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A novel approach for quantification of particle motion and particle mixing during agitation thermal processing

Anubhav Pratap Singh*, Anika Singh, Hosahalli S. Ramaswamy

Department of Food Science and Agricultural Chemistry, Macdonald Campus of McGill University, 21, 111 Lakeshore, Ste-Anne-de-Bellevue, Quebec H9X 3V9, Canada

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ABSTRACT

In this work, a new approach was used for visualizing particle motion and quantifying particle mixing during reciprocating agitation. Effects of various processing parameters on particle motion/mixing were investigated experimentally at room temperature by adjusting concentration of covering liquid (glycerin) to match flow behavior at higher temperatures. Particle motion was characterized by tracing the motion of single particle every 15 s. Particle mixing was quantified using mixing time calculated by observing the movement of the center of mass of particles of two colors. Results showed that particle and liquid movement was much more rapid and uniform in horizontal orientation; whereas in vertical orientation, most of the mixing and motion was concentrated in the upper half of the container. Visualization of the particle motion revealed that higher density particles sank at the bottom of the container and had lower level of mixing. Mixing time was only 15–70 s for horizontal orientation, as compared to 150–420 s for vertical orientation, and was affected significantly by reciprocation frequency, liquid viscosity and particle concentration. The calculated mixing time correlated well with data on heat transfer coefficients from previous work, implying that the heat transfer phenomenon is strongly dependent on the inherent particle motion/mixing behavior.

1. Introduction

It is well recognized that container agitation is an effective approach to counter the deleterious effects of heat during thermal processing (Ramaswamy et al., 1997). The movement of liquid and particles inside agitating cans helps in achieving enhanced mixing conditions and increased turbulence. This aids in speeding up the process of heat transfer to the cold-spot and achieving greater temperature uniformity inside the can, both of which are highly desirable to reduce processing times (Pratap Singh et al., 2015a; Singh et al., 2015a). Thus, the phenomenon of heat transfer during agitation thermal processing is strongly correlated with the extent of particle motion and particle mixing achieved due to agitation. In this context, flow visualization studies are a perfect tool to better understand the flow pattern of liquid and mixing behavior of particulates and their related influence on associated heat transfer coefficients (Rao and Anantheswaran, 1988).

Various studies have been conducted to investigate the effect of liquid and particle motion during agitation processing. Hiddink et al. (1976) studied the flow visualization of liquids (water, 75% glycerin and silicon oil) in cans during natural convection heating using a particle-streak method to observe the flow patterns. Later, Stoforos and Merson (1990) studied the motion of spherical particles in axially rotating cans and characterized the relative particle-to-fluid velocity under idealized conditions of particle motion in rotating cans. Their results also revealed that particles followed much more complicated path (flow pattern) than idealized in mathematical analyses. In another study Stoforos and Merson (1992) attempted to use this technique to explain the decrease of h_{fp} values when increasing rotational speed or decreasing liquid viscosity for a heavier particle (Teflon sphere in 350 cst silicone oil) in axial rotation. Ramaswamy and Sablani (1997) studied the motion of a single particle in a can during end-over-end rotation and explained the differences in h_{fp} between various experimental conditions. Sablani and Ramaswamy (1998) studied the multiple particle mixing behavior in water and oil subjected to end-over-end rotation and discussed the effects of various operating parameters on heat transfer coefficients. Sablani and Ramaswamy (1996) also conducted particle motion studies on nylon particles using

* Corresponding author.
E-mail address: anubhav.singh@mail.mcgill.ca (A. Pratap Singh).

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different particle concentrations, particle size, particle shape and rotational speeds in end-over-end mode of rotation. Meng and Ramaswamy (2007) analyzed the relative movement of particles in viscous fluids in containers subjected to simulated flow conditions representing thermal processing of cans under end-over-end agitation. They used carboxymethyl cellulose as a covering fluid and adjusted the concentration to match those at higher temperatures so that particle mixing behavior prevailing at thermal processing conditions could be observed at room temperatures. They observed that with low viscous fluids, the particle mixing was rapid and the particle rotation was more frequent and with high viscous fluid, the particle mixing was slow due to restricted motion. However, none of these studies have established a reliable way for quantifying the extent of particle mixing, although Sablani and Ramaswamy (1998) and Meng and Ramaswamy (2007) have relied on visual analysis of the results.

Reciprocating agitation is a new mode of agitation which has grasped attention of researchers recently. This mode of agitation relies on rapid back and forth motion of containers (Pratap Singh et al., 2015b) to create agitation. Recent literature (Pratap Singh and Ramaswamy, 2015; Pratap Singh et al., 2015b; Batmaz and Sandeep, 2015; Singh and Ramaswamy, 2015, 2016; Singh et al., 2015b; c; Walden and Emanuel, 2010) throws insight into the heat transfer phenomenon. However, no work has been conducted to actually visualize the particle motion and particle mixing for understanding the inherent mechanism of fluid flow which affects heat transfer. Thus, the objective of the present work was, therefore, to carry out a flow visualization study to observe particle/fluid motion in Newtonian fluids to enable a better understanding of heat transfer problem associated with liquid-particulate cans during reciprocation agitation thermal processing.

2. Materials and methods

2.1. Materials

Experiments were carried out in a pilot scale reciprocating retort, described in details in our earlier work (Pratap Singh et al., 2015b; Pratap Singh and Ramaswamy, 2015). In short, this retort consisted of a reciprocating basket, capable of holding 4 No. 2 metal cans (size: 307 × 409), connected to a reciprocating rod. The reciprocating rod was powered by a slider-crank mechanism via a ½ HP magnetic motor. The retort could be used to provide reciprocation of frequency between 0 and 5 Hz and amplitude between 3 and 30 cm.

All the experiments were conducted at room temperature, with the retort door held open for visual observation and video recording. For this purpose, glass containers, 7.5 cm diameter and 10 cm height were used in place of metal cans. Experiments were conducted for both single and multiple particles containing various concentrations of covering liquid (glycerin) under vertical (V) and horizontal (HA) container orientations. More details about the types of orientations and their effects on heat transfer during reciprocating agitation thermal processing are described in Pratap Singh and Ramaswamy (2015). 19 mm spheres of Nylon (1130 kg/m^3), polypropylene (830 kg/m^3) and Teflon particles (2210 kg/m^3) of uniform size & weight were used to simulate particles of different densities. The thermo-physical properties of these materials lie close to that of real food and are available in Pratap Singh and Ramaswamy (2015) and Singh and Ramaswamy (2015).

2.2. Viscosity adjustment

Since the experiments were conducted at room temperature, the concentration of covering liquid (glycerin) was adjusted to match the bulk average temperature during the equilibration time of a typical thermal process. The bulk average temperature was assumed to be 85 °C. This was done so that particle mixing behavior prevailing at thermal processing conditions could be observed at room temperatures. For this, viscosity of glycerin was measured using a controlled stress rheometer (AR 2000, TA Instruments, New Castle, DE, USA) and the data was analyzed using a data analysis software (Rheology Advantage Data Analysis Program, TA version 2.3 s). 2 ml of different glycerin solutions made with Milli-Q water (EMD Millipore, Massachusetts, USA) were placed on the flat plate of the cone and plate geometry (60 mm, 2° steel cone) with the instrument programmed at 20 °C. Zero gap and instrument rotational mapping was efficiently performed before executing the experiments so as to get reliable results. Each test was conducted using the flow procedure consisting of temperature ramp from 20 °C to 90 °C at the rate of 5 °C/min at the constant shear stress of 0.1768 Pa.

2.3. Visualization and quantification

In the single particle study, effect of particle density was studied using 19 mm spherical particles of three different materials i.e. Polypropylene, Nylon, and Teflon representing different densities of particles in equivalent concentrations of 50 and 100% glycerin. These experiments were conducted at 2 Hz and 15 cm amplitude with a headspace of 12 mm. With multiple particles in the containers, 19 mm spherical Nylon particles were used to study the effect of particle concentration (20, 30 and 40%), liquid consistency (glycerin concentrations representative of 50 and 100% at 85 °C) and reciprocation frequency (1, 2 and 3 Hz). These experiments were conducted at 15 cm amplitude with a headspace of 12 mm. The corresponding experimental levels were chosen on the basis of results of our earlier heat transfer studies (Pratap Singh and Ramaswamy, 2015; Pratap Singh et al., 2015b; Singh and Ramaswamy, 2016) on reciprocating agitation thermal processing. For observing the multi-particle mixing behavior under different processing conditions, at the beginning of the experiment, the glass containers were filled with two layers of particles of different colors (black and white) and appropriate fluid.

All experiments were performed in three replicates and under two orientations (HA − longer axis of can placed *horizontally along* the axis of reciprocation; V − longer axis of can placed *vertically* perpendicular to the axis of reciprocation). HP orientation (longer axis of can placed *horizontally perpendicular* to the axis of reciprocation) was not considered as it was difficult to videotape the cans when it was placed in this orientation and as the heat transfer in this orientation was found in between the HA and vertical orientation (Pratap Singh and Ramaswamy, 2015). Henceforth, horizontal orientation refers to HA orientation.

All the experiments were videotaped, played subsequently on computer in slow motion and photographed for characterization of the particle motion and mixing. In each run, the experiment was conducted for sufficient time to allow sufficient mixing of the particles. Snapshots for analysis of particle motion and particle mixing were taken at every 15 s for vertical orientation and every 5 s for horizontal orientation cans. In single particle scenario, the position of single particle inside the can was traced every 15 s and was presented to reveal the movement of particle inside the container.

In multiple particle scenario, the mixing of the two color particles was observed by the movement of the black and white particles. For this, the center of mass of the particles of two color was calculated for each snapshot using Eq. (1). The movement of the center of mass of each color demonstrated the motion of the particles and the distance between the center of mass of each color