FOOD AND BIOPRODUCTS PROCESSING XXX (2016) XXX–XXX

Contents lists available at ScienceDirect

Food and Bioproducts Processing

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

# Thermal mixing via acoustic vibration during continuous flow cooling of viscous food products

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ARTICLE INFO

*Article history:*
Received 29 February 2016
Received in revised form 4 July 2016
Accepted 19 July 2016
Available online xxx

*Keywords:*
Continuous flow cooling
Thermal mixing
Acoustic vibration
Sweet potato puree
Banana puree
Apple sauce
Cheese sauce

ABSTRACT

During conventional continuous flow cooling of viscous foods, laminar flow and low thermal conductivity lead to a wide temperature distribution within the product, resulting in non-uniformity, slow cooling processes and degradation of final food quality. It was hypothesized that continuous flow cooling would be enhanced by equalizing the temperature profile (thermal mixing) during cooling. In this study, a computer-controlled frequency, audio transducer amplifier was used to impose transversal vibration motion on a 180° bend pipe and generate thermal mixing of viscous foods, such as sweet potato puree, banana puree, apple sauce and cheese sauce, at the temperature range of 110–60 °C. Applying vibration at the maximum amplifier volume and 20 Hz, the resonance frequency of the unit, the initial radial temperature distribution of 3–20 °C was reduced to a temperature difference of 0–4 °C, for all the food products. Although parameters such as the magnitude of the initial temperature difference and the gel formation at the pipe wall, which occurs during the cooling of these kinds of food materials, need to be controlled better for future applications of this method.



## 1. Introduction

In continuous flow thermal processing of viscous and multiphase food products, such as fruit and vegetable purees, soups and typical dairy products, rapid heat transfer and uniform thermal treatment are vital in reducing time and cost of the total process, as well as in keeping the final quality of the product (nutrients, color, texture, etc.). Advanced heating technologies, such as continuous flow microwave (MW) systems, ohmic and radio frequency heating technologies, provide uniform rapid volumetric heating which reduces the come up time and minimizes the final food product quality losses (Coronel et al., 2005; Steed et al., 2008; Cullen et al., 2012). For cooling processes, the absence of an advanced cooling technology, combined with the laminar flow characteristics and the low thermal conductivity of highly viscous food products, leads to a wide temperature distribution within the product, resulting in unequal thermal treatment and reduction of final food quality.

Food production systems, which utilize advanced thermal methods, could benefit from operational enhancements of the cooling stage of the process, both for existing and future installations. Cooling processes of highly viscous, low conductivity foods can be enhanced significantly by improving radial mixing, which can be achieved by turbulent flow conditions or chaotic advection (Metcalfe and Lester, 2009; Eesa and Barigou, 2010; Saatdjian et al., 2011). However, in highly viscous food products, due to the dominant viscous forces, turbulent flow requires a huge amount energy due to high pressure drop (Saatdjian et al., 2011). Mixing under the

*Abbreviations:* 1-D FFT, one-dimension Fast Fourier Transformation; CAPPs, Center for Advanced Processing and Packaging Studies; NCSU, North Carolina State University (NCSU); MW, microwave; $T_c$, temperature at the center of the pipe; $T_w$, temperature at the wall of the pipe.

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http://dx.doi.org/10.1016/j.fbp.2016.07.008

**Nomenclature**

*Greek letters*

$\Delta T_{c\text{-}w}$ temperature difference between the temperatures at the center and the wall (°C)

*Subscripts*

c center

w wall

laminar regime can be enhanced through the mixing technique of chaotic advection. Chaotic advection is a mixing technique in the laminar flow regime where chaotic fluid motion is generated through passive (by periodic changing the geometry of flow) and active (applying periodic non-linear forces) methods. Chaotic advection generates chaotic trajectories and breaks the mixing barriers, that is, the streamlines where the fluid elements flow in laminar flow (Aref, 1984; Ottino, 1989; Aref, 2002; Cullen, 2009). Chaotic advection applies simple non-turbulence flows (chaotic flow), to create rapid mixing, due to periodic stretching and folding of fluid elements, which result in an exponential increase on interfacial area and pattern with high gradients (density, pressure, temperature, etc.) to facilitate chaotic mixing (Aref, 2002; Cullen, 2009). Chaotic advection is a method used in thermal processing of highly viscous materials, for heat transfer enhancement (Acharya et al., 1992, 2001; Metcalfe and Lester, 2009), and thermal mixing, by improving the radial temperature uniformity (Lester et al., 2009; Eesa and Barigou, 2010; El Omari and Le Guer, 2010a,b; Saatdjian et al., 2011; Le Guer and El Omari, 2012). The most common studied and industrially used examples of chaotic advection heat transfer enhancement applications are the scraped surface heat exchangers and the static mixers (Carlson, 1991; Etchells and Meyer, 2004).

Applying an efficient method of thermal mixing during the cooling process, between each cooling section (cooling unit), will improve the radial temperature distribution within the food product and that would result in more equal thermal treatment of all food parts, maximizing the final food product quality and enhancing the total cooling process. In this work, acoustic and mechanical vibration were used to generate chaotic flow and achieve thermal mixing (temperature equalization) within the product flow, during cooling process of different viscous foods. Thermal homogenization of sweet potato, banana puree, apple sauce and cheese sauce during cooling cycle was studied for different parameters of acoustic and mechanical vibration, such as frequency and amplitude of vibration.

## 2. Materials and methods

### 2.1. Test materials

For this series of experiments, different highly viscous food products such as sweet potato puree (Yamco LLC, Snow Hill, NC, USA), apple sauce, banana puree (Aseptia/Wright Foods, Troy, NC, USA), and cheese sauce (Advanced Food Products, Clear Lake, WI, USA) were used as the tested materials. These materials were chosen, because they are products showing very good results during applications of advanced heating technologies such as MW heating, while due to their low thermal conductivity, slow cooling process and wide temperature distribution are characteristics during convection-driven continuous flow cooling process. Approximately 5 gallons of food product samples were sufficient to fill the system and allow for recirculation of the test samples at flow rates of $5.6 \times 10^{-5}$ m$^3$/s, $5.8 \times 10^{-5}$ m$^3$/s and $6.3 \times 10^{-5}$ m$^3$/s.

### 2.2. Experimental set up

To study thermal mixing during the cooling cycle of continuous flow thermal processing of highly viscous foods, a recirculating complete thermal treatment system was assembled, consisting of three basic sections: heating, cooling and mixing. The thermal treatment system consisted of a food grade progressive cavity pump Seepex MD-012 12 (Fluid Engineering Inc., Birmingham, AL, USA), a continuous flow MW system consisted of a total of 13 bench-top Panasonic Inverter MW ovens, with a maximum power input of 16.350 kW, at the commercial MW frequency of 2450 MHz, which have been used for the heating stage.

To study the effects of acoustic and mechanical vibration on cooling and thermal mixing, a custom made tube in shell heat exchanger was used as cooler. At the exit of this custom cooler a recirculating test system was closed with the mixing unit, which was used to equalize the cooling-induced temperature profiles (Fig. 1).

The mixing unit was conceived, designed and built to be easily applicable and adaptable, as a connecting element between successive individual tube-in-tube straight cooling segments with an intent to enhance the performance of existing convectional cooling installations, in food industry. The mixing unit was constructed using a 180° bend tube segment (formed from two silicone rubber-lined, reinforced flexible tube segments, each 0.53 m long and a stainless steel 180° elbow) mounted at the top of a low sonic frequency tactile audio transducer *Buttkicker LFE* (The Guitammer Company, Westerville, OH, USA). Moreover, the 180° bend pipe was chosen, due to the potential synergistic effect of transversal vibration with the centrifugal forces of the curved tube, on generation of chaotic fluid motion within the product.

A computer frequency generator program, *FreqGen 1.13* (Digital River Inc., Minnetonka, MN, USA) was used to control the frequency and duration of the vibration treatments. The amplitude of vibration was controlled via a power amplifier type BKA1000-N (The Guitammer Company, Westerville, OH, USA), which was connected in line with the FreqGen 1.13 and the Buttkicker LFE. The implemented treatment parameters of vibration were measured and recorded using an accelerometer, a vibration data logger device, the *SlamStick*™ (Mide Inc., Medford, MA, USA) and the recorded data were retrieved, reviewed and processed via the computer program *Slamstick viewer* (Mide Inc., Medford, MA, USA). T-type thermocouples were located in multiple positions through the MW heating system, cooler and at the entrance and exit of the mixing unit. A special T-type thermocouple probes – *Keyhole Multi-point probes* (Windridge Sensors LLC, Holly Springs, NC), were used to measure the temperature profiles of test materials, each with 3 different radial temperature sensing points, one triple-point probe at the inlet and another one the outlet of the 180° bend pipe of the mixing unit. The three sensing points of these probes were located at the center of the pipe, close to the pipe wall and at an intermediate point. Time-temperature data were recorded once per second using a data acquisition