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Computational Evaluation of Reciprocally Agitated End-over-End (RA-EoE) Processing of Canned Food Products

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Starting with the retort processing of canned food products, horizontal axial and End-over-End (EoE) rotation have been the innovative approaches for mechanical agitation for temperature uniformity. Shaking process of reciprocal agitation has been recently introduced, and the objective of all these processes is to reduce processing time to enable energy savings and improved quality. Rather effective EoE rotation has been demonstrated in computational - experimental studies, and reciprocal agitation process was reported to impose forces up to 3-4 g to enhance the convection mixing. While liquid foods (with Newtonian fluid properties) face a significant process improvement with increased EoE rotation reciprocal agitation rates, effects of these process are limited for non-Newtonians. An increase in the rotational rate was even demonstrated to reverse the mixing effect converting the heat transfer to conduction. Considering the possible advantages of the individual process, the objective of this study was to demonstrate a combined effect of simultaneous EoE and reciprocal agitation (RA-EoE) on heat transfer – temperature uniformity enhancement and determine optimal rotation and oscillation rates. For this purpose, this study was computationally carried out in 2-dimensional (2-D) geometry where a rectangular cross-section consisted of a Newtonian (water) liquid with 10% head space (air). The use of a 2-D case was preferred to avoid computational expenses of 3-D simulations. To predict temperature changes and velocity evolution inside the system, a multi-phase model was developed using a finite volume method, based on discretization of governing equations for liquid and gas phases in a non-inertial reference frame of moving mesh, up to 80 rpm rotation and reciprocal agitation rates were used, and the results demonstrated a possible improvement in the temperature increase and uniformity combining the two agitation methods.

1. Introduction

Canning is still the most effective way of food thermal processing and one of the most effective ways for food preservations. Following the invention of cans and retorts for pressurized processing, using agitation during the process became a common way to enhance heat transfer rate and enable a temperature uniformity within the can. These agitation processes have been used for liquid products, and horizontal rotation and end-over-end (EoE) rotation systems were the most applied cases. In an EoE process, the can symmetry lies in the rotation plane or free-axial where the can symmetrical axis is horizontal and perpendicular to the rotation plane (Hughes et al., 2003). This process was firstly proposed by Clifcorn et al. (1950). Fluid dynamics play a significant role in addition to the natural convection process. The natural convection currents are distorted by the applied agitation, and all these involve complex interactions of gravitational buoyancy, centrifugal, Coriolis and viscous forces (Boonpongmaee and Makotani, 2009). While a certain number of studies in the literature investigated the heat transfer and fluid dynamics coupling in an EoE processing experimentally, Sarghini and Erdogdu (2016) were the first ones to propose a numerical approach to determine the effect of EoE rotation on the heat transfer rate of particulate canned food products. While horizontal and EoE processes have dominated the canning of liquid and particulate liquid foods, a new agitation process has found an application in the last two decades. In the process, a reciprocation agitation was carried out horizontally, and it has been demonstrated to increase the agitation by imposing additional forces with a rapid back – forth motion applied.

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While, in the horizontal and EoE rotation, there was a limitation in the agitation process due to the balance between the gravitational and centrifugal forces, the reciprocal agitation process included the horizontal acceleration in addition to the gravitational forces (Walden and Emanuel, 2010). Erdogdu et al. (2016 ; 2017) investigated this process with a numerical computational approach, and optimum reciprocal agitation rates were determined for Newtonian liquids, and the viscosity effects were further demonstrated. An optimum rate of 80 rpm was computationally calculated using the experimentally validated numerical model. Considering the possible advantages of the individual process, the objective of this study was to demonstrate a combined effect of simultaneous EoE and reciprocal agitation (RA-EoE) on heat transfer – temperature uniformity enhancement and determine optimal rotation and oscillation rates.

2. Methods

For the given objectives, this study included a computational numerical model development in a 2-dimensional rectangular geometry. The rectangular geometry was preferred to represent a cross-section of a can. Figure 1 represents this computational geometry. It consisted of a Newtonian liquid (distilled water) and air (the head space). The test was, therefore, referred to a two-phase heat transfer problem.

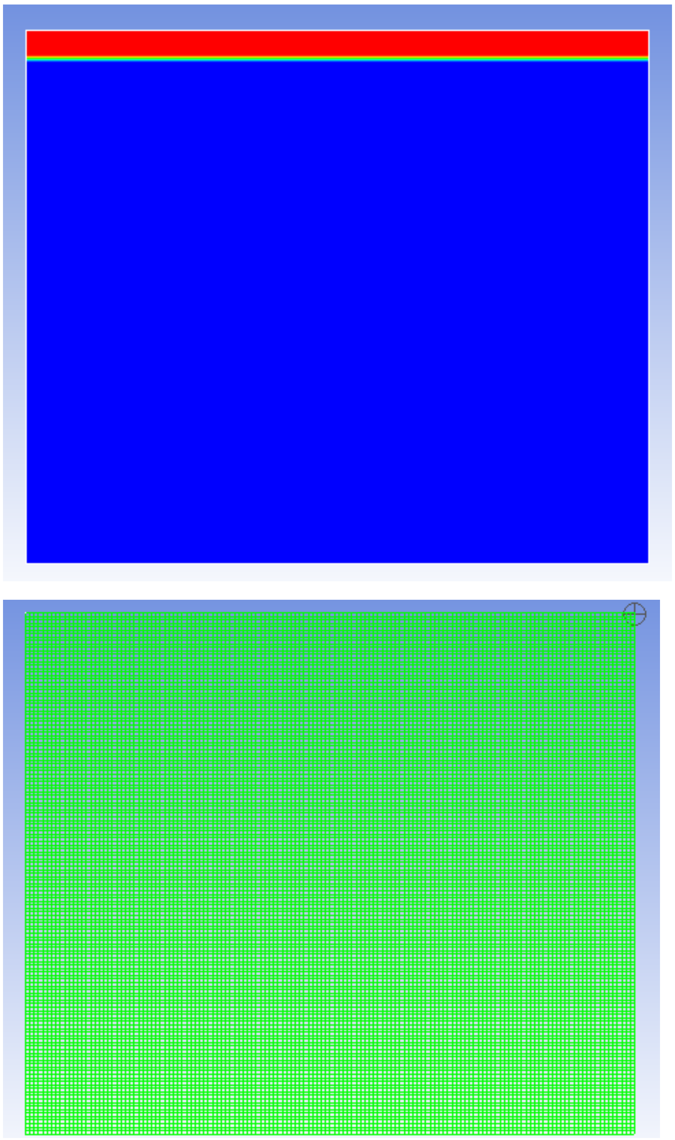

Figure 1. 2-dimensional two-phase (water – air) system with the computational geometry.

The thermal and physical properties applied in the numerical calculations are given in Table 1 (all these properties were used as a function of temperature).

Table 1. Thermo – physical properties of air and water.

Water	Viscosity (Pa-s)	$\mu = -0.0000000021 \cdot T^3 + 0.0000022109 \cdot T^2 - 0.00078049 \cdot T + 0.092683$
	Thermal conductivity(W/m-K)	$k = -0.00000909 \cdot T^2 + 0.007075 \cdot T - 0.693928$
	Specific heat (J/kg-K)	$c_p = 0.0092 \cdot T^2 - 5.6859 \cdot T + 5058.2$
	Density (kg/m³)	$\rho = +0.00001387 \cdot T^3 - 0.017012 \cdot T^2 + 6.1926 \cdot T + 295.238$
Air	Viscosity (Pa-s)	$\mu = 0.000000045 \cdot T + 0.00000507$
	Thermal conductivity(W/m-K)	$\rho = 0.00001067 \cdot T^2 - 0.010327 \cdot T + 3.3139$
	Specific heat (J/kg-K)	$k = 0.0000737 \cdot T + 0.003722$
	Density (kg/m³)	$c_p = 1006.43$

** Temperature (T) in -K-.*

2.1 Numerical method

Simulations were performed by using the Volume of Fluid (VOF) (Rider et al., 1998) approach relying on the fact that two or more fluids are not interpenetrating. The volume of fluid (VOF) method is an Eulerian free-surface modelling technique for tracking and locating the free surface or a fluid-fluid interface. As such, VOF is an advection scheme allowing to track the shape and position of the interface, but it is not a standalone flow solving algorithm, and this is why the Navier–Stokes equations describing the motion of the flow have to be solved separately. The details of the numerical methods was given in detail by Sarghini and Erdogdu (2016) and Erdogdu et al. (2017).

For the numerical solution procedure, a finite volume method (FVM) based solver (Ansys Fluent V18, Ansys, Inc., Canonsburg, PA, USA) was used to solve the preceding partial differential governing equations of the given two-phase flow problem with a moving geometry by using the following numerical schemes:

- a multiphase model for VOF approach with two Eulerian phases as explained above,
- the pressure-velocity coupling carried out with PISO scheme with skewness-neighbour coupling,
- transient formulation (second order implicit),
- spatial discretization for gradient based on Green-Gauss node; for pressure on PRESTO; for momentum on QUICK; for volume fraction on Compressinve; and for energy on QUICK scheme.

For the numerical solution, the 2-dimensional computational geometry consisted of ≈21000 nodes. A compressive interface capturing scheme for arbitrary meshes was applied to track the interface adopting a moving mesh approach for hydrodynamic and shear forces. The surface tension value along the interface of air and water was assigned to be 0.72 N/m, and the time step size used in all simulations was 1E-4 s.

2.2 Computational model

The dimensions of the 2-dimensional rectangular computational geometry was 98.2×115 mm in height and length. This was the vertical cross-section of a horizontal can in diameter of 98.2 mm and 115 mm height. The amount of the headspace (air) was 10% (9.82 mm) located on the top of the system. For this geometry, a combination of the EoE and reciprocal agitation rates were applied, and the results were analysed based on the average temperature increase and temperature uniformity. The rotation and reciprocal agitation rates between 20 to 80 rpm in various combinations were applied. In addition to these simulation cases, only EoE rotation at 20 rpm was also simulated. Temperature was set at 300° for a uniform initial temperature distribution, and 394 K was for the boundary conditions with an assumption of infinite heat transfer coefficient. For all the surfaces, no-slip condition was applied, and the reciprocal agitation rate was calculated using the following equation:

$$v = r \cdot \omega \cdot \sin(\omega \cdot t) \quad (1)$$

Where v was the reciprocal velocity applied (m/s), ω was the shaking rate (rpm), t is the time (s), and r is the crank radius of the system (0.075 m).

3. Results and Discussion

Figure 2 shows the effect of EoE and reciprocal agitation rates on the average temperature increase within the 2-dimensional system. The additional reciprocal agitation rate of 20 rpm over the 20 rpm EoE rotation did not make an improvement effect on the heat transfer rate and temperature increase. However, the increase of reciprocal agitation rate to 80 rpm made a certain contribution over the process time. This was noted effectively after 30 s. Figures. 2 and 3 show the temperature distribution and headspace movement at the 35th s of the process for different combinations of the EoE and reciprocal agitation rates. The temperature distribution and the average temperature change was rather similar for the 20 rpm EoE process and the combination of 20 rpm EoE – reciprocal agitation. This demonstrates the significant effect of the EoE rotation at the lower agitation rates. The headspace movement for these two cases was also very similar. However, when the reciprocal agitation rate was increased to 80 rpm, a significant effect on the temperature increase was observed (Figure 3c). In addition, the temperature uniformity was also better than the other two cases indicating the effect of reciprocal agitation at higher rates. The movement of the headspace bubble was not affected by the increase in the reciprocal agitation rate while the EoE rotation was the dominant effect on this. This behaviour of the headspace bubble might be due to the viscosity effects, and as previously noted by Erdogdu et al. (2016), the viscous forces generated by water because of its Newtonian behaviour (e.g., there is no effect of the shear rate on the viscosity changes) might not have enough power to cause a significant movement of the headspace.

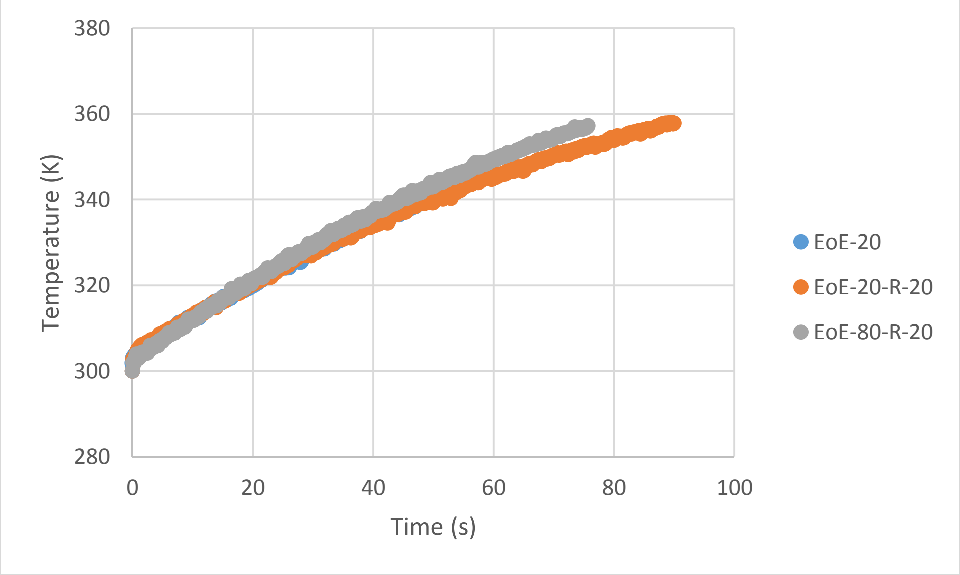

Figure 2. Effect of end-over-end (EoE) and reciprocal agitation (R) combinations on the average temperature increase.

In this kind of rotation – agitation system, the evolution of flow field and temperature distribution involves the interactions between inertial forces due to the rotational and agitation effects, gravitational buoyancy forces (to lead to the formation of the natural convection) and viscous forces. Based on the observed temperature distribution, the rotational – agitation forces had a certain effect over viscous and gravitational forces. As seen in Figure 3, the natural convection effects were reduced especially with the increase in the reciprocal agitation rate.

4. Conclusions

The results demonstrated the significant effect of the combined rotational – inertial (agitation) forces over gravitational and viscous forces especially at the higher reciprocal agitation rate. Combining these with the temperature changes and investigation of the viscosity effects (especially the case for a non-Newtonian liquid) would be a valuable information for literature and engineering design considerations. Further details are required to understand buoyancy effects vs inertial effect on particulate to determine the optimal rotation and reciprocal agitation rates. The results of this study will be expended to 3-D cases with non-Newtonian liquids and used to suggest a new innovation process to canning industry for improving retention of nutrients and health-promoting compounds of processed foods.

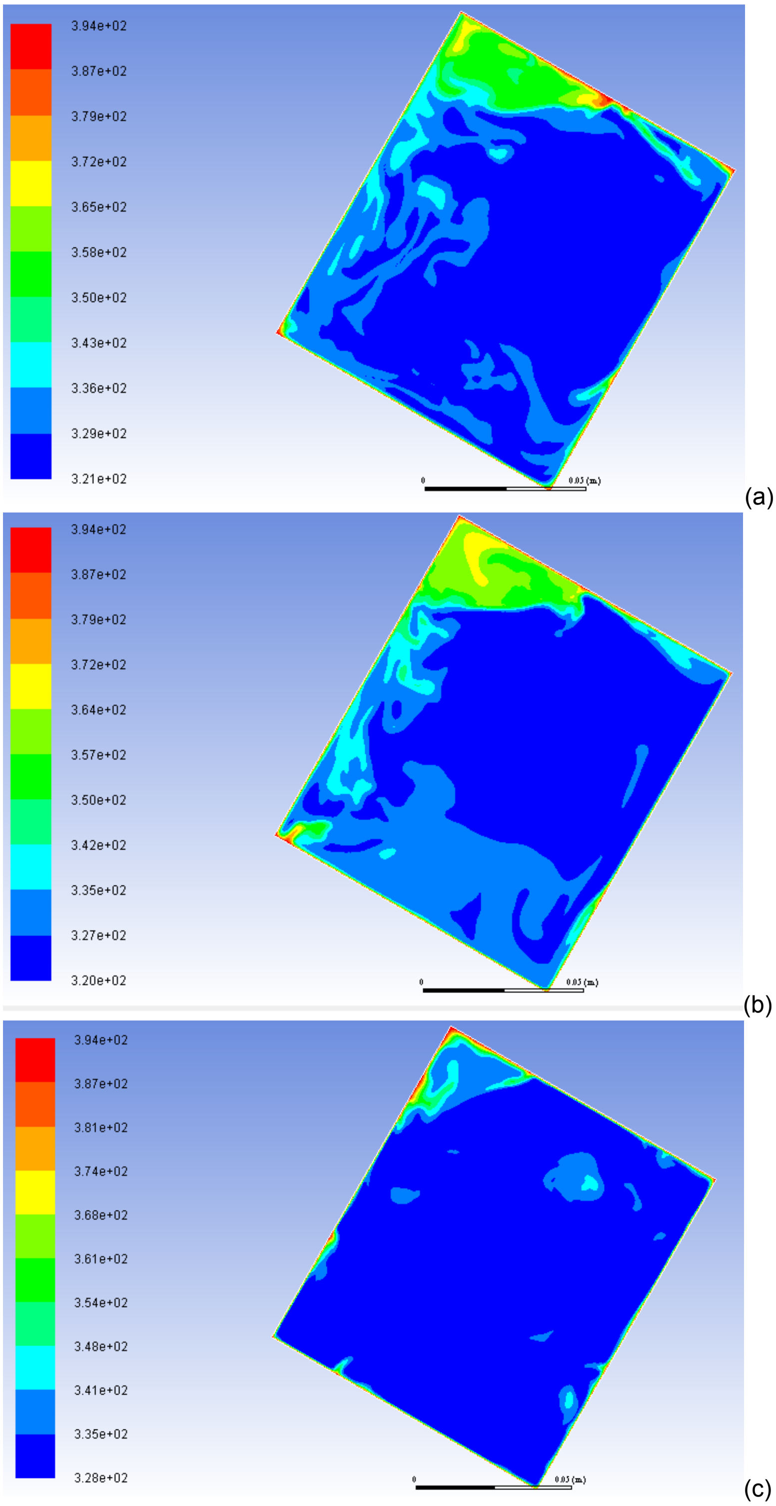

Figure 3. Effect of end-over-end (EoE) and reciprocal agitation rate on the temperature distribution at the 35th s of the process; (a) EoE-20 rpm, (b) EoE-20 rpm – R-20 rpm, (c) EoE-20 rpm – R-80 rpm.

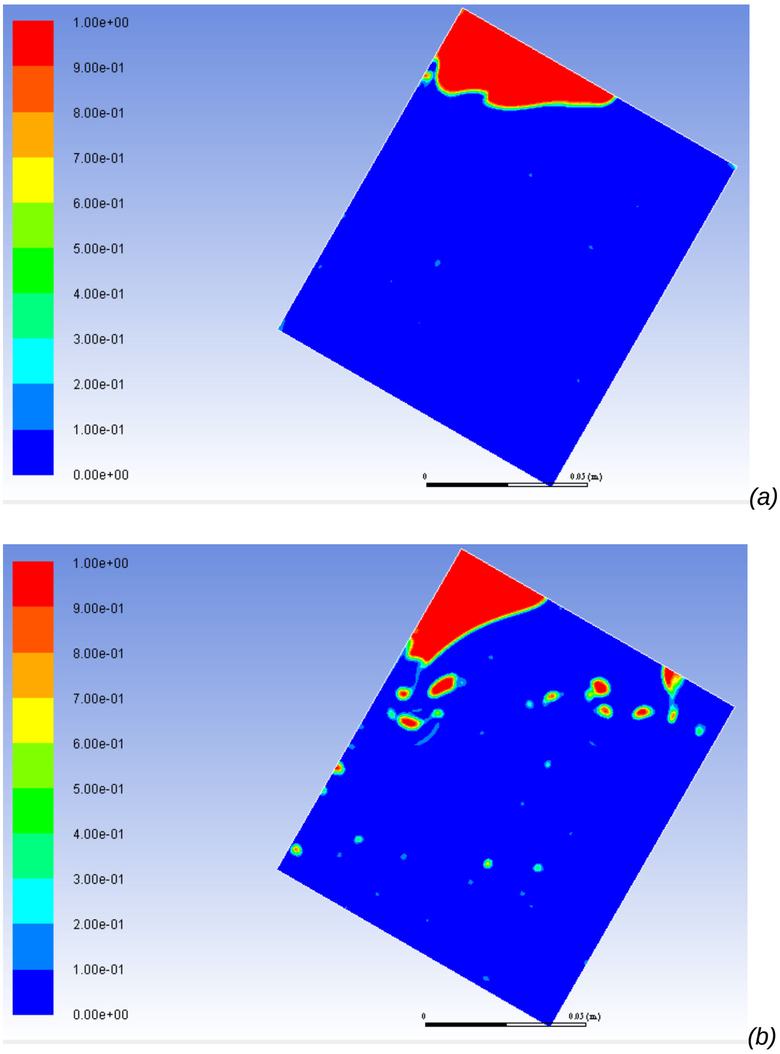

Figure 4. Effect of end-over-end (EoE) and reciprocal agitation rate on the headspace (air) movement at the 35th s of the process; (a) EoE-20 rpm, (b) EoE-20 rpm – R-80 rpm.

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