Measurement of Dielectric Properties of Pumpable Food Materials under Static and Continuous Flow Conditions

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ABSTRACT: Continuous flow microwave sterilization is an emerging technology that has the potential to replace the conventional heating processes for viscous and pumpable food products. Dielectric properties of pumpable food products were measured by a new approach (under continuous flow conditions) at a temperature range of 20 to 130 °C and compared with those measured by the conventional approach (under static conditions). The food products chosen for this study were skim milk, green pea puree, carrot puree, and *salsa con queso*. Second-order polynomial correlations for the dependence of dielectric properties at 915 MHz of the food products on temperature were developed. Dielectric properties measured under static and continuous flow conditions were similar for homogeneous food products such as skim milk and vegetable puree, but they were significantly different for *salsa con queso*, which is a multiphase food product. The results from this study suggest that, for a multiphase product, dielectric properties measured under continuous flow conditions should be used for designing a continuous flow microwave heating system.

Keywords: continuous flow, microwave heating, multiphase product, sterilization

Introduction

Microwaves are a part of the electromagnetic spectrum and have a frequency between 300 MHz and 300 GHz. They lie between the radio (3 kHz to 300 MHz) and infrared (300 GHz to 400 THz) frequencies of the electromagnetic spectrum. Microwave radiation has the ability to heat materials by penetrating and dissipating heat in them. Because of this ability, microwaves have been used in the polymer and ceramic industries (joining, sintering, combustion synthesis, melting, epoxy curing, preheating rubbers, and thermosetting), medicine (thawing frozen tissues, warming blood, and tumor therapies), and textiles (drying) (Saltiel and Datta 1999). Microwaves have been used for several food processing operations, including thawing, blanching, pasteurization, sterilization, dehydration, baking, and roasting (Bengtsson and Ohlsson 1974). Continuous flow microwave sterilization is an emerging technology that has the potential to replace conventional heating processes for viscous and pumpable food products. Some of the advantages associated with microwave heating are instant start-up; faster heating; improved color, flavor, and texture; and nutrient retention.

Interaction of microwaves with materials depends on their dielectric properties, which determine the extent of heating of a material when subjected to electromagnetic fields. Therefore, knowledge of dielectric properties is important for the design of a continuous flow microwave heating system. Dielectric properties consist of dielectric constant and dielectric loss factor. Dielectric constant is a measure of the ability of a material to store electromagnetic energy, whereas dielectric loss factor is a measure of the ability of a material to convert electromagnetic energy to heat (Metaxas and Meredith 1983). Dielectric properties can be defined in terms of complex permittivity (ϵ). The complex permittivity (ϵ) is composed of a real part (ϵ', relative dielectric constant) and an imaginary part (ϵ'', relative dielectric loss factor) and is given by the equation (Saltiel and Datta 1999):

$$\varepsilon = \varepsilon_0(\varepsilon' - j\varepsilon'') \quad (1)$$

where $j = (-1)^{0.5}$ and ϵ_0 is the permittivity of free space (8.86×10^{-12} F/m) [correction added after online publication 4/11/07: In Eq. 1, $j\epsilon$ was changed to $j\epsilon''$]. Loss tangent (tan δ), a parameter used to describe how well a product absorbs microwave energy, is the ratio of dielectric loss factor (ϵ'') to the dielectric constant (ϵ'). A product with a higher loss tangent will heat faster under microwave field as compared to a product with a lower loss tangent (Nelson and Datta 2001). Dielectric properties of food products depend on the frequency of the microwaves, temperature, composition, and density of the materials (Datta and others 2005).

Power penetration depth (δ_p), often used in microwave heating applications, is the distance in meters at which power drops to e^{-1} of its value at the surface of the material and is given by the following equation (Nelson and Datta 2001):

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

where λ is the wavelength of the microwave in free space in meters. The above equation is valid for a plane wave incident upon a semi-infinite slab. Power penetration depth is used to calculate the tube diameter for a continuous flow microwave heating system.

The 3 most popular methods for measuring dielectric properties are the open-ended coaxial probe, transmission line, and resonance cavity methods. Of the 3 methods, the open-ended coaxial probe method is the preferred one for measuring dielectric properties of food products because it can measure dielectric properties over a wide frequency range, it is easy to use, and it can be used for liquids and solids equally well (Engelder and Buffler 1991). Many studies have been undertaken to determine the dielectric properties

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of food products using the open-ended coaxial probe method (Tran and others 1984; Nelson and others 1994; Nelson and Bartley 2002; Sipahioglu and Barringer 2003; Guan and others 2004; Nunes and others 2006). In all of these studies, dielectric properties were measured by heating the food product in a water or oil bath. There are inherent problems associated with this approach of measuring dielectric properties under static conditions. The dielectric property of only a small portion of the material, in the vicinity of the dielectric probe, is measured. Thus, the measurement by this approach may not be representative of the dielectric properties of the bulk for a multiphase food product. It is well known that physical structure of the food products has an effect on dielectric properties (Ryynanen 1995). The rate of heating under static conventional heating conditions is slower as compared to the rate of heating under continuous flow microwave heating conditions. At the slower rate of heating under static conditions, there is higher degree of protein denaturation and starch gelatinization between 50 and 80 °C (Sakonidou and others 2003; Li and others 2006). Protein denaturation and starch gelatinization change the physical structure of food products. Thus, for the food products, which have protein or starch as one of the major constituents, dielectric properties measured under static conditions will be different from those measured under continuous flow microwave heating.

The present study was undertaken to develop a new approach to measure dielectric properties of pumpable food products under continuous flow microwave heating conditions at a temperature range of 20 to 130 °C and compare then with the dielectric properties measured under static conditions. In this new measurement method, the food product is continuously pumped across the dielectric probe. Therefore, different parts of the food product are in contact with the probe at different times. Thus, this approach gives a better representation of the dielectric properties of the bulk of the food product.

Materials and Methods

Sample selection

The food products chosen for this study were skim milk, green pea puree, carrot puree, and *salsa con queso*. Skim milk and 3 brands of *salsa con queso* (Brands A, B, and C representative of the category of *salsa con queso*) were purchased from a local supermarket (Food Lion, Raleigh, N.C., U.S.A.). These samples were stored in a refrigerator prior to use in the experiments. Frozen green pea and carrot puree were purchased from Stahlbush Islands Farm Inc. (Corvallis, Oreg., U.S.A.). These purees were thawed at room temperature for several hours prior to processing.

Measurement under static conditions

Dielectric properties of the samples under static conditions were measured using an open-ended coaxial probe (Model HP 85070B, Agilent Technologies, Palo Alto, Calif., U.S.A.) connected to a network analyzer (Model HP 8753C, Agilent Technologies) (Figure 1). HP 85070B is a large diameter probe with an outer diameter (OD) of 19 mm. The network analyzer was calibrated by leaving the probe in contact with air, metal, and 25 °C deionized 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. The variable step size for temperature increment was chosen because the goal of this study was to determine the dielectric properties at sterilization temperatures. The samples were placed in a pressurized cylindrical cell (inner diameter [ID] 35 mm and height 36.5 mm) and heated in an oil bath (Model RTE111, Neslab Instruments Inc., Newington, N.H., U.S.A.) to attain the testing temperature.

Measurement under continuous flow conditions

Dielectric properties of the samples under continuous flow conditions were measured inline using an open-ended coaxial probe (Model HP 85070E, Agilent Technologies) connected to a network analyzer (Figure 1). HP 85070E is a small diameter probe with an outer diameter (OD) of 2.2 mm, which can be inserted in 1 of the 3 ports of a smart gasket (Rubber-Fab, Newton, N.J., U.S.A.). The dielectric properties were measured at temperatures from 20 °C to 130 °C and frequencies from 300 to 3000 MHz. A schematic of the experimental system to measure dielectric properties during continuous flow microwave heating is shown in Figure 2. The product was heated using a 5-kW microwave unit, which has been described below.

Five-kilowatt microwave unit

The microwave unit, shown in Figure 2, consists of a 5-kW microwave generator (Industrial Microwave Systems, Morrisville, N.C., U.S.A.) operating at 915 MHz, a waveguide of rectangular cross-section, and a specially designed focused applicator (Drozd and Joines 2001). A tube of 1.5″ 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) with a variable speed motor (Tri- Clover Rotary Pump, Model PRE3-1M, Ladish Co., Kenosha, Wis., U.S.A.). The average residence time of the product in the applicator for a flow rate of 0.9 L/min was 21.13 s. The temperatures at the inlet and outlet of the applicator were recorded using a thermocouple arrangement described by Coronel and others (2003) and a datalogging system (Model DAS-16, Keithley Metrabyte Inc., Taunton, Mass., U.S.A.). The dielectric probe (HP 85070E) was inserted at the outlet of the applicator in 1 of the 3 ports of the smart gasket (Coronel and others 2003) as shown in Figure 2.

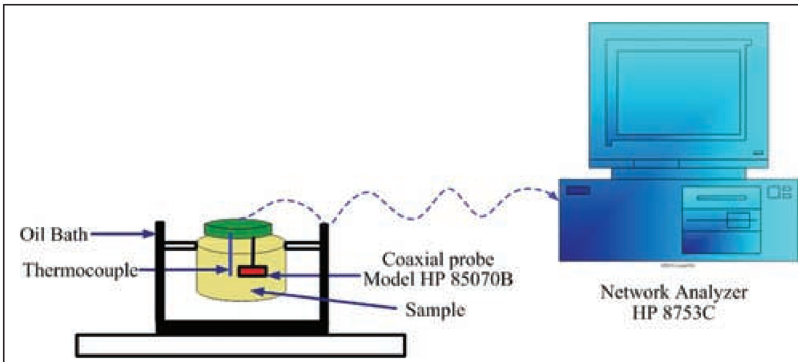

Figure 1 — Schematic of the experimental system to measure dielectric properties under static conditions

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 both the treatments (static conditions and continuous flow conditions) were significantly different. The statistical data analysis toolbar of MS Excel was used for statistical analysis (Microsoft Corporation, Redmond, Wash., U.S.A.).

Results and Discussion

Skim milk

The dielectric properties of skim milk at 915 MHz were measured under continuous flow conditions and were compared with those measured under static conditions and published by Coronel and others (2003), as shown in Figure 3. Dielectric properties of skim milk measured under static and continuous flow conditions from 20 to 120 °C were similar. This is expected because skim milk is a homogeneous product, and it does not have protein or starch as a major constituent. However, dielectric properties measured under continuous flow conditions at 130 °C were significantly different from those under static conditions, which might be a result of a change of phase at that high temperature under static conditions. The effect of temperature on dielectric properties under static and continuous flow conditions was similar with ϵ' decreasing with an increase in temperature and ϵ'' increasing with an increase in temperature, which is in accordance with the observations of Datta and others (1997) for food products with moisture content greater than 60%. Second-order polynomial correlations for the dependence of dielectric properties of skim milk on temperature at 915 MHz were developed and are shown in Table 1.

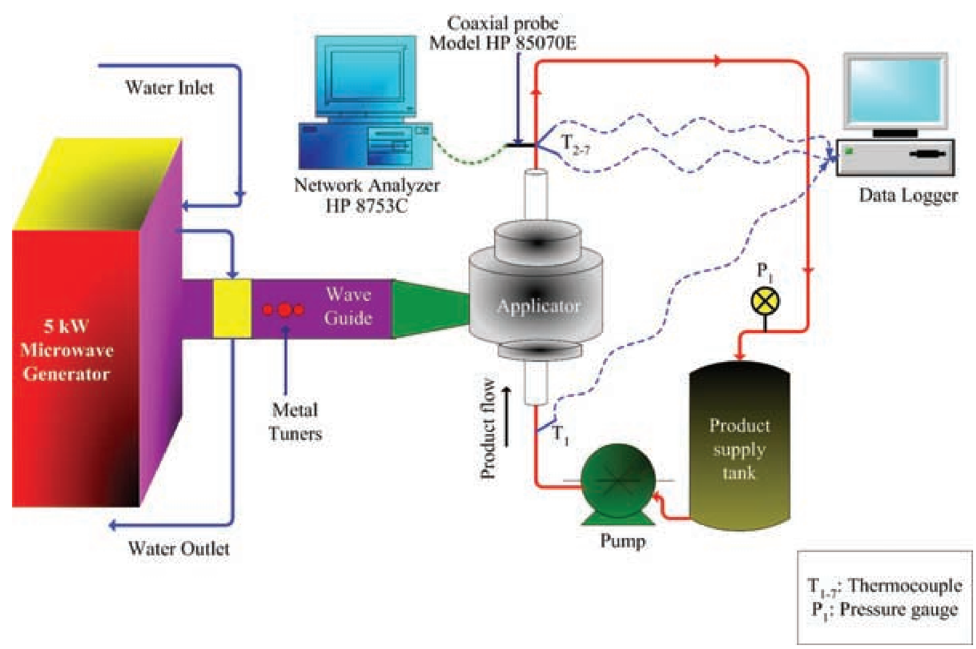

Figure 2—Schematic of the experimental system to measure dielectric properties under continuous flow conditions

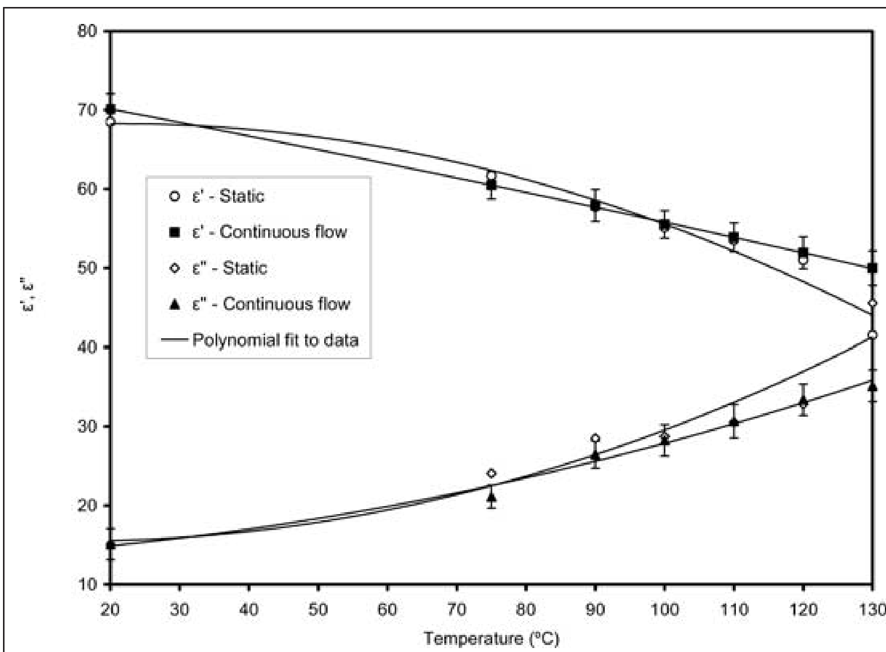

Figure 3—Dielectric constant (ϵ') and dielectric loss factor (ϵ'') of skim milk at 915 MHz

Vegetable purees

The dielectric properties of green pea and carrot puree at 915 MHz measured under static and continuous flow conditions are shown in Figure 4 and 5, respectively. Dielectric properties of both the purees measured under static and continuous flow conditions were similar. This is expected because these purees are homogeneous. The values of dielectric constant (ϵ') and dielectric loss factor (ϵ'') for green pea puree were similar to those reported by Tong and others (1994). The values of ϵ' and ϵ'' at 20 °C and 915 MHz (Figure 4) are 66.74 and 15.31, respectively, and the correlation by Tong and others (1994) predicts the values of ϵ' and ϵ'' to be 64.49 and 13.24, respectively. The effect of temperature on dielectric properties under static and continuous flow conditions was similar with ϵ' decreasing with an increase in temperature and ϵ'' increasing with an increase in temperature, which is similar to the results obtained for skim milk. Second-order polynomial correlations for the dependence of dielectric properties of both vegetable purees on temperature at 915 MHz were developed and are shown in Table 1.

Salsa con queso

The dielectric properties of 3 different brands (Brands A, B, and C) of *salsa con queso* at 915 MHz measured under static and continuous flow conditions are shown in Figure 6, 7, and 8, respectively. Dielectric constant measured under both the conditions was similar for Brand A except at 125 °C. However, the dielectric constant for brands B and C were significantly different at all temperatures except 20 °C. Dielectric loss factor of *salsa con queso* at 915 MHz measured under static and continuous flow conditions are significantly different ($P < 0.05$) for all the 3 brands at all temperatures except 20 °C. However, there was an exception for Brand B at temperatures

Table 1 — Dielectric properties of different food materials as a function of temperature at 915 MHz

Sample	Correlations (T in °C)	r^2
Skim milk (static conditions)	$\epsilon' = 67.3 + 0.0878\ T - 0.0021\ T^2$	0.960
	$\epsilon'' = 16.0 - 0.0590\ T + 0.0020\ T^2$	0.903
Skim milk (continuous flow conditions)	$\epsilon' = 73.4 - 0.1615\ T - 0001\ T^2$	0.999
	$\epsilon'' = 13.5 + 0.0489\ T + 0.0009\ T^2$	0.989
Green pea puree (static conditions)	$\epsilon' = 70.0 - 0.1708\ T + 9E\text{-}05\ T^2$	0.988
	$\epsilon'' = 13.3 + 0.0852\ T + 0.0005\ T^2$	0.977
Green pea puree (continuous flow conditions)	$\epsilon' = 74.8 - 0.2957\ T + 0.0007\ T^2$	0.994
	$\epsilon'' = 13.2 + 0.0829\ T + 0.0005\ T^2$	0.986
Carrot puree (static conditions)	$\epsilon' = 77.5 - 0.1631\ T - 0.0003\ T^2$	0.994
	$\epsilon'' = 19.0 - 0.0047\ T + 0.0021\ T^2$	0.998
Carrot puree (continuous flow conditions)	$\epsilon' = 77.5 - 0.2022\ T - 1E\text{-}05\ T^2$	0.969
	$\epsilon'' = 18.4 + 0.0359\ T + 0.0019\ T^2$	0.995
Salsa con queso (brand A) (Static conditions)	$\epsilon' = 58.4 + 0.0100\ T - 0.0007\ T^2$	0.990
	$\epsilon'' = 34.1 - 0.0317\ T + 0.0038\ T^2$	0.998
Salsa con queso (brand A) (continuous flow conditions)	$\epsilon' = 57.8 + 0.0423\ T - 0013\ T^2$	0.827
	$\epsilon'' = 19.5 + 0.6047\ T + 0.0002\ T^2$	0.929
Salsa con queso (brand B) (static conditions)	$\epsilon' = 63.0 + 0.0250\ T - 0.0007\ T^2$	0.998
	$\epsilon'' = 56.7 - 0.2509\ T + 0.0065\ T^2$	0.999
Salsa con queso (brand B) (continuous flow conditions)	$\epsilon' = 70.5 - 0.1860\ T - 7E\text{-}05\ T^2$	0.997
	$\epsilon'' = 25.4 + 0.7519\ T + 0.0008\ T^2$	0.996
Salsa con queso (brand C) (static conditions)	$\epsilon' = 53.9 + 0.0426\ T - 0.0005\ T^2$	0.985
	$\epsilon'' = 36.3 + 0.0363\ T + 0.0046\ T^2$	0.999
Salsa con queso (brand C) (continuous flow conditions)	$\epsilon' = 61.9 - 0.1568\ T - 6E\text{-}05\ T^2$	0.943
	$\epsilon'' = 24.2 + 0.8100\ T + 0.0009\ T^2$	0.998

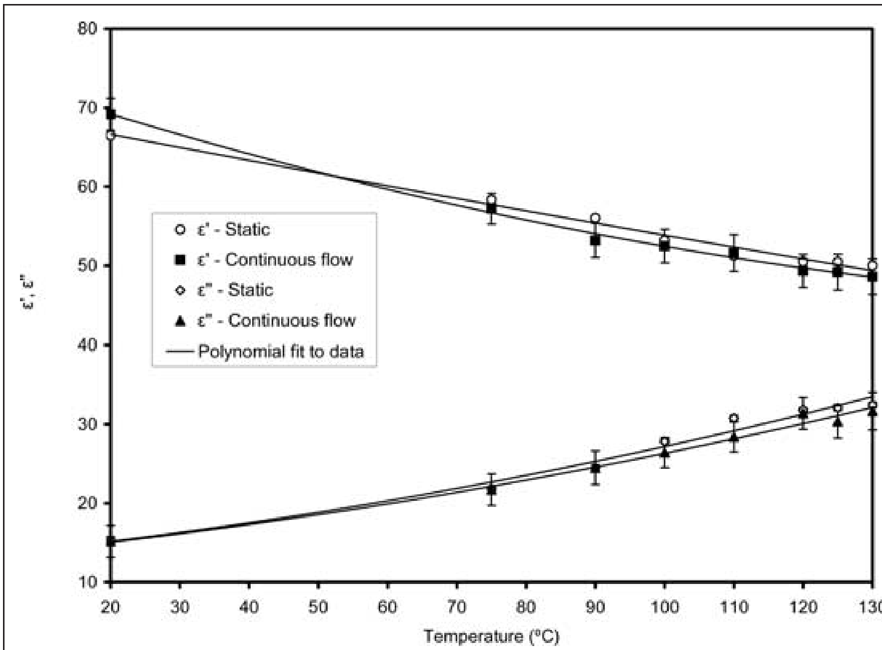

Figure 4 — Dielectric constant (ϵ') and dielectric loss factor (ϵ'') of green pea puree at 915 MHz

above 120 °C where the dielectric loss factors were similar for measurements under static and continuous flow conditions. This result is expected for a multiphase product such as *salsa con queso*. Under static conditions, dielectric properties of only a small portion of the product are measured. Therefore, measurement by this approach might underpredict or overpredict dielectric properties based on the components of the product in contact with the probe surface. Thus, measurement under static conditions is not representative of the dielectric properties of the bulk of the product. Second-order polynomial correlations for the dependence of dielectric properties of the three brands of *salsa con queso* on temperature at 915 MHz were developed and are shown in Table 1.

It was observed that the measurement under static conditions underpredicted ϵ'' and overpredicted ϵ' for all the brands at higher temperatures. This resulted in a lower value of loss tangent for the measurements under static conditions. Thus, dielectric properties under static conditions for *salsa con queso* will predict a slower rate of heating under a microwave field. Equation 2 was used to calculate the power penetration depth for the 3 brands of *salsa con queso*. Power penetration depths for Brands A, B, and C at 20 °C were 0.0128, 0.0108, and 0.01 m, respectively. The deviations in power penetration depths for the measurement under static and continuous flow conditions were 0.6% to 18%, 3.9% to 32%, and 4.6% to 22.8% for brands A, B, and C, respectively.

Apart from measuring the true values of dielectric properties for a multiphase product, this new approach to measure dielectric properties can be used to monitor physicochemical changes such as protein denaturation and starch gelatinization in a food product during thermal processing. Monitoring such changes can become a tool for research and development in the food industry. Thus, it is recommended that, for a multiphase product, dielectric properties measured under continuous flow conditions should be used for designing a continuous flow microwave heating system.

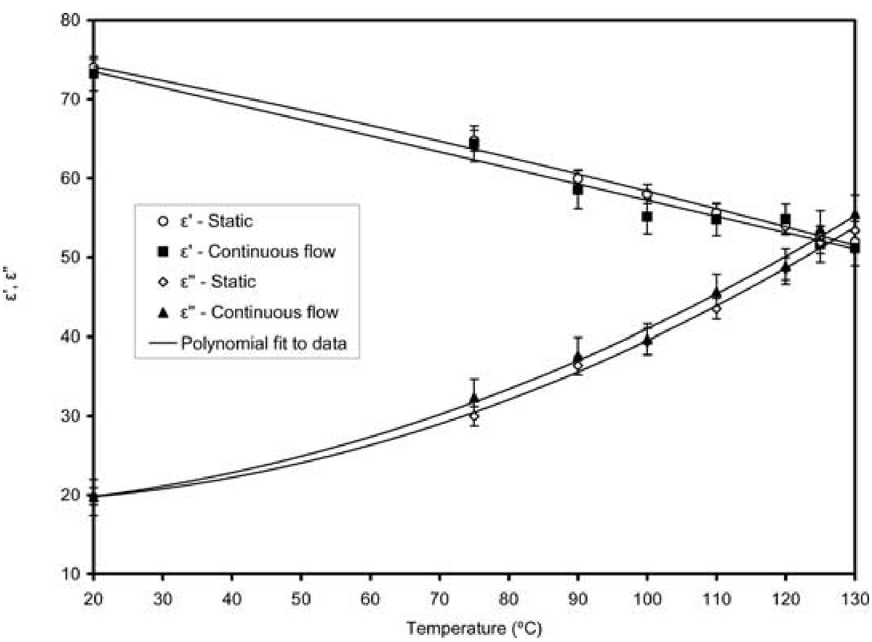

Figure 5 — Dielectric constant (ϵ') and dielectric loss factor (ϵ'') of carrot puree at 915 MHz

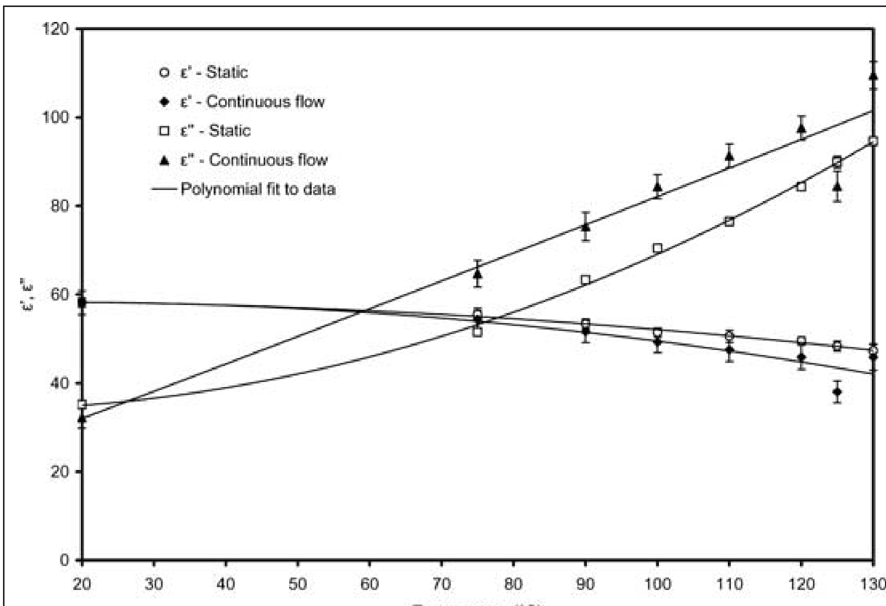

Figure 6 — Dielectric constant (ϵ') and dielectric loss factor (ϵ'') of *salsa con queso* (Brand A) at 915 MHz

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Conclusions

Dielectric properties of pumpable food products were measured by a new approach (under continuous flow conditions) at a temperature range of 20 °C to 130 °C and compared with the dielectric properties measured by the conventional approach (under static conditions). Second-order polynomial correlations for the dependence of dielectric properties of the food products on temperature at 915 MHz were developed. The results showed that the dielectric properties measured under static and continuous flow conditions were similar for homogeneous food products such as skim milk and vegetable puree, but they were significantly different for *salsa con queso*, which is a multiphase food product. The results suggest that, for a multiphase product, dielectric properties measured under continuous flow conditions should be used for designing a continuous flow microwave heating system. This new approach to measure dielectric properties can be used to monitor physicochemical changes in a food product during thermal processing, which can be used as a tool for research and development in the food industry.

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The use of trade names in this publication does not imply endorsement by the North Carolina Agricultural Research Service of the products named nor criticism of similar ones mentioned.

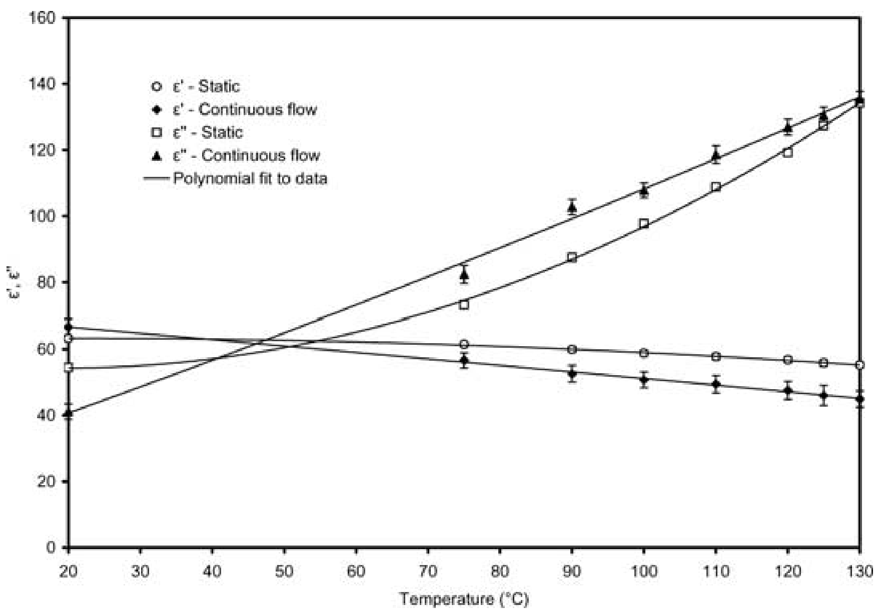

Figure 7 — Dielectric constant (ϵ') and dielectric loss factor (ϵ'') of *salsa con queso* (Brand B) at 915 MHz

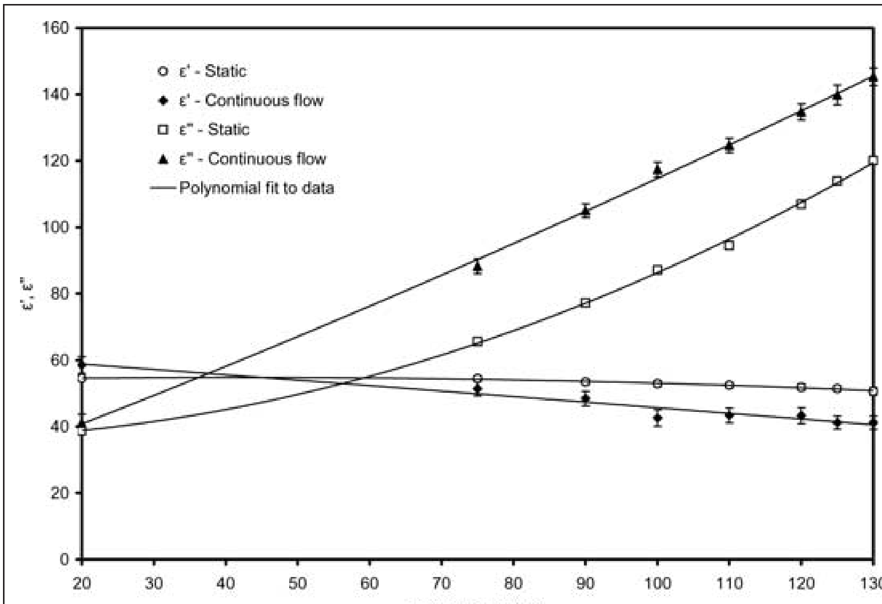

Figure 8 — Dielectric constant (ϵ') and dielectric loss factor (ϵ'') of *salsa con queso* (Brand C) at 915 MHz

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