LWT - Food Science and Technology 65 (2016) 185–196

Contents lists available at ScienceDirect

LWT - Food Science and Technology

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

Heat transfer coefficients during thermal processing of model particulate mixtures in non-Newtonian fluids undergoing reciprocation agitation as affected by process variables

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

A R T I C L E I N F O

Article history:
Received 27 December 2014
Received in revised form
21 July 2015
Accepted 27 July 2015
Available online 30 July 2015

Keywords:
Heat-transfer coefficient
Non-Newtonian fluids
Particulate fluids
Reciprocating agitation
Thermal processing

A B S T R A C T

Overall (U) and fluid-to-particle heat-transfer coefficients (h_{fp}) in canned particulates (Nylon spheres) suspended in non-Newtonian fluid (CMC dispersions) undergoing reciprocation agitation thermal processing was evaluated in a pilot-scale reciprocating retort. Five influencing process variables affecting U and h_{fp} were selected. A CCRD and a $3 \times 3 \times 2$ full-factorial design of experiments were used to relate the coefficients U and h_{fp} to the various process variables *viz.* reciprocation frequency; reciprocation amplitude; temperature; liquid viscosity and headspace.

U and h_{fp} varied in the range 524–1124 W/m^{2o}C and 549–1610 W/m^{2o}C respectively. Analysis of variance showed frequency, amplitude, liquid viscosity, headspace and temperature to be significant factors for h_{fp}, and frequency, amplitude and liquid viscosity for U ($p < 0.001$). Increasing the reciprocation frequency from 1 to 4 Hz almost doubled the value of both the heat transfer coefficients. Similarly increasing the reciprocation amplitude from 5 to 25 cm, resulted in 30–35% increase in the values of heat transfer coefficients. Overall with increase in temperature, frequency, amplitude, and headspace, associated h_{fp} and U values also increased, but with increasing liquid viscosity, both h_{fp} and U showed a decrease. Finally, optimization of processing conditions was carried out to minimize quality losses due to particle motion (agitation intensity) and thermal damage (severity of thermal processing).

1. Introduction

Thermal processing applications have shifted their focus to new technologies like high-temperature short-time (HTST) processing, or aseptic processing, or processing under container agitation, or processing in thin profile formats (Ramaswamy, Abbatemarco, & Sablani, 1993) to produce high quality canned products. Agitation of containers, in form of rotation (Dwivedi & Ramaswamy, 2010) or oscillation (Sablani & Ramaswamy, 1999), has been extensively used to reduce quality loss associated with thermal processing of canned foods. Commercial rotary retorts, like Sterilmatic (FMC Corp., San Jose, CA), Steristar (Malo Inc., Tulsa, OK), Rotomat (Stock America, Inc., Milwaukee, WI), provide agitation through rotation of cans in end-over-end or axial mode. More recently, a new form of container agitation, namely, reciprocation agitation, is being promoted to improve associated heat transfer rates (Walden & Emanuel, 2010). Reciprocating agitation has been found to be effective in reducing process times and quality loss indicator due to the rapid rate of heating (Singh, Singh, & Ramaswamy, 2015a). However, excessive use of reciprocation agitation may result in quality loss in some situations (ex. breakdown of particles). Thus, it is necessary to optimize this process to minimize agitation losses while taking advantage of the rapid heating process.

Data on overall heat-transfer coefficient (U) and fluid-to-particle heat transfer coefficient (h_{fp}) are needed for modeling of heat transfer in a liquid particulate system (Stoforos & Merson, 1992). A review of various methodologies for calculating these coefficients (U and h_{fp}) during thermal processing is available in Singh, Singh, and Ramaswamy (2015b). Various researchers have used these methodologies to evaluate U and h_{fp} during various rotary agitation systems like end-over-end (Anantheswaran & Rao, 1985; Meng & Ramaswamy, 2005, 2007; Ramaswamy et al., 1993 and Sablani & Ramaswamy, 1999) and axial rotation (Deniston, Hassan, & Merson, 1987; Dwivedi & Ramaswamy, 2010; Lenz & Lund, 1978)

---

* Corresponding author.
E-mail address: hosahalli.ramaswamy@mcgill.ca (H.S. Ramaswamy).

http://dx.doi.org/10.1016/j.lwt.2015.07.072
0023-6438/

and have found rotational speed, retort temperature, headspace volume, system geometry, rotation radius, liquid viscosity, particle shape, particle size, particle density etc. to be key variables affecting heat transfer. A detailed review of the effect of these process variables on the values of U and h_{fp} and the heat transfer phenomenon is available in Singh, Singh, and Ramaswamy (2015c). However, there is lack of research work on U and h_{fp} during reciprocation mode of agitation, although it is claimed that this process can reduce process times more than 20-fold compared to a still process and more than 10-fold compared to a rotary process (Walden & Emanuel, 2010). Singh et al. (2015a) demonstrated 46–62% reduction in process time during reciprocating agitation compared to still mode and Singh and Ramaswamy (2015) quantified effect of some operating variables on U and h_{fp} during various container orientations possible during reciprocating agitation. However, both these works used glycerin, a Newtonian fluid, as the covering medium, but most of the real fluid foods are non-Newtonian in nature.

Hence, the goal of present study was to evaluate the effect of key process variables on the coefficients U and h_{fp} associated to reciprocation agitation thermal processing of canned particulates suspended in non-Newtonian fluid. To the best of our knowledge, no such detailed work has been carried out with non-Newtonian fluid during reciprocating agitation.

2. Material and methods

2.1. Modified steam retort for facilitating reciprocation agitation

A pilot-scale vertical steam retort modified to include reciprocating agitation was used in this study. For this, a reciprocating cage (inside the retort) connected to slider crank assembly (outside of retort) was installed in the existing retort (Fig. 1a). The slider crank assembly converted rotation of motor into reciprocating motion (back and forth motion) of cage. The system was designed in such a way that accommodated horizontal reciprocation of reciprocating cage (12 cm, length 35 cm and height 17 cm) placed inside a vertical retort (diameter 62 cm and depth 100 cm) up to a maximum frequency of 5 Hz. The reciprocating cage was designed to hold one level of 4 cans (No. 2) along the radial direction of the retort (cans could be place horizontal or vertical, parallel or perpendicular to the axis of rotation) with two cans on each side of the axis of reciprocation for balancing. Reciprocation amplitude could be varied between 3 cm and 30 cm by changing the position of reciprocating crank on the rotating shaft of slider crank assembly. The system was powered by a ½ hp direct current magnetic motor. The motor speed (and thus the frequency of reciprocation) was controlled through an external voltage controller. Further details about modification mechanisms and voltage calibration are available in Singh et al. (2015a) and Singh and Ramaswamy (2015).

2.2. Materials used

Metal cans of size 307 × 409 (Home Canning Co., Montreal, QC) were used in the study. Aqueous dispersions of Carboxylmethyl cellulose (CMC, Sigma, St. Louis, MO) were used as a model non-Newtonian fluid. Different concentrations of CMC solution (0, 0.2, 0.5, 0.8 and 1 g/100 g), was used to provide various range of starting viscosities. Because the concentrations of CMC aqueous solutions were small, specific heat of all CMC concentrations were assumed to be same as water (Anantheswaran & Rao, 1985). To overcome uncertainty in thermo-physical properties associated using real foods, Nylon spheres (Small Parts Inc., Miami, FL) of 19 mm diameter were used as food simulating particles (rather than real food), as it's thermal properties (heating behavior) are most relevant to real food and do not change with temperature. Table 1 summarizes the thermo-physical properties of liquid and particles at bulk mean temperature extracted from available literature (Meng & Ramaswamy, 2005). Use of CMC concentrations between 0.20 and 1.00 % and Nylon as a food simulating particle can be justified by the fact that their rheological and thermo-physical properties are similar to that of real foods (Table 1).

2.3. Temperature measurement

Cans were filled with prepared CMC solution and 48 spherical Nylon particles of 19 mm diameter (giving particle concentration of 32.7 g/100 g) to the required headspace. Liquid temperatures inside the can were monitored using CNS copper-constantan needle-type thermocouples (locking connector, C-10, Ecklund Harrison Technologies, Inc. Cape Coral, FL) with tips located at the geometric center of can (Fig. 1b). Particle-center temperature were measured using flexible CNS copper-constantan wire thermocouples ($d = 0.0762$ mm, Omega Engineering Corp., Stamford, CT) introduced into the particle center through a fine hole and fixed by a small amount of epoxy glue (Fig. 1b). Thermocouple signals were recorded at 1 s intervals. Additional details about can preparation and temperature measurements can be found in Singh et al. (2015c). A schematic of temperature measurement and experimental setup is shown in Fig. 1a.

2.4. Thermal processing

For thermal processing, duplicate cans were placed vertically (Fig. 1a) in the modified reciprocating retort equidistant from the axis of reciprocation. Empty space in the cage was filled with dummy cans to provide ballast. Reciprocating crank was pivoted to the proper position on rotating shaft to achieve the required amplitude. Motor was turned on at the required reciprocation frequency. Steam was turned on and retort was heated up to processing temperature. During the sterilization cycle, steam temperature and system pressure were maintained at the preset value through the retort control system. After completing the process, steam was turned off and water inlet to the retort was opened while the reciprocation was still on. Cans were then cooled by circulating cold water in the retort, until all temperatures reached below 30 °C.

2.5. Experimental design and statistical analysis

Based on some preliminary experiments, five most influencing process variables were selected: retort temperature, reciprocation frequency, reciprocation amplitude, CMC concentration, and can headspace. The influence of these variables were studied using two experimental designs (a central composite rotatable design – CCRD, and a full-factorial design). The CCRD design involved 20 experiments for five levels of retort temperature (110, 114, 120, 126, 130 °C), CMC concentration (0.0, 0.2, 0.5, 0.8 and 1.0 g/100 g) and reciprocation frequency (1, 1.6, 2.5, 3.4, and 4 Hz). The fixed variables were: can headspace of 12 mm, and amplitude of reciprocation of 15 cm. The 3 × 3 × 2 full factorial design involved 18 experiments with three levels of reciprocation frequency (1, 2, 3 Hz), three levels of reciprocation amplitude (5, 15, 25 cm), and two headspace levels (6 and 12 mm contributing to 5% and 10% of the total volume of can respectively). The fixed variables were: operating temperature of 121.1 °C, and CMC concentration of 1 g/100 g. All experiments were conducted with duplicate cans and each test run was replicated twice. Analysis of variance (ANOVA) was used to determine significant terms in the model for each response. The adequacy of model was checked by looking at the R^2 and adjusted-R^2 values and by ensuring that the lack of fit was not significant and coefficient of variation was below 10%.