °C for centerline exit temperatures of 110 °C, 130 °C, and 140 °C, respectively, with average exit temperatures of 80 °C, 101 °C, and 107 °C, respectively. Figure 4 shows the interpolated temperature profiles in a cross-section of the tube at an exit location of the heating section of the 5-kW unit tested for the exit temperatures targeted at 110 °C and 130 °C. Interpolation of the temperature profile was carried out using the existing acquired temperatures into a 20 × 20 square mesh using SigmaPlot (Systat Software Inc., Point Richmond, Calif., U.S.A.). The mesh was trimmed to resemble a round shape by eliminating all elements outside of the radius of the thermocouple assembly. It is shown in Figure 4 that the maximum temperature was achieved close to the center of the tube, and the minimum temperature was in the areas nearby the walls. The temperature profile showed that the product close to the wall that faced the microwave generator had a higher temperature than the side opposite to the generator. This observation was consistent with that of Coronel and others (2003).

The rheological properties of the samples treated to different centerline exit temperatures (the temperature at the center of the tube at the exit of the heating section) are shown in Figure 5. All the samples exhibited shear-thinning behavior, that is, lower apparent viscosity at higher shear rates as reported by Kyereme and others (1999). The rheological behavior was modeled using a Herschel-Bulkley model ( $\sigma = \sigma_0 + K \dot{\gamma}^n$ ), as described by Steffe (1996). The average values of the parameters were as follows: yield stress ( $\sigma_0$ ),  $89.0 \pm 2.7$  Pa, the consistency coefficient (K),  $18.78 \pm 1.76$  Pa·s<sup>n</sup>, and the average flow behavior index (n),  $0.39 \pm 0.07$ . As indicated in Figure 5, the apparent viscosities of the different SPP samples were not different among the treatments ( $P > 0.05$ ).

Color measurements of the samples corresponding to different centerline exit temperatures are shown in Figure 6. There were no significant differences ( $P \geq 0.05$ ) in  $L^*$  (lightness) and  $a^*$  (redness) values between the control and the thermal treated samples. The  $b^*$  (yellowness) values of the thermal treated samples showed a significant increase ( $P \leq 0.05$ ) as compared with the control. However,



**Figure 3—Calculated values of maximum operating diameter for sweetpotato purees (SPP) at 915 MHz as a function of temperature**

there was no significant difference in the values of  $b^*$  between the 130 °C and 140 °C treatments. The total change in color compared with the control, was calculated as  $(\Delta E = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}})$  and had values of 10, 20, and 20 for centerline exit temperatures of 110 °C, 130 °C, and 140 °C, respectively.

**Tests in the 60-kW microwave unit**

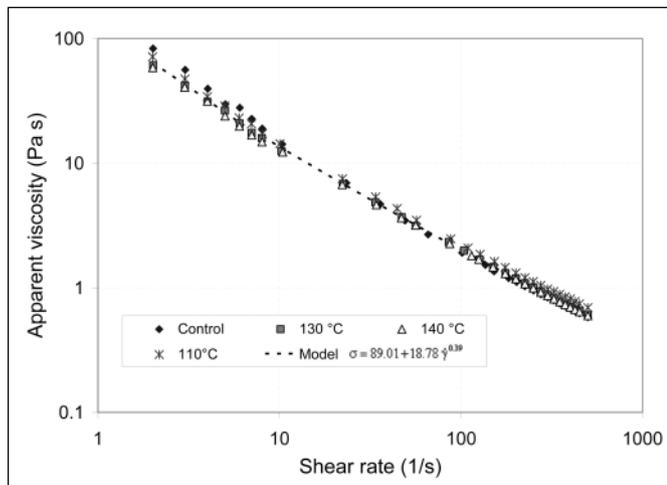
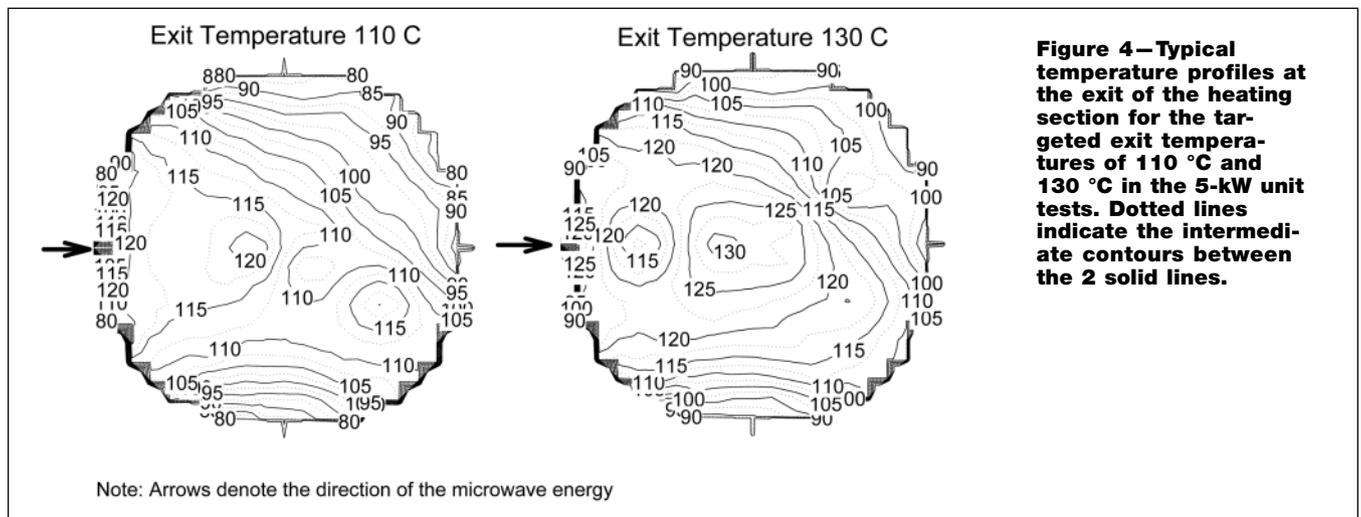
With the information gathered from the tests on the 5-kW microwave unit, test runs using the 60-kW unit were carried out as a pilot plant experiment with the objective to obtain a shelf-stable product. The flow rate was set to 4.0 L/min, and to obtain a shelf-stable product, the centerline temperature at the exit of the holding tube should reach 135 °C with a holding time of 30 s that was equivalent to a sterilization value ( $F_0$ ) > 13 min (Stumbo 1973). The power generated by the system was adjusted to achieve the required centerline exit temperature.

As observed in the 5-kW tests, the temperature differences between the centerline (135 °C) and the walls (70 °C) of the tube were large, as shown in Figure 7. Because of the high viscosity of the SPP, mixing might not occur when the material passed through the holding tube. Therefore, the product closer to the walls received a lesser thermal treatment ( $F_0 < 0.1$  min). Visual examination of the

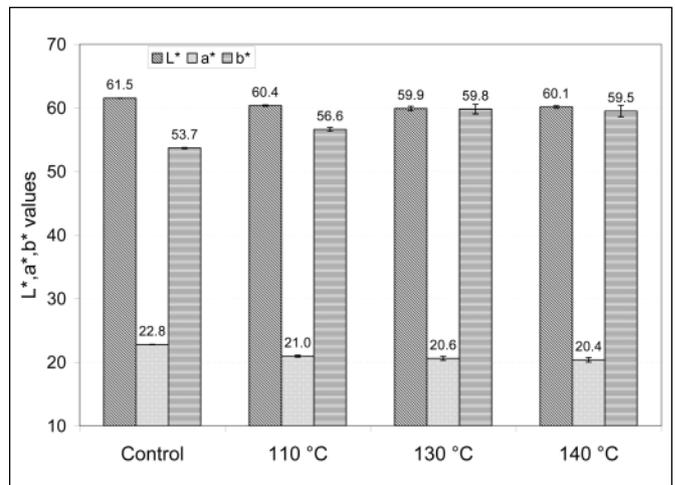
refrigerated product indicated that microbial spoilage had not occurred after 30 d.

To minimize the nonuniformity in temperature within the product, static mixers were installed at the exit of each of the microwave applicators of the system. Mixing at the exit of the heaters was intended to diminish any temperature differences within the product at the exit of the heaters to improve the thermal treatment and, consequently, the shelf life of the product. The 2nd experiment was carried out with centerline exit temperature of 140 °C at the exit of the second heater and a holding time of 30 s. The centerline temperature was increased to achieve a minimum temperature of 135 °C at the end of the holding tube.

Temperature distribution throughout the cross-sectional area was more uniform (Figure 8), which was attributable to the mixing effect of the static mixers on the flowing purees. The temperature differences between center and wall were reduced from 48.4 °C to 20.1 °C after going through the 1st static mixer and from 37.6 °C to 11.7 °C after the 2nd static mixer. At the inlet of the holding tube, SPP had a temperature profile with a minimum temperature of 135 °C and a maximum of 146.7 °C, as shown in Figure 8. The fastest particle (at the center of the tube) received the least heat treatment. The fastest fluid elements (center) received a thermal treat-



**Figure 5—Apparent viscosities at different shear rates of sweetpotato purees (SPP) samples from the 5-kW unit tests**

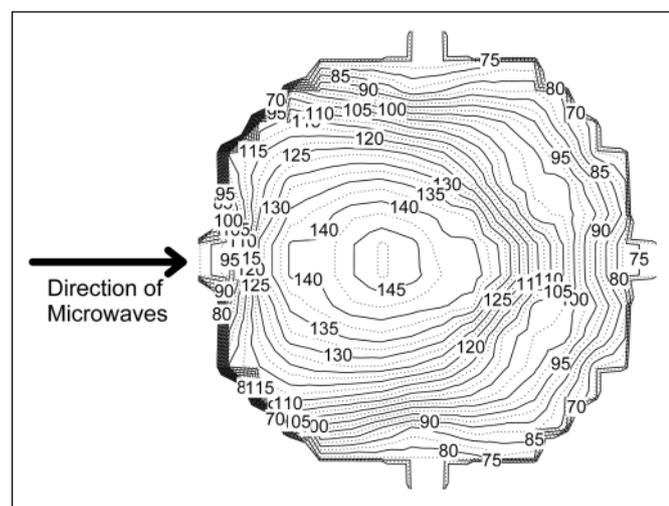


**Figure 6—Hunter color values of sweetpotato purees (SPP) samples from the 5-kW unit tests**

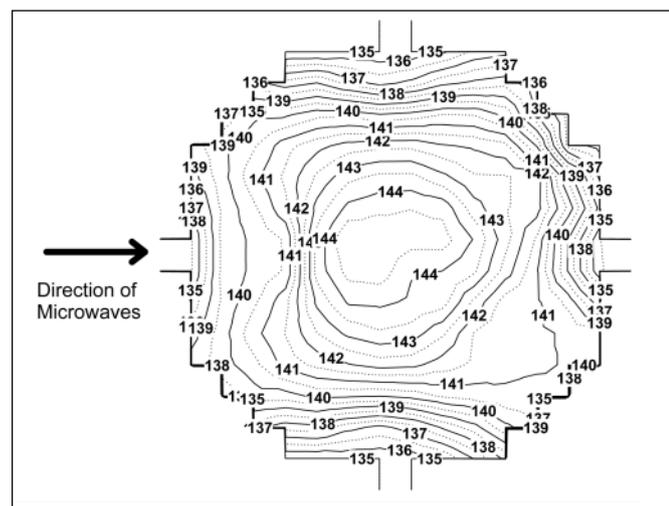
ment equivalent to  $F_0 > 20$  min, which rendered a commercially sterile product, which should be shelf-stable. Microbiological tests of the final product were performed to confirm the destruction of microorganisms and the shelf-stability of the product. Results of these microbiological tests in the form of total aerobic plate counts for bacteria, molds and yeast showed no presence of viable microorganisms after 1, 15, and 90 d.

### Conclusions

Aseptically packaged sweetpotato puree was successfully produced using a continuous-flow microwave heating system. The resulting product packed in flexible plastic containers had the color and apparent viscosity comparable to the untreated puree and was shelf-stable. This process can be applied to several other vegetable and fruit purees. Further studies on the retention of nutrients by this processing method are in progress to establish advantages of the process.



**Figure 7—Typical temperature profile at the inlet of the holding tube during the 60-kW unit test before static mixers were implemented. Dotted lines indicate the intermediate contours between the 2 solid lines.**



**Figure 8—Typical temperature profile at the inlet of the hold tube during the 60-kW test after static mixers were used. Dotted lines indicate the intermediate contours between the 2 solid lines.**

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### Nomenclature

$a^*$  = CIE lab color redness  
 $b^*$  = CIE lab color yellowness  
 $f$  = frequency (Hz)  
 $F_0$  = sterilization value  
 $K$  = consistency index ( $\text{Pa s}^n$ )  
 $L^*$  = CIE lab color lightness  
 $n$  = flow behavior index  
 $T$  = temperature ( $^{\circ}\text{C}$ )  
 $\dot{\gamma}$  = shear rate ( $1/\text{s}$ )  
 $\epsilon'$  = dielectric constant  
 $\epsilon''$  = loss factor  
 $\sigma$  = shear stress (Pa)  
 $\sigma_0$  = yield stress (Pa)

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