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Intensification of Heat Sterilization Process for Liquid Foods using Taylor–Couette Flow System

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Heat sterilization are widely used in almost all food manufacturing areas. For heat sterilization of liquid foods which has high viscosity and shear-thinning property, Taylor–Couette (TC) flow system having two coaxial cylinders is applied in this study, and its performance of heat transfer TC flow for a high viscous shear-thinning fluid is investigated numerically.
Taylor vortices generated between the cylinders enhance heat transfer from the surface of outer cylinder to the fluid. Thus Nusselt number significantly increased in Taylor vortex flow region. The empirically correlation equation of the global Nusselt number was constructed using two model parameters. Furthermore, heat transfer of Taylor–Couette flow with an axial flow was simulated. When Taylor vortex is formed, heat transfer from the surface of outer cylinder was enhanced significantly. It can be found that Taylor–Couette flow system has potential for intensification of continuous sterilization process.

1. Introduction

Heat sterilization process for liquid foods, ranging from milk and fruit juices to sauces and ketchup, is crucially important for human hygiene. Especially, continuous sterilization is preferable to batch sterilization due to its better uniformity of thermal treatment. Continuous ultra high temperature (UHT) sterilizers are widely used in food industries to ensure microbial safety. Many researchers has been investigated the performance of heat transfer and sterilization for viscous foods in continuous UHT sterilizers (Simpson and Williams, 1974; Kumar and Bhattachrya, 1991; Jung and Fryer, 1999). However, when continuous UHT sterilizations are applied to high viscous fluids like mayonnaise and ketchup, the flow condition in the sterilization is laminar flow where heat transfer by convection motion is poor. Thus, the temperature distribution, which induces a non-uniform heat treatment, is caused by the insufficient heat transfer. Although turbulent flow promotes heat and mass transfer, power consumption significantly increases and degradation of quality factors such as color and vitamin concentration would be induced. In order to design efficient and mild sterilization process, Kelder et al. (2002) applied Dean vortex generated in a curved pipe to sterilization process. They showed that Dean vortex flow enhanced heat transfer and promoted sterilization numerically. However, the degree of convection motion of Dean vortex flow is not so strong. This means that such flow system would be limited to relatively low viscous fluid process.
In this study, Taylor–Couette (TC) flow system was proposed for heat sterilization of high viscous foods. TC flow system consists of of two coaxial cylinders with the inner one rotating. Above a critical circumferential Reynolds number, Re_{cr}, pairs of counter-rotating toroidal vortices (Taylor vortices) appear, which are spaced regularly along the cylinder axis. This toroidal vortex motion enhances not only heat and mass transfer, but also mixing. In addition, all fluid elements leaving the annulus have the same residence time when a relatively small axial flow is added (Kataoka et al., 1975). Therefore, TC flow system enables converting a batch operation to a continuous one. By making use of these advantages, TC flow system has been applied to food processes: enzymatic fructose-glucose isomerization (Giordano et al., 2000), starch gelatinization and saccharification (Hubacz et al., 2013; Masuda et al., 2013), and inactivation of *Escherichia coli* in liquids

(Orlowska et al., 2014). When TC flow system is applied to heat sterilization processes, the excellent performance of heat transfer would promote destruction of spores like *Clostridium botulinum*. Furthermore, most of high viscous foods have non-Newtonian property, especially shear-thinning property, i.e. its viscosity decreases with increasing shear-rate. The additional advantage of using TC flow system for sterilization of liquid foods seems to be a positive influence of shear stress field, which is generated by the rotation of the inner cylinder, on rheological properties of foods by causing significant reduction of apparent viscosity. In order to utilize TC flow system as a new type of heat sterilizer, characteristics of heat transfer of Taylor vortices for shear-thinning fluids should be understood. Actually, the characteristics of heat transfer for Newtonian fluid systems have been experimentally and numerically investigated by many researchers (Kataoka, 1975; Kataoka et al., 1977; Ball and Farouk, 1987; Ball and Farouk, 1989; Ball et al., 1989; Kedia et al., 1998). However, the understanding of it for shear-thinning fluids is still poor. For example, Khellaf and Lauriat (2000) investigated the characteristics of fluid flow and heat transfer for a Carreau model fluid in TC flow with the radial heating numerically. Their results indicated that the flow became oscillatory when increasing the shear-thinning property. In addition, it was successfully confirmed that the reduction in apparent viscosity due to the shear-thinning effect decreased the friction factor at the rotating cylinder. However, the empirically correlation equation of Nussellt number (*Nu*) which is practically useful for the estimation of heat transfer performance is not fully established.
The objective of this study is to construct the *Nu* correlation equation for shear-thinning fluids. Heat transfer of TC flow with temperature distribution in the radial direction was investigated by numerical simulation. Furthermore, in order to propose the continuous TC flow sterilizer, heat transfer with axial flow was also simulated.

2. Numerical simulation

2.1 Governing equations

The fluid was considered as an incompressible shear-thinning fluid in a steady state. In a three-dimensional calculation, the governing equations of the shear-thinning fluid flow are the conservation equations of mass, momentum and heat as shown in Eqs. (1) – (3),

$$\nabla \cdot \mathbf{u} = 0 \tag{1}$$

$$(\mathbf{u} \cdot \nabla)\mathbf{u} = -\frac{\nabla p}{\rho} + \frac{1}{\rho}\nabla \cdot (2\eta \mathbf{D}) - \mathbf{g}\beta (T - T_{ref}) \tag{2}$$

$$\mathbf{u} \cdot \nabla T = \frac{\lambda}{\rho C_{\mathrm{p}}} \nabla^2 T \tag{3}$$

where $\boldsymbol{u}$ is the velocity, p is the pressure, ρ is the density, η is the viscosity depending on the shear-rate, $\boldsymbol{D}$ (= ($\nabla \mathbf{u}$ + $\nabla \mathbf{u}^{\mathrm{T}}$) / 2) is the rate of deformation tensor, $\boldsymbol{g}$ is the gravitational acceleration, β is the coefficient of volume expansion, T is the temperature, λ is the thermal conductivity, and C_{p} is the specific heat capacity. Here, the viscous dissipation energy was neglected. Accumulation terms in governing equations were omitted because of the steady state simulation.
As an example of shear-thinning liquid foods, the rheological properties of 1.0wt% hydroxymethylcellulose aqueous solution, with ρ = 1003 kg/m^3 at T = 293.15 K, was used for numerical simulation (Kaminoyama et al., 2011). The rheological properties of the solution could be expressed by Carreau model (1972). The viscosity constitutive equation of the model is expressed as follows:

$$\eta = (\eta_0 - \eta_\infty)\left[1 + (B \cdot \gamma)^2\right]^{(n-1)/2} + \eta_\infty \tag{4}$$

where γ is the shear-rate, η_0 is the zero shear-rate viscosity, η_∞ is the infinite shear–rate viscosity, B is the characteristic time and n is the power index. Here, the shear-rate is defined as $\gamma = \sqrt{2\boldsymbol{D}:\boldsymbol{D}}$, which is the magnitude of the rate of deformation tensor. When the square root is taken, the sign must be so chosen that γ is a positive quantity. η_0 is usually much larger than η_∞ for shear-thinning fluids and it follows that the value of η_∞ could be ignored in this simulation.
The temperature dependence of the viscosity is modelled by an Arrhenius function:

$$\eta = \eta_{\mathrm{ref}} \exp\left[E\left(\frac{1}{T} - \frac{1}{293.15}\right)\right] \tag{5}$$

Finally, by combining Eq. (4) and (5), the viscosity constitutive equation with the temperature dependency is expressed as follows:

$$\eta = \eta_0 \exp\left[E\left(\frac{1}{T} - \frac{1}{293.15}\right)\right]\left[1 + (B \cdot \gamma)^2\right]^{(n-1)/2} \tag{6}$$

All other fluid properties were assumed to be independent of temperature. The values of β, C_p and λ were assumed to be same as glycerine, 505 1/K, 2390 J/kg·K and 0.285 W/m·K at 293.15 K, respectively. Figure 1 shows the relation between the apparent viscosity and the shear-rate. The value of η_0 at 293.15 K was 4.2 Pa·s, and the values of B, n and E were 1.2 s, 0.5 and 7.60, respectively.

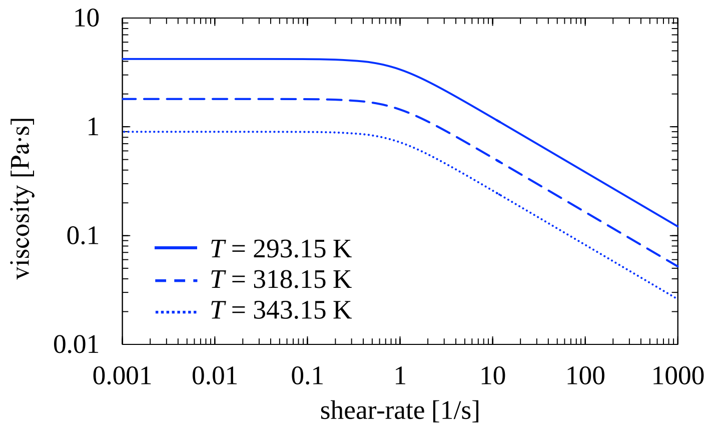

Figure 1: Relation between apparent viscosity and shear-rate at each temperature.

2. 2 Computational system

A computational domain for TC flow system is shown in Fig. 2. The TC flow system consisted of concentric cylinders (length: L = 300 mm), rotating inner cylinder (outer radius: R_i = 12.5 mm) and the fixed outer cylinder (inner radius: R_o = 17.5 mm). The origin of coordinate was set at the middle of the left wall of the inner cylinder as shown in Fig. 2. The gap width, d, was 5.0 mm. The radius ratio, R_i / R_o, was 0.71. The fluid was filled in the gap. By the rotation of the inner cylinder, Taylor–Couette flow could be generated.

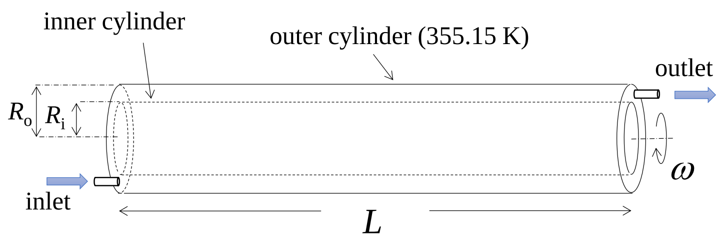

Figure 2: Computational domain for TC flow system

The boundary conditions for this simulation were as follows:

- Inlet boundary conditions: Without the axial flow, it was treated as the fixed fall at T = 348.15 K. With the axial flow, the constant axial inlet velocity of fluid, u, with T = 298.15 K was set at u = 0.124 cm/s.
- Outer cylinder boundary conditions: All components of velocity were 0m/s; the temperature was set at 358.15 K.
- Inner cylinder boundary conditions: The circumferential velocity was given by ωR_i [m/s]; the axial and radial velocity were 0 m/s; without the axial flow rate, the temperature was set at 348.15 K; with the axial flow, no heat transfer.
- Outlet boundary conditions: The pressure at the outlet was set at 0.

The number of grids was 1,310,720 (32 × 64 × 640 in radial, azimuthal and axial directions, respectively), in this study. According to Masuda et al. (2017), this number of girds is sufficient for the simulation of TC flow system having the same geometry. The governing equations were discretized based on a finite volume method, and the second-order central difference scheme was applied to a convection and viscous term. The SIMPLE scheme was used for pressure–velocity coupling. All simulations were conducted using CFD software RFLOW developed by R-FLOW Co., Ltd.

3. Results and discussion

3. 1 Heat transfer without axial flow

Figure 3 shows the axial profiles of the calculated local Nusselt number, Nu_L. The Nu_L was calculated from the gradient of temperature at the outer cylinder wall defined as (Noui-Mehidi et al., 2007):

$$Nu_L = \frac{2dl}{\lambda} = 2d\left(\frac{\partial T}{\partial r}\right)_{r=Ro} \tag{7}$$

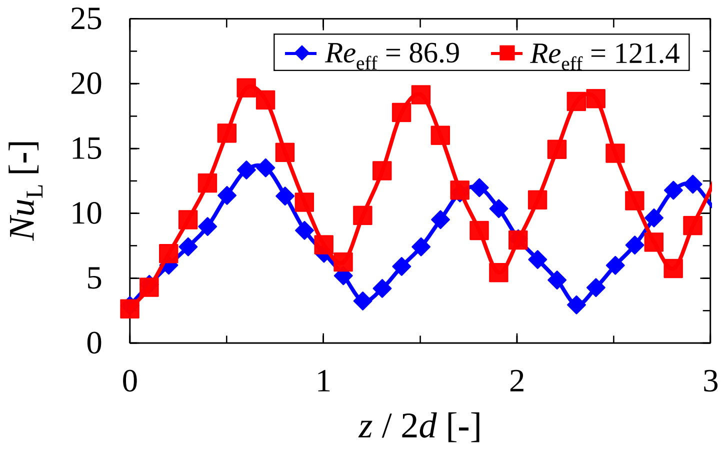

Figure 3: Axial variation of local Nusselt number at Re_{eff} = 86.9 and 121.4

Re_{eff} in the circumferential direction is defined as follows,

$$Re_{eff} = \frac{\rho R_i \omega d}{\eta_{eff}} \tag{8}$$

It should be noted that Re_{cr} is 82.2 for R_i / R_o = 0.71 (Taylor, 1923). Owing to the shear-thinning property, the viscosity spatially changes with the spatial distribution of shear-rate in the annular space. Thus, it is essential to estimate the effective shear-rate properly in order to calculate the effective Re (Re_{eff}) from the effective viscosity, η_{eff}. Masuda et al. (2017) proposed an empirical correlation between the rotational speed of the inner cylinder (ω) and the effective shear-rate (γ_{eff}) as follows,

$$\gamma_{eff} = \left\{77.05n^{0.32}\left(\frac{R_i}{R_o}\right)^2 - 88.73n^{0.31}\left(\frac{R_i}{R_o}\right) + 26.85n^{0.21}\right\} \cdot \omega \tag{9}$$

In this simulation, the value of n, which is a rheological parameter in Carreau model, was 0.5. Using Eq. (9), the effective shear-rate can be estimated from ω and n easily. From these considerations, the effective viscosity can be estimated to calculate Re_{eff} using Eq. (8).

As shown in Fig. 3, the Nu_L increased with increasing Re_{eff} due to the enhancement of heat transfer at high Re_{eff}. Furthermore, the variation of Nu_L shows a sinusoidal periodicity in the axial direction as the result of the arrangement of Taylor vortices in a counter-rotating pair of vortices. This tendency is similar to the axial variation of the local Sherwood number at the outer cylinder measured by Kataoka et al. (1977).The maximum values of the Nu_L are observed at the outflow boundary regions, i.e. the regions where the fluid flow between two vortices creates a jet directed towards the outer cylinder, while the minimum values are observed at the inflow boundary regions where the fluid flow is directed towards the inner cylinder.

Figure 4 shows the dependency of the global Nusselt number, Nu_G, on Re for Newtonian and shear-thinning fluid system. It should be noted that the value of n in Carreau model was set at n = 1 for the simulation of Newtonian fluid. The global Nusselt number is defined as follows,

$$Nu_G = \int_0^L Nu_L \, dz \tag{10}$$

The Nu_G dramatically increases in Taylor vortex flow region for both Newtonian and shear-thinning fluid systems. This tendency agrees with the experimental and theoretical results by Aoki et al. (1967). As shown in Fig. 4, the performance of heat transfer for the shear-thinning fluid was deteriorated compared with the case of Newtonian fluid. It is inferred that the viscosity distribution caused by the shear-thinning property leads to the deterioration of fluidity. Above Re_{cr}, the theoretical and empirical equations of Nu_G are reported by Aoki et al. (1967), as follows,

$$Nu_{G} = A + B\left(1 - Re_{cr}^{2} / Re^{2}\right) \tag{11}$$

where A and B are constants. The value of A means the Nu_G in no vortex region, i.e. Couette flow region, while the value of B expresses the dependency of Nu_G on Re. The fitting lines based on Eq. (11) are also drawn in Fig. 4. The values of A and B are 4.5 and 3.4 for the shear-thinning fluid, and 20 and 0.35 for the Newtonian fluid, respectively. This means that the performance of heat transfer for the shear-thinning fluid in no vortex region was reduced compared with the Newtonian fluid. On the other hand, the dependency of Nu_G on Re for the shear-thinning fluid are greater than it for the Newtonian fluid. This difference would be explained by the effect of viscosity distribution in the annulus space. Thus, the empirically correlation equation of Nu_G using two parameters was constructed. In the future, the validity of the correlation equation and the physically detailed meaning of both parameters (A and B) will be investigated.

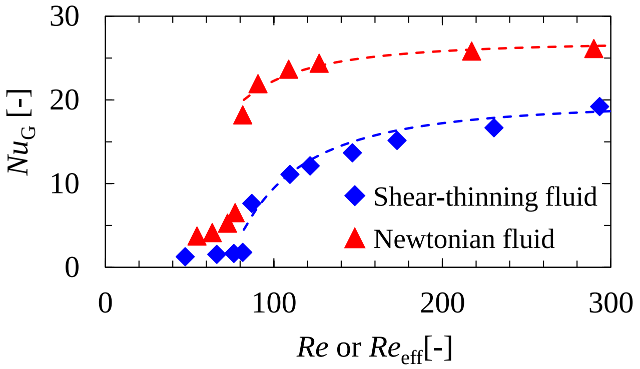

Figure 4: Dependency of global Nusselt number for shear-thinning fluid and Newtonian fluid

3. 2 Heat transfer of continuous Taylor–Couette flow

Figure 5 shows the axial distribution of temperature for the shear-thinning fluid at the middle of gap at u_{ax} = 0.124 cm/s. There was no vortex at ω = 50 rad/s, on the other hand, Taylor vortex flow was observed at ω = 80 rad/s in the whole region of apparatus. At ω = 65 rad/s, there was no vortex until z / L = 0.12. The rise in the temperature by heat transfer from the surface of outer cylinder causes the decrease in the fluid viscosity. This leads to the increase in the local Re_{eff}. After z / L = 0.12, Taylor vortices appeared because the local Re_{eff} exceeds Re_{cr}. The axial position where the temperature at the middle of gap reaches the heating temperature of 95%, T = 353.9 K, was z / L = 0.35 (ω = 50 rad/s), z / L = 0.13 (ω = 65 rad/s) and z / L = 0.10 (ω = 80 rad/s), respectively. In other words, Taylor vortices allows the fluid temperature to rapidly heating up to the target temperature. This would significantly affect the sterilization of liquid foods at the initial stage. The continuous TC flow system has the potential for intensification of heat sterilization process. In the future, the results of numerical simulation with a model of spores destruction will be investigated numerically.

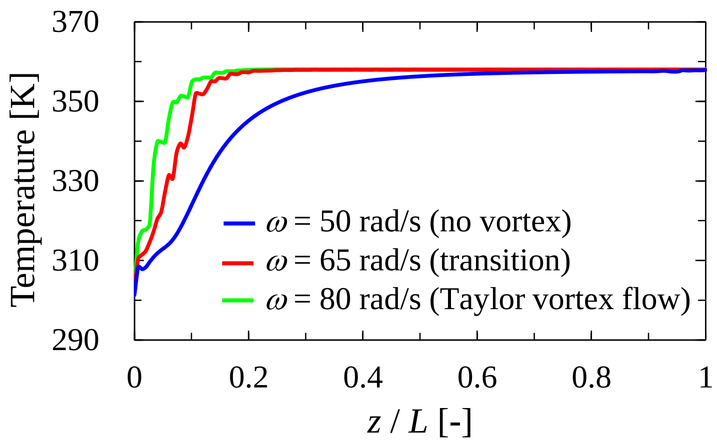

Figure 5: Axial distribution of temperature at middle of gap at u_{ax} = 0.124 m/s (shear-thinning fluid)

4. Conclusions

Towards intensification of heat sterilization process, TC flow system was utilized. Preliminarily, the performance of heat transfer of TC flow system was investigated using numerical simulation. The variation of Nu_L shows a sinusoidal periodicity in the axial direction as the result of the arrangement of Taylor vortices in a counter-rotating pair of vortices. Without the axial flow, the empirically correlation equation of Nu_L for the shear-thinning fluid was constructed using two parameters, *A* and *B*. The validation of the correlation equation will be experimentally conducted in the future. Heat transfer of TC flow with the axial flow was also investigated. The potential for intensification of heat sterilization process using TC flow system was successfully presented. In the future, the numerical simulation with a model of destruction will be conducted, including the evaluation of retention of quality factors which is modelled by the vitamin thiamine.

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