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Effect of Rheological Properties of Liquid Foods on Heat Sterilization Process in Taylor–Couette Flow Apparatus

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This study numerically investigates the effect of rheological liquid foods on heat sterilization process using Taylor–Couette flow sterilizer (TCFS). As model thermal processing, the destruction of Clostridium botulinum and thiamine was selected. It was found that the equivalent lethality slightly decreased with increase in the strength of shear-thinning property. On the other hand, there was no clear difference in the retaining performance of thiamine. Furthermore, the power consumption decreased with the increase in the strength of shear-thinning property. Thus, from the viewpoint of energy saving, it can be concluded that the utilization of TCFS to stronger shear-thinning food systems is more effective.

1. Introduction

Heat sterilization process is one of the most important process, which provide near complete inactivation of microorganisms including spores, in food industries. Commonly, a tubular heat exchanger or a plate heat exchanger are used as the typical sterilizer. From the practical viewpoint, there exist many problems in heat sterilization process for highly viscous foods. In the highly viscous food system, the flow condition in the sterilizer is often laminar, in which transport of momentum, heat, and mass is dominated by the molecular diffusion, due to the high viscous force. Thus, the efficient sterilization is not conducted by the traditional heat exchanger. The typical solution for the improvement of heat transfer is utilizing eddies in turbulence. However, a large amount of energy is required for reaching turbulence in highly viscous food systems. Furthermore, a high shear force in turbulence would induce a mechanical destruction of nutritional components (Ilo and Berghofer, 1998). Thus, how to enhance the transport rate of momentum, heat and mass under laminar flow should be discussed for intensification of heat sterilization. Kelder et al. (2002) applied Dean vortex flow, which appears in a curved pipe, to heat sterilization process even under laminar flow. Their results suggest that the velocity component in the radial direction, which is caused due to the toroidal motion of Dean vortex flow, enhances heat transfer from the wall to the bulk fluid. As a result, the performance of sterilization is significantly improved. Thus, process design of sterilization from the fluid from and heat transfer is effective.
Previously, in order to intensify heat sterilization process, Masuda et al. (2017, 2019) applied Taylor–Couette flow system to heat sterilization process. Taylor–Couette flow is the flow between two concentric cylinders with the inner one rotating. When Reynolds number in the circumferential direction, *Re*, exceeds a critical value (Re_{cr}), there appear pairs of counter-rotating toroidal vortices spaced regularly along the axis, arising from the basic shear flow, as shown in Figure 1. Due to the toroidal motion in vortices, heat/mass transfer as well as mixing is enhanced. Besides, all fluid elements leaving the annulus have the same residence time when a relatively small axial flow is imposed (Kataoka, 1975). Thus, TC flow sterilizer (TCFS) enables foods to experience excellent thermal treatments while every molecule has the same thermal history. In order to evaluate the sterilization performance of TCFS, it is necessary to understand not only sterilization efficiency but also how much nutritional constituents are retained after processing. Masuda et al. (2019) numerically

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investigated the performance of TCFS based on two model reactions: destruction of *Clostridium botulinum* and thiamine. They showed that Taylor vortices enhance heat sterilization process suppressing thermal destruction of nutritional components.
In order to establish heat sterilization process using TCFS, rheological properties of various foods should be taken into consideration. There is a wide variety of rheological properties of foods: Newtonian fluid, shear-thinning fluid, shear-thickening fluid, and viscoelastic fluid. In this study, the shear-thinning property was focused on because many foods (e.g. mayonnaise, milk, etc.) have the shear-thinning property. Fluid flow and heat transfer in Taylor–Couette flow system are influenced by the shear-thinning property (Masuda et al., 2019). The viscosity distribution, caused by the shear-thinning property, in the annular spaces decreases the fluidity. This leads the decrease in local Nusselt number. Thus, it is necessary to understand the effect of degree of shear-thinning property on heat sterilization process. The objective of this study is to numerically investigate such effect by varying the rheological parameter which expresses the degree of shear-thinning property. For two types of shear-thinning foods, lethality development , nutrient retention and power consumption was evaluated.

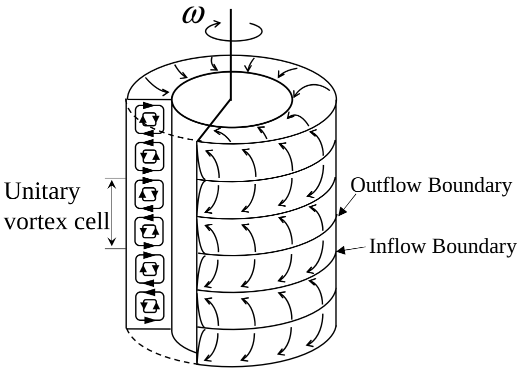

Figure 1: Schematic picture of Taylor–Couette flow

2. Numerical simulation

2.1 Governing equations

The liquid food was considered as an incompressible fluid having the shear-thinning fluid in a steady state. In a three-dimensional simulation, governing equations are conservation equations of mass, momentum, heat, and chemical species as shown in Eqs. (1)-(4):

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

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

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

$$\mathbf{u} \cdot \nabla C = \nabla \cdot (D_{\mathrm{C}} \cdot \nabla C) + S \tag{4}$$

where $\mathbf{u}$ is the velocity, p is the pressure, ρ is the density, η is the viscosity depending on the shear-rate, $\mathbf{D}$ (= ($\nabla\mathbf{u}$ + $\nabla\mathbf{u}^{\mathrm{T}}$) / 2) is the rate of deformation tensor, $\mathbf{g}$ is the gravitational acceleration, α is the coefficient of volume expansion, T is the temperature, T_{ref} is the reference temperature, λ is the thermal conductivity, C_{p} is the specific heat capacity, C is the concentration, D_{c} is the diffusion coefficient, and S is the scalar source term. Accumulation terms in governing equations were removed because the steady state was assumed.
In this study, in order to express the relationship between the apparent viscosity and the shear-rate, Carreau model was used as shown in Eq. (4).

$$\eta = \eta_0[1 + (\beta \cdot \dot{\gamma})^2]^{(n-1)/2} \tag{5}$$

where η_0 is the zero shear-rate viscosity, β is the characteristic time, and n is the power-law exponent. Here, n is the slope of decreasing viscosity with the shear-rate. Furthermore, the dependence of apparent viscosity on the temperature was added to Eq. (5) because shear-thinning fluids are usually sensitive to the temperature. The dependence was expressed by Arrhenius function:

$$\eta = \eta_{\mathrm{eff}} \exp\left[\frac{E}{R}\left(\frac{1}{T} - \frac{1}{T_{\mathrm{ref}}}\right)\right] \tag{6}$$

where *E* is the activation energy and *R* is the gas constant. By combining Eqs. (5) and (6), the viscosity constitutive equation is represented as

$$\eta = \eta_0 \exp\left[\frac{E}{R}\left(\frac{1}{T} - \frac{1}{T_{\mathrm{ref}}}\right)\right]\left[1 + (\beta \cdot \dot{\gamma})^2\right]^{(n-1)/2} \tag{7}$$

In this study, two types of shear-thinning fluids were used: a moderate shear-thinning fluid (n = 0.5) and a strong shear-thinning fluid (n = 0.3). Figure 2 shows rheological properties of model fluids at T = 395.65 K.

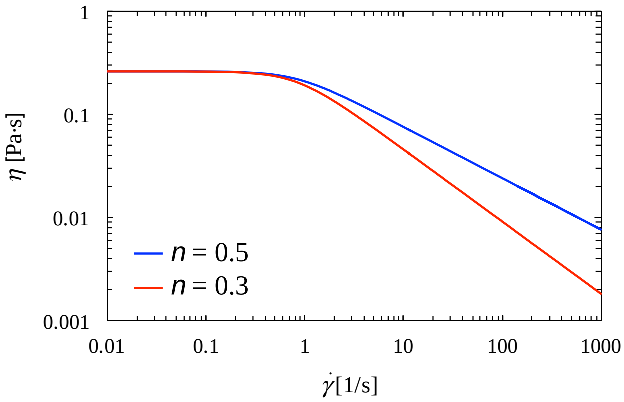

Figure 2: Rheological properties of fluids

In this study, T_{ref} was set to 293.15 K, the value of η_0 was 0.27 Pa·s at 395.65 K, and β and E were 1.2 s and 26.1 kJ/mol. Other physical and thermal properties of 1.0wt% hydroxymethylcellulose aqueous solution was selected as that of model fluids. Thus, physical and thermal properties including ρ, α, C_p, and λ, were 1003 kg/m^3, 3.30 × 10^{-4} 1/K, 3.71 kJ/kg·K, and 0.534 W/m·K, respectively (Kaminoyama et al., 1999).

2.2 Computational system

A computational domain of TCFS is shown in Figure 2. TCFS 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).

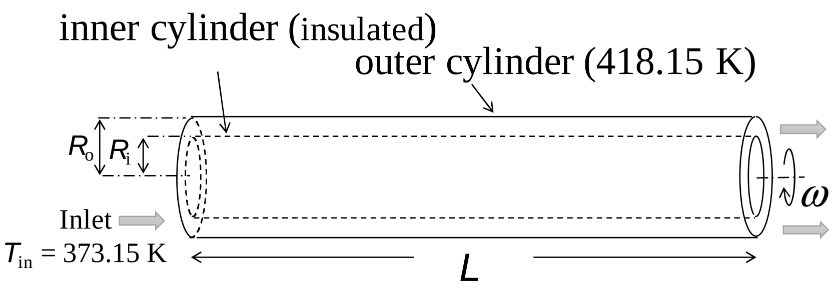

Figure 3: Computational domain of Taylor–Couette flow sterilizer (TCFS)

The boundary conditions were as follows:
1) Inlet boundary conditions: The constant axial inlet velocity of fluid, u_z, with T_{in} = 373.15 K was set at u = 5.0 × 10^{-4} m/s. Thus, the residence time, $\tau = L / u$, was 300 s. The initial concentration of thiamine at the inlet, C_0, was assumed to be 40 mg/L.
2) Outer cylinder boundary conditions: All components of velocity were 0 m/s; the temperature, T_o, was set at 418.15 K.
3) Inner cylinder boundary conditions: The circumferential velocity, u_θ, was given by ωR_i [m/s]; the axial and radial velocities were 0 m/s; no heat/mass transfer.
4) Outlet boundary conditions: The pressure at the outlet was set at 0.

Actually, in order to avoid back flows, an extended section was imposed (Masuda et al., 2019). For simulations, OpenFOAM® 4.0 code was utilized. The governing equations were discretized based on a finite volume method. The second-order QUICK (Quadratic Upstream Interpolation for Convective Kinematics) scheme was applied to the convection term, and the second-order central difference scheme was applied to a viscous term. For the convection term in the conservation equation of chemical species, the total variation diminishing (TVD) scheme was applied to the convection term (Srinivasan et al., 2005). The Semi Implicit Method for Pressure Linked Equations (SIMPLE) method was used for pressure-velocity coupling. The number of cells was 901,120 (32 × 128 × 220, in radial, circumferential, and axial directions, respectively). It is noted that the validation of simulation code and the optimization of the number of cells were already conducted by Masuda et al. (2019).

2.3 Model reactions

In this study, two reactions (destruction of *Clostridium botulinum* spores and thiamine) were assumed to evaluate the performance of TCFS. *Clostridium botulinum* spores presence in foods is a significant threat to public health, and for this reason, the destruction of its spores is quite important (Chotyakul et al., 2011). With respect to the destruction of spores, a first-order reaction model is widely used. Besides, as a representative example of thermal destruction of vulnerable constituents, the destruction of the vitamin thiamine was selected. The thermal destruction of thiamine is appropriately expressed by a second-order reaction. The detailed procedure for the implementation to simulations is described in the paper by Kelder et al. (2002) or Masuda et al. (2019). Briefly speaking, the degree of destruction of *Clostridium botulinum* spores was evaluated based on the equivalent lethality (F_0), and the retaining of thiamine was estimated from the residual concentration of thiamine at each axial position. It is noted that F_0 was calculated from the temperature field obtained by numerical simulations while the thiamine concentration was directly calculated by solving Eq. (4).

3. Results and discussion

In order to discuss from the viewpoint of fluid flow and heat transfer, the definition of *Re* is quite important in shear-thinning fluid systems. Because the viscosity spatially changes due to the shear-thinning property, the definition of effective *Re* (Re_{eff}) based on the effective viscosity (η_{eff}) in the system is necessary. The method to determine Re_{eff} for Taylor–Couette flow systems proposed by Masuda et al. (2017, 2019) was used in this study. Re_{eff} in the circumferential direction was varied from 0 to 172.6. In this Re_{eff} region, the flow condition corresponds from Couette flow to laminar Taylor vortex flow.

Figure 4 shows the axial distribution along the axis for (a) the equivalent lethality (F_0) and (b) the normalized bulk concentration of thiamine (C_{b}^*) at Re_{eff} = 101.1. The normalized bulk concentration is obtained as follows:

$$C_{\mathrm{b}}^* = \frac{C_{\mathrm{b}}}{C_0} \tag{8}$$

where C_{b} is the bulk concentration of thiamine and is expressed by

$$C_{\mathrm{b}} = \frac{\int_{R_{\mathrm{i}}}^{R_{\mathrm{o}}} u_{\mathrm{z}} C \cdot 2\pi r \mathrm{d}r}{\int_{R_{\mathrm{i}}}^{R_{\mathrm{o}}} u_{\mathrm{z}} \cdot 2\pi r dr} \tag{9}$$

As shown in Fig. 4 (a), the slight difference in F_0 between n = 0.3 and 0.5 was observed. At same Re_{eff}, the outflow of Taylor vortices from the inner cylinder to the outer cylinder becomes weak with the increase in the degree of shear-thinning property (Masuda et al., 2019). This leads the increase in the thickness of velocity boundary layer and temperature boundary layer at the surface of outer cylinder. As a result, the heat flux from the surface of outer cylinder decreased with the increase in the degree of shear-thinning property at same Re_{eff}. This difference in the heat flux caused the decrease in F_0 at n = 0.3. Nevertheless, it should be noted that Taylor vortices generated in the annular space significantly enhanced heat transfer from the outer surface due to the velocity component in the radial direction of Taylor vortices. As a result, the equivalent lethality also improved, and this increase was regarded as a quantum leap which is the one of the most important for process intensification (Masuda et al., 2019). Figure 4 (b) indicates that C_{b}^* monotonically decreased along the axis because heat transfer from the outer surface induces the thermal destruction of thiamine. There is no crucial difference between n = 0.5 and 0.3 in C_{b}^*. This means that the rheological properties of foods are not so sensitive to the retaining performance of nutritional components. It is considered that there is a trade-off relationship between the enhancement of heat transfer and the avoidance of thermal destruction of nutritional constituents. Furthermore, in order to establish an optimum heat sterilization process using TCFS, the discussion from the viewpoint of power consumption should be conducted.

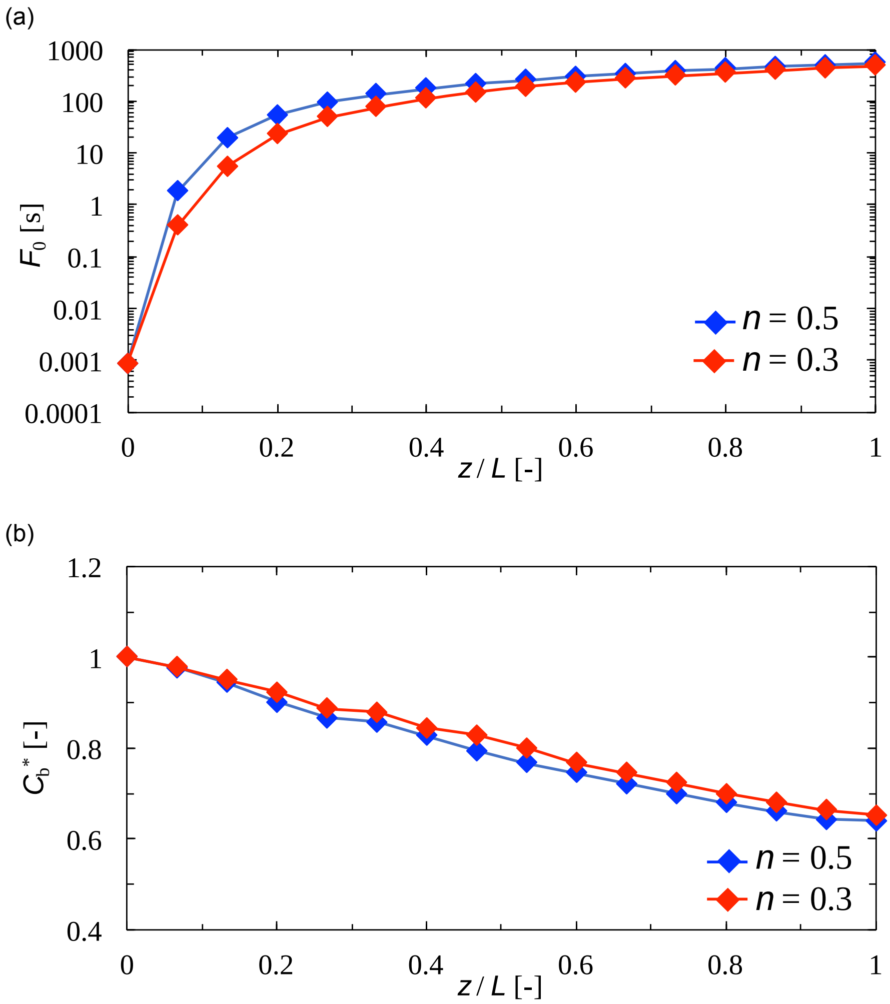

Figure 4: Axial distribution along the axis: (a) lethality, (b) normalized bulk concentration of thiamine

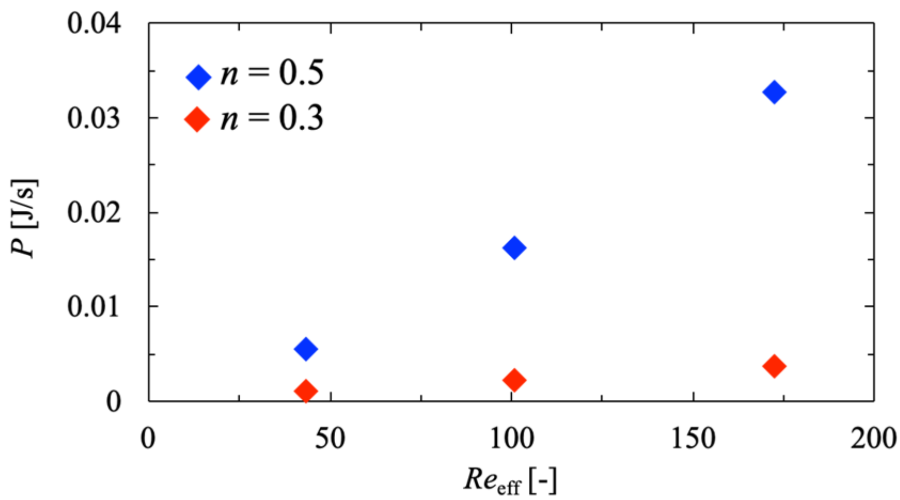

Figure 5: Dependence of power consumption on Re_{eff}

Figure 5 preliminarily shows the dependence of power consumption of TCFS, P, on Re_{eff}. The power consumption is defined as follows

$$P = \omega R_i \iint \tau_{r\theta} \, dA \tag{10}$$

where $\tau_{r\theta}$ is the component of shear stress tensor at the surface of the inner cylinder obtained from the numerical simulations and d*A* is the differential surface of the inner cylinder. As clearly shown in Fig. 5, *P* decreased with the increase in the degree of shear-thinning property at same Re_{eff}. This is because the decrease in the apparent viscosity by the shear force generated by the rotation of the inner cylinder is improved by the increase in the degree of shear-thinning property. As a result, it is possible to suppress the power consumption in more stronger shear-thinning fluids.

4. Conclusion

This study numerically investigated the effect of rheological properties of foods on heat sterilization process using Taylor–Couette flow sterilizer (TCFS). The following conclusions were deduced:

1. The equivalent lethality slightly decreased with the increase in the degree of shear-thinning property. This can be explained by the fact that the shear-thinning property weaken the heat flux from the surface for outer cylinder. On the other hand, there was no clear difference in the retaining performance of nutritional components.
2. The power consumption decreased with increase in the degree of shear-thinning property at same effective Reynolds number. This is because the decrease in the apparent viscosity by the shear force generated by the rotation of the inner cylinder is improved by the increase in the degree of shear-thinning property.

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