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Determining the optimal shaking rate of a reciprocal agitation sterilization system for liquid foods: A computational approach with experimental validation

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ABSTRACT

A new canning process where a reciprocating agitation is carried out in horizontally oriented containers has been recently demonstrated to reduce processing times and enable energy savings with less degradation in the quality of processed food products. Reciprocal agitation by imposing additional forces enhances convective mixing with increased production efficiency. The reciprocal agitation uses the horizontal acceleration in addition to gravity and sum of these forces lead to a considerable increase in the heat transfer rates. In the literature, there have been experimental approaches to evaluate heat transfer enhancement. However, due to the balance among these forces, there might be an optimum reciprocal agitation rate for the increased heat transfer depending upon the physical properties of the liquid processed. Therefore, the objectives of this study were to determine the optimum agitation rates by developing a computational model for heat transfer. For this purpose, a multi-phase model simulation was performed using a finite volume method based on discretization of governing flow equations for liquid and gas phase in a non-inertial reference frame of moving mesh. Experimental studies for model validation were carried out in a reciprocally agitated retort using 98.2 mm × 115 mm cans containing distilled water with 2% headspace as a model case. The model results were in agreement with the experimental data, and the optimum reciprocal agitation rate was determined. The results of this study are to be used to optimize the process with respect to improve the health-promoting compounds of processed foods.

1. Introduction

Traditional canning has been a convenient way and provided a generalist and economic method for processing and preservation of food products. Consumer demands for high quality foods, however, force the food processors to improve and innovate their processing. It is a well-known fact that the shorter the process time at a given process condition, while still achieving the required safety for consumption, the less the damage to the sensory and nutritive quality of the food products. Based on this concept, following the use of retorts for canning, the agitation retorts were introduced

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in 1920s with the agitation mechanism based on horizontal axial rotation (Ates et al., 2014). Vertical rotation of the cans was later introduced with the end-over-end rotation principle (Clifcorn et al., 1950). Introduction of agitation mechanism in canning for liquid or liquid–solid particles containing food products was the result of a certain disadvantage of the static retort systems (Rosnes et al., 2011). The primary challenge in the static processing is the slow heat penetration resulting in a lack of consistency in sensory and nutritive properties (Ohlsson, 1980).

Considering the effective heat transfer rates obtained with agitation, a reciprocating horizontal agitation with rapid back and forth motion of the horizontal containers in an oscillating way has been proposed to increase the heat transfer rate further, and an agitating retort with high frequency longitudinal mechanism was developed in 2006 (Ates et al., 2014). Both horizontal and end-over-end based agitation retorts suffer from the limitation of that the applied forces to enable the motion within the container were a balance between gravity and centrifugal forces (Walden and Emanuel, 2010). Due to this balance, the agitation increases the heat transfer rate up to an optimum while further agitation might not affect or might influence the process in a negative way depending especially upon the viscosity of food product. A detailed analysis and comparison among the gravity and centrifugal forces for the case of axial rotation effects in horizontal axial rotation of cans were reported by Erdogdu and Tutar (2012) and Tutar and Erdogdu (2012). The reciprocal agitation, however, used the horizontal acceleration in addition to gravity, and the sum of these forces enabled a considerable increase in the heat transfer rates with reductions in the process time (Walden and Emanuel, 2010).

The first studies in the food engineering literature using the reciprocating agitation systems were experimental based to demonstrate the possible process time reductions and improvements in the heat transfer rates. Bermudez-Aguirre et al. (2013a) demonstrated the improvement in heat transfer coefficient under static and horizontal gentle-rocking modes. Ates et al. (2014), for example, compared the novel agitating retort and static retort processes for bacterial inactivation, and it was concluded that agitating retort process significantly lowered the required process time. The study by Singh et al. (2015a) focused on evaluating the heat transfer enhancement under reciprocal agitation while Singh et al. (2015b) developed an experimental methodology to determine the heat transfer coefficient in canned particulate fluids under reciprocating frequencies up to 3 Hz. Singh and Ramaswamy (2015a) focused on the effect of product related parameters on heat transfer while Singh and Ramaswamy (2015b) determined the effect of the orientation of cans during reciprocating agitation thermal processing. Singh et al. (2016) introduced the concept of reciprocal agitation process to improve the quality of canned green beans during thermal processing. Singh and Ramaswamy (2016) carried out an optimization study for the heat transfer rate and reciprocation intensity for thermal processing of liquid particulate mixtures. These studies were based on experimental approaches while a similar situation was explored by Liffman et al. (1997) and Pesch et al. (2008) in a computational–theoretical way for convection due to horizontal shaking and heated fluid layers subjected to time-periodic horizontal accelerations, respectively.

Even though there were certain findings reported for the effect of reciprocal agitation on the temperature increase and enhanced heat transfer rate (Bermudez-Aguirre et al., 2013a; Ates et al., 2014; Singh and Ramaswamy, 2015a,b, 2016; Singh et al., 2016), development of a computational model (with one exception where the heat transfer coefficient based lumped model without considering the temperature distribution was introduced by Bermudez-Aguirre et al. (2013b) and determining the optimal agitation rates were not focused in detail. For determining the optimal conditions, one exception was reported by Singh and Ramaswamy (2016) where the optimal conditions of reciprocation intensity for liquid particulate mixtures were experimentally determined. The optimization studies based on a computational model are significant since the computational model might also be used also for process development purposes. Therefore, the primary objective of this study was to determine the optimal agitation rate in a reciprocal agitation process using an experimentally validated computational model. The secondary objectives were first to develop a computational numerical model for heat and momentum transfer inside the reciprocally agitated cans to determine the temperature distribution and velocity changes and then experimentally validate the model.

2. Materials and methods

For the given objectives, the study consisted of experimental and computational parts. In the experimental part, a water filled can was processed in boiling water and agitating conditions. In both cases, the horizontally oriented can contained water as a test liquid to represent a low viscosity Newtonian liquid. The time–temperature data obtained at the geometric center in the first experiments were used to develop and validate the computational model, to decide upon the computational parameters with the mesh independency studies. Following the mesh independency study, the computational model was validated with the temperature data obtained under horizontal agitating conditions, and the model was applied to horizontal agitation rates from 20 to 140 rpm to obtain the agitation rate in the direction of the axis of the horizontal can resulting in maximum heat transfer. In the reciprocal agitation systems, the crankshaft, used to derive the horizontal motion, angular velocity is related to engine revolutions per min (rpm).

2.1. *Experimental methodology*

The first step in this study was to decide upon the computational parameters and test the accuracy of the computational method. For this objective, an experimental study with a canned water sample (98.2 mm × 115 mm cans filled with distilled water with 2% headspace) was carried out in a Microflow 911 EAT Shaka retort (Steriflow, Roanne, France) in boiling water under stationary conditions. The retort system was heated by direct steam injection, equipped with a preheating tank to process water. This processed water was then circulated through a heat exchanger (only used for cooling) to the retort and spread by a perforated plate to obtain water raining over the cans. The can was fixed in a horizontal position in the boiling water. Type-T thermocouple connected to a data logger E-Val Flez (Ellab, Copenhagen, Denmark) was located at the geometrical center using ring gaskets and locking-receptacles. The experimental set-up was shown in Fig. 1.

The can material was a steel sheet with a thickness of 0.19 mm and thermal conductivity value of 15–16 W/m^2 K. This enabled the assumption of the negligible conduction effect of