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Role of distributed heating on enhancement of thermal mixing for liquid food processing with heat flow visualization method

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ABSTRACT

Thermal treatment is an important step in food processing. The conventional methods of heating of an enclosure may result in inadequate thermal mixing and poor temperature distribution leading to energy wastage. In this work, an alternative, energy-efficient method of distributed heating of the cavity is studied and compared with the isothermal bottom wall heating case in enhancing the thermal mixing and improving the temperature distribution in the cavity. Steady laminar natural convection of liquid food materials with a representative Prandtl number, $Pr = 3.14$ is studied in the range of Rayleigh number, $Ra = 10^3$–10^5 in differentially and discretely heated square cavities. Detailed analysis is carried out by visualizing the heat flow by heatlines. Further, the thermal mixing and the temperature uniformity are analyzed based on the cup-mixing temperature and root-mean square deviation. It is found that the thermal management policy of distributed heating significantly influences the thermal mixing and the temperature uniformity within liquid food. In a case with multiple discrete heat sources, a remarkable uniformity in temperature across the cavity is achieved with moderate thermal mixing. Based on heatlines, cup-mixing temperature and root-mean square deviation, optimal heating policy for food processing may be chosen.

Industrial Relevance: Three types of discrete heating situation are considered. Numerical simulations were carried out to predict the temperature and flow characteristics. Numerical simulation results were benchmarked or validated with literature data. Thus, current numerical simulation results are useful to select the suitable heating strategy for efficient thermal processing of liquid food. The proposed methodology with the numerical data would be useful to practicing industries for efficient juice heating.

1. Introduction

Thermal treatment is one of the most important steps in food processing where the food is subjected to heat treatment for pasteurization, concentration, drying, and cooling. Thermal processing of food is also carried out to enhance the flavor, palatability, texture and color modifications, and to increase the shelf life (Cliff, Fukumoto, King, Edwards, & Girard, 2000; Heinz, Toepfl, & Knorr, 2002; Kato, Shimoda, Suzuki, Kawaraya, Igura, & Hayakawa, 2003; Nisperoscarriedo, & Shaw, 1990; Su & Wiley, 1998). However, improper thermal treatment of food may result in undesirable effects such as loss of volatile aroma, vitamin degradation, structural modifications of proteins etc which may lead to deterioration of quality and flavor, lowering of food digestibility and bio-availability of enzymes and other essential acids, which in turn influences the consumer acceptability of the food product (Fellows, 2000).

In recent years, latest technologies have been developed for food processing such as radio frequency heating (Awuah, Ramaswamy, Economides, & Mallikarjunan, 2005; Geveke, Brunkhorst, & Fan, 2007; Manzocco, Anese, & Nicoli, 2008; Orsat, Gariepy, Raghavan, & Lyew, 2001; Piyasena, Dussault, Koutchma, Ramaswamy, & Awuah, 2003), microwave heating (Bhattacharya & Basak, 2006; Boillereaux, Alamir, Curet, Rouaud, & Bellemain, 2011; Lombrana, Rodriguez, & Ruiz, 2010; Tajchakavit, Ramaswamy, & Fustier, 1998), ohmic heating (Icier & Ilicali, 2005; Lemmens, Tiback, Svelander, Smout, Ahrne, Langton, Alminger, Van Loey, & Hendrickx, 2009; Marcotte, Ramaswamy, & Piette, 1998; Zhu, Zareifard, Chen, Marcotte, & Grabowski, 2010), and non-thermal processing methods (Mertens & Knorr, 1992) such as high pressure processing (Butz, Edenharder, Fister, & Tauscher, 1997), electrical pulse treatment (Alkhafaji & Farid, 2007, 2008; Deeth, Datta, Ross, & Dam, 2007; Jaeger, Meneses, & Knorr, 2009; Meneses, Jaeger, Moritz, & Knorr, 2011), and ultraviolet irradiation (Allende & Artes, 2003). Heat treatment is one of the important processing applications for food industries and considering the limitations associated with the heat treatment, there is a need to develop optimal strategies for thermal processing in order to achieve the larger heating rate with large degree of temperature uniformity.

Several process intensification methods such as agitation, thin-profile heating and other optimization and controlling strategies have been proposed for enhanced thermal processing of food materials (Banga, Balsa-Canto, Moles, & Alonso, 2003). Agitation is carried out

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by the rotation of the cans either in horizontally orientation (i.e. axial rotation) or in vertical position (called 'end-over-end (EOE)' rotation). EOE rotation significantly improves the mixing, turbulence and heat transfer rates due to the movement of the head-space bubble in the container (Abbatemarco & Ramaswamy, 1994; Knap & Durance, 1998). New approaches such as variable retort temperature (VRT) are gaining attention which improve both the economy and quality of thermally processed foods (Durance, 1997).

A few earlier studies were carried out for thermal treatment of liquid food for various applications (Goula & Adamopoulos, 2010; Mehauden, Cox, Bakalis, Fryer, Fan, Parker & Simmons, 2009; Silva & Gibbs, 2012; Zhu et al., 2010). Thermal treatment of liquid foods such as fruit and vegetable juices, milk, beverages etc. is associated with the flow of liquid food in the container, in addition to heat transfer. The phenomena of natural convection set in where the fluid rises up due to buoyancy and hence there is a coupling between fluid flow and heat transfer. Neglecting the effect of natural convection may lead to longer heating times than required, which results in over processed food products (Naveh, Kopelman, & Pflug, 1983). Several studies are reported on the natural convection during thermal processing of canned foods (Dwivedi & Ramaswamy, 2010; Erdogdu & Tutar, 2011; Erdogdu, Uyar, & Palazoglu, 2010; Ghani & Farid, 2006; Ghani, Farid, Chen, & Richards, 1999, 2001; Karaduman, Uyar, & Erdogdu, 2012; Kiziltas, Erdogdu, & Palazoglu, 2010; Tutar & Erdogdu, 2012). In many of the studies mentioned above, the studies are carried out by applying uniform temperature at one or more walls of the container. Maintaining the temperature uniformity is the critical issue in this type of heating methodology as high thermal gradients occur near the hot walls and there exist a 'slowest heating zone (SHZ)' in the container. Non-uniformity in temperature is the issue of major concern as that leads to improper sterilization and thermal run-away situations. Design of thermal systems of improved temperature uniformity at the no additional energy cost may be very useful in enhancing the thermal processing of foods in an energy efficient way. Current work deals with one such approach based on 'distributed heating methodology'.

Distributed heating approach involves the use of discrete heat sources located on the walls of the container/cavity. The discrete heat sources induce circulations at discrete locations in the cavity which enhances the thermal mixing locally. The local thermal mixing significantly improves the overall heat transfer rates and eliminates the use of any external mixing. In addition, the important advantage that is offered by the distributed heating approach is the temperature uniformity which is remarkably higher compared to conventional differential heating. Further, the location, size and thermal strength of the heat sources can be altered for greater control over the desired temperature distribution. The approach of distributed heating is an emerging approach of process intensification and only a few studies are reported on this approach. Plumat (1977) showed that glass-melting can be enhanced by the use of heated strips. Further, Sarris, Lekakis, and Vlachos (2000, 2004) have investigated the effect of horizontal heated strips in an industrial glass melting tank and concluded that position of heat strip plays an important role on the flow currents, temperature distribution in glass melt and enhances the thermal penetration. Ma, Guo, Zhang, Li, and Fu (2005) carried out studies on the oxidation of liquid lead and lead–bismuth eutectic in a discretely heated enclosure which is heated from the lower part and cooled from the upper part of the side walls for enhancement of oxygen transport in liquid metal by natural convection. As mentioned above, the parameters such as location, size and thermal strength of the heat sources play major role in designing of the distributed thermal system. The optimization of these parameters may be carried out by advanced optimization such as artificial intelligence, genetic algorithms etc., but these methods do not give insight into the fundamental physics of heat transfer process and they also do not explain why a specified set of parameters give optimal results on a physical basis. The present study attempts to study the heat transfer during thermal treatment of food materials by visualizing the flow of heat energy.

Visualization is a powerful technique to gain fundamental understanding of the physical process involved. Various researchers have used this technique for analyzing mixing behavior and the associated heat transfer within cans (Meng & Ramaswamy, 2007; Merson & Stoforos, 1990; Rao & Anantheswaran, 1988; Sablani & Ramaswamy, 1997, 1998; Siriwattanayotin, Yoovidhya, Meepadung, & Ruenglertpanyakul, 2006). Motion of spherical particles in axially rotating cans were visualized by Merson and Stoforos (1990). Sablani and Ramaswamy (1997, 1998) visualized the motion of a single particle and multi-particle mixing behavior of water and oil in a can subjected to end-over-end rotation. Siriwattanayotin et al. (2006) visualized the thermal deactivation of microorganisms during the sterilization of canned liquid food based on invert sugar concentration. Recently, Meng and Ramaswamy (2007) visualized the particle motion in high viscous fluids to understand the heat transfer between particle and liquid. It may be noted that, although fluid flow visualization can be carried out experimentally, it is not possible to visualize the heat flow experimentally. Advanced methods, such as use of thermal liquid crystals, indicate only the spatial variation of temperature. Analysis of the 'flow of heat' based on the temperature is inadequate when convection is involved.

Numerical simulation methods are gaining importance in recent years for solving various problems in food industry. Reviews of application of computational fluid dynamics (CFD) in food industry has been presented by Xia and Sun (2002) and Norton and Sun (2006). The important feature of CFD is that it provides a detailed understanding of flow physics which otherwise may not be obtained from experimental studies. In the current study, the numerical approach is employed for the visualization of heat flow through liquid food materials. Heat flow visualization during convective flow of fluid may be analyzed by using the concept of 'heatlines', proposed by Kimura and Bejan (1983). Heatlines are analogous to streamlines and they represent the trajectories of flow of heat energy. Heatlines are mathematically represented by 'heatfunction' and proper dimensionless form of 'heatfunction' is closely related to Nusselt numbers. Several studies based on heatlines are reported in the literature (Aggarwal & Manhapra, 1989; Basak & Roy, 2008; Da Silva, Lorente, & Bejan, 2005; Morega & Bejan, 1993, 1994; Trevisan & Bejan, 1987; Zhao, Liu, & Tang, 2007).

The current work is focused on the application of distributed heating methodology and analysis of its role in enhanced thermal processing of food materials. The study is based on visualization of heat flow. The temperature distribution and the thermal mixing due to discrete heat sources is analyzed based on heatlines. Three different cases are considered (see Fig. 1(b–d)): (1) cavity with uniformly heated isothermal bottom wall and isothermal cold side walls, (2) cavity with isothermal heat sources located at central portions of side and bottom walls and (3) cavity with multiple isothermal heat sources located at lower corners as well as at central portions of side and bottom walls. Top wall is maintained adiabatic in all the cases. It may be noted that in all the cases, the total length of dimensionless heat sources sums to 1. Thus, the role of distributed heating (as in cases 2 and 3) in enhancing the thermal mixing and/or temperature distribution in the cavity may be analyzed by comparing with that of the case where total length of heat source is applied at a single wall (case 1). Non-linear coupled partial differential equations of flow and temperature fields are solved using Galerkin finite element method. The analysis is further extended to study various heating regimes based on Rayleigh number ranging between 10^3 and 10^5 and strategies for optimal thermal processing are discussed.

2. Mathematical formulation and simulation

2.1. Velocity and temperature distributions

The physical domain of the system is depicted in Fig. 1(a). Although the physical containers are 3-dimensional, a semi-infinite approximation can be made along the Z-direction so that comparative studies in