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Enhancement of Heat Transfer Using Taylor Vortices in Thermal Processing for Food Process Intensification

Hayato Masuda

Abstract

We are witnessing a transition from the traditional to novel processing technologies in the food industry to address the issues regarding energy, environment, food, and water resources. This chapter first introduces the concept of food process intensification based on vortex technologies to all food engineers/researchers. Thereafter, the novel processing methods for starch gelatinization/hydrolysis and heat sterilization based on Taylor–Couette flow are reviewed. In fluid mechanics communities, the Taylor–Couette flow is well-known as a flow between coaxial cylinders with the inner cylinder rotating. Recently, this unique flow has been applied in food processing. In starch processing, enhanced heat transfer through Taylor vortex flow significantly improves gelatinization. In addition, effective and moderate mixing leads to an increase in the reducing sugar yield. In sterilization processing, the enhanced heat transfer also intensifies the thermal destruction of *Clostridium botulinum*. However, a moderate heat transfer should be ensured because excessive heat transfer also induces thermal destruction of the nutritional components. The Taylor–Couette flow is only an example considered here. There are various flows that intensify the heat/mass transfer and mixing in food processing. It is expected that this chapter will stimulate the development of food processing based on fluid technologies, toward food process intensification.

Keywords: food process intensification, thermal processing, Taylor–Couette flow, starch hydrolysis, heat sterilization

1. Introduction

In manufacturing processes, including those specific to the food industry, sustainable development is necessary because there is a limit on the energy and other resources. To achieve this goal, chemical industries have considered process intensification (PI) that might result in a paradigm shift. Although the definition of PI is still under discussion, a dramatic reduction in the process size is one of the common goals. One of the methods to achieve size reduction is the enhancement of transport rates, such as momentum, heat, and mass. For example, Harvey [1] successfully showed that, in the ester saponification process, the apparatus size was reduced by one-tenth compared with a traditional batch reactor, using an oscillatory baffled

reactor exhibiting an excellent mixing performance. Therefore, PI technologies would bring about innovation in all the manufacturing processes. In fact, the introduction of PI technologies has promoted various processes, for example, biopharmaceutical processes [2, 3]. The concept of PI should also be applied to food processing to establish energy/resource-saving processing. However, PI has not gained significant attention in the food industry. Boom et al. [4] analyzed three reasons for this: 1) food processing is largely based on traditional methods; 2) processing costs represent a small fraction of the total cost of food production, with the raw material representing the major portion of the total cost in most cases; and 3) the requirement of absolute food safety is a necessary obstacle to processing innovation. However, we should consider the transition from traditional food processing to novel processing by leveraging PI technologies, considering the environment, energy, and increasing population.

Few researchers have attempted to accomplish food process intensification by controlling fluid (liquid food) motion to enhance the mixing and heat/mass transfer. For example, Müller et al. [5] proposed a novel UV-C treatment device for juices based on the Dean vortex technology. Dean vortex flow occurs in a coiled tube owing to centrifugal instability [6]. They successfully showed that the Dean vortex flow promoted the inactivation of microorganisms because the fluid element is more frequently transported to the irradiation region through convective motion. Zhang et al. [7] successfully demonstrated the efficient manufacturing method of *Fuzhu* (also known as *Yuba*) through Rayleigh–Bénard convection. Rayleigh–Bénard convection is the flow between horizontal planes whose temperature at the lower plane is higher than that at the upper plane [8]. The driving cause underlying the Rayleigh–Bénard convection is the local distribution of the fluid density. Therefore, the novel concept based on fluid engineering has the potential for innovation in food processing.

In this chapter, aiming toward food process intensification, the application of a unique vortex flow between rotating cylinders (Taylor–Couette flow) to thermal processing is introduced.

2. Taylor–Couette flow

Taylor [9] first discovered and analyzed the unique vortex flow generated between cylinders with the inner cylinder rotating. This flow experiences several transitions with an increase in the rotational speed of the inner cylinder. The flow dynamics are characterized by the Reynolds number [$Re = \rho R_i \omega d / \eta$] in the circumferential direction, where ρ , R_i , ω , d , and η are the fluid density, inner cylinder radius, rotational speed of the inner cylinder, gap width, and fluid viscosity, respectively. At a relatively low Re , a Couette flow is observed with no pressure gradient in the flow direction. When Re exceeds a critical Re (Re_{cr}), toroidal vortices appear to be counter-rotating, spaced regularly along the axis, as shown in **Figure 1**. These vortices are called Taylor vortex flows. In addition, each vortex cell is called a Taylor cell. The value of Re_{cr} that depends on the radius ratio R_i/R_o , was theoretically derived by Taylor [9]. After the initial transition, as Re increases, the Taylor vortex flow cascadingly transitions to a singly periodic wavy vortex flow, quasi-periodic wavy vortex flow, and weakly turbulent wavy vortex flow [10, 11]. Finally, the flow develops into a fully turbulent vortex flow. The dynamics of the Taylor–Couette flow are interesting from the viewpoint of not only fluid mechanics, but also process engineering because this flow system has few advantageous characteristics as a reactor. First, mixing and heat/mass transfer are enhanced by the toroidal motion within the Taylor cells. Second, each Taylor cell is extruded through a single

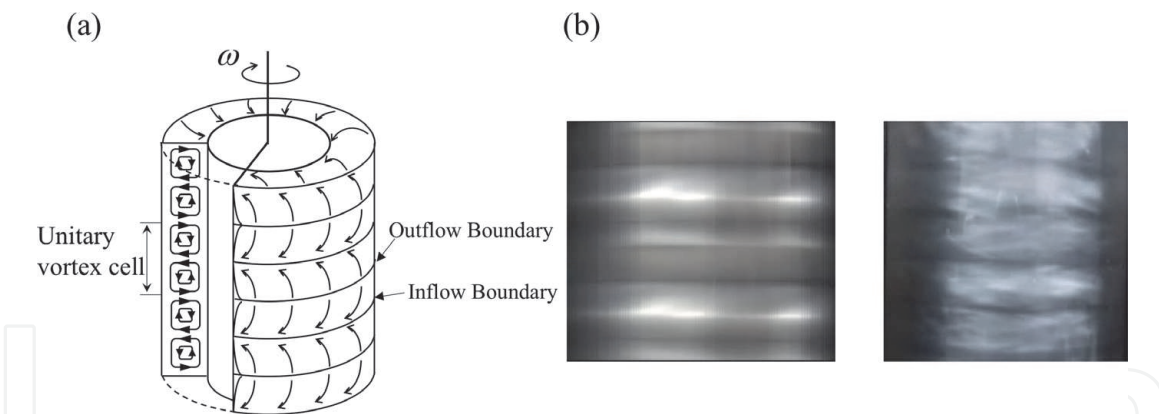


Figure 1. Taylor–Couette flow: (a) schematic picture and (b) flow visualization. The left and right figures show the laminar Taylor vortex flow and wavy vortex flow, respectively. The black band corresponds to inflow boundaries.

file without breakdown when a small axial flow is added. In addition, mass transfer between the Taylor cells is prevented by an inward boundary where an inward secondary flow is formed. This implies that the axial dispersion that is a negative factor for uniform processing, is suppressed, while local mixing and heat/mass transfer are enhanced. Therefore, the continuous and uniform production is possible using this flow system as a reactor. Since Kataoka et al. [12] reported the excellent performance of Taylor–Couette flow in a chemical reactor, Taylor–Couette flow has been applied to various chemical processes, such as emulsion polymerization [13], photocatalytic reaction [14], particle synthesis [15], reverse osmosis [16], particle classification [17], and gas absorption [18]. According to these studies, the Taylor–Couette flow reactor has the potential to effectively intensify the processes compared with a traditional reactor, such as stirred tank reactor. In fact, among the chemical engineering communities, it is well-known that the Taylor–Couette reactor enables PI. Furthermore, few researchers have suggested that the Taylor–Couette flow apparatus is suitable for processes with shear-sensitive materials, such as food and bio-processes because the local strong shear force is absent. Haut et al. [19] applied the Taylor–Couette flow to the cultivation of CHO cells and reported the possibility of the Taylor–Couette flow-based bioreactor. To the best of our knowledge, the research conducted by Giordano et al. [20] is the first attempt of applying the Taylor–Couette flow in food processes. They showed that fructose–glucose isomerization could be efficiently conducted using a Taylor–Couette flow reactor. Subsequently, few researchers reported the excellent performance of Taylor–Couette flow in the non-thermal inactivation of bacteria in juice [21–23]. Although the application of Taylor–Couette flow to food processes is rather limited to non-thermal processing, efficient heat transfer by Taylor vortices should be utilized in thermal processing. Few research groups including the author have been trying to intensify thermal food processing based on Taylor–Couette flow. The intensification of starch processing and heat sterilization is introduced in this chapter.

3. Food process intensification using Taylor–Couette flow

3.1 Intensification of starch processing

Starch is typically a biopolymer that consists of 25% amylose (linear structure) and 75% amylopectin (branched structure). Detailed information on starch from the viewpoint of chemistry is reviewed in other articles [24]. Starch processing is frequently encountered in the manufacturing process of various types of food, such

as beer, beverages, bread, and sauce. From a practical viewpoint, one of the most important types of starch processing is starch hydrolysis that comprises gelatinization, liquefaction, and saccharification. Enzymatic hydrolysis is described in this chapter because it is more prevalent than the other starch modifications, such as thermal and chemical treatment [25, 26]. In the starch hydrolysis process, the fluid viscosity intricately changes, as shown in **Figure 2**.

A significant increase in the viscosity was observed during gelatinization. Further, when enzyme (α -amylase) is added, the viscosity decreases as starch chains are broken down into glucose, maltose, maltotriose, and few higher oligomers. This intricate viscosity change is not favorable to the food engineers because the key operation is different between gelatinization and enzymatic liquefaction/saccharification processes. During gelatinization, heat transfer from the heated surface due to starch suspension and mass transfer between starch grains and water are required. In liquefaction/saccharification, highly efficient mixing of gelatinized starch and a small amount of enzyme is the most important operation. Therefore, individual apparatuses must be used. Consequently, the total size of starch hydrolysis process becomes large, as Baruque et al. indicated [28].

To make the total size compact, Baks et al. proposed the simultaneous and continuous processing of gelatinization and liquefaction/saccharification using an extruder [29, 30]. As shown in their studies, even at a high concentration of starch (600 g/L), gelatinization was completely conducted using the extruder. However, a high shear force was applied to the starch suspension in the extruder. This high shear force induces inactivation of the enzyme (α -amylase) [31, 32]. Therefore, other apparatuses such as stirred vessels are necessary for liquefaction/saccharification after gelatinization [30]. Paolucci-Jeanjean et al. [33] proposed a unique membrane reactor to conduct enzymatic hydrolysis using only one apparatus. However, the starch concentration was limited to 150 g/L because of the absence of mechanical agitation.

To intensify starch hydrolysis using a single apparatus, Masuda et al., Hubacz et al., and Matsumoto et al. applied a Taylor–Couette flow reactor for continuous starch hydrolysis [27, 34–39]. The features of the Taylor–Couette flow are described in the previous section. Taylor–Couette flow enhances not only mixing, but also heat/mass transfer. Therefore, it is expected that both gelatinization, where

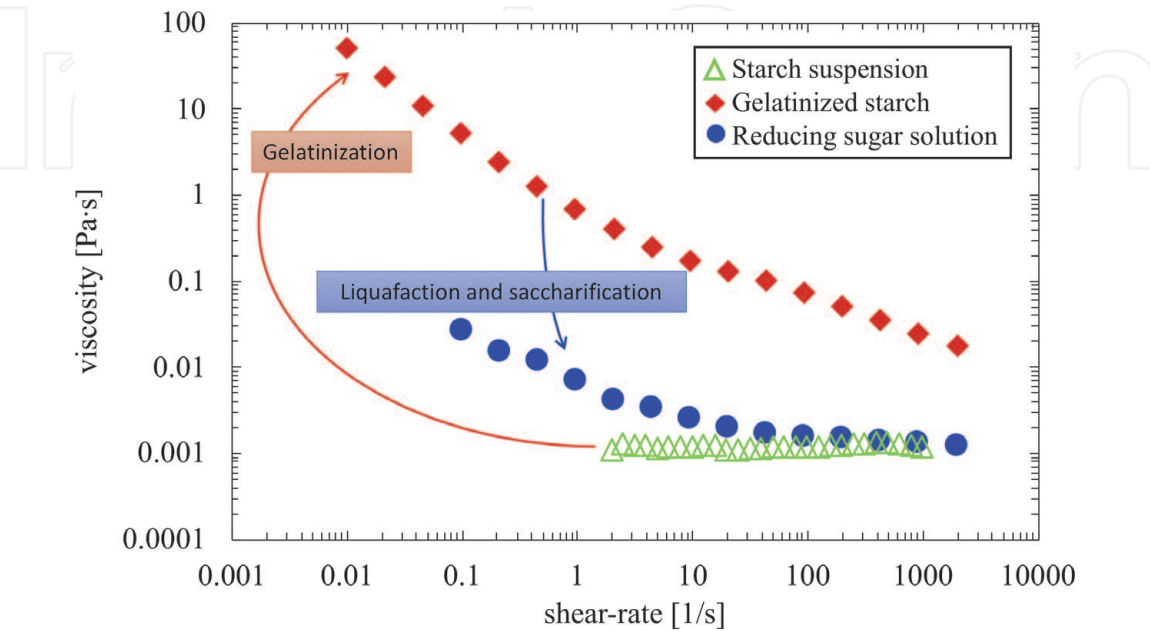


Figure 2. Viscosity change at various shear rates during starch gelatinization/liquefaction/saccharification [27].

heat/mass transfer is necessary and liquefaction/saccharification, where mixing is necessary, are intensified using a single Taylor–Couette flow reactor.

As an example, a Taylor–Couette flow reactor utilized by Masuda et al. [35] is shown in **Figure 3**. The reactor consisted of a rotating inner cylinder, a stationary outer cylinder, and two divided water jackets. A starch suspension was introduced into the inlet. The enzyme was continuously fed using a syringe pump from the port set in the middle of the reactor. Therefore, the first and second half parts of the reactor were regarded as corresponding to the gelatinization and liquefaction/saccharification processes, respectively. High-temperature water was pumped in the first water jacket to promote gelatinization. Furthermore, moderate temperature water was pumped into the second water jacket to avoid the thermal deactivation of α -amylase.

The effects of Taylor vortices on starch gelatinization and hydrolysis were experimentally and numerically investigated in detail. **Figure 4** shows the impact of Taylor vortex flow on the degree of starch gelatinization (DSG). A high value of DSG was obtained when Taylor vortices were formed because the Taylor vortex flow enhanced the heat transfer from the heating surface. It should be noted that microscopic mass transfer around the starch granules was not considered in their simulation [36].

However, ascertaining whether Taylor vortices are formed within the reactor is not straightforward because the reactor is enwrapped in water jackets made of stainless steel. Therefore, to simulate the fluid flow in the reactor during starch gelatinization, Hubacz et al. [36] empirically established a mathematical model to describe the change in the rheological properties in response to gelatinization, as follows:

$$\eta = \frac{(0.0013DSG + 0.0031)}{1312^{n-1}} \dot{\gamma}^{n-1}, \tag{1}$$

where n [–] and $\dot{\gamma}$ [1/s] are the rheological model parameter and shear rate, respectively. **Figure 5** shows the axial velocity distribution near the inlet when the initial concentration of starch, C_0 , is 50 g/L at the following values of ω : (a) 10 and (b) 22 rad/s. As clearly shown in **Figure 5**, at $\omega = 10$ rad/s, it is confirmed that there

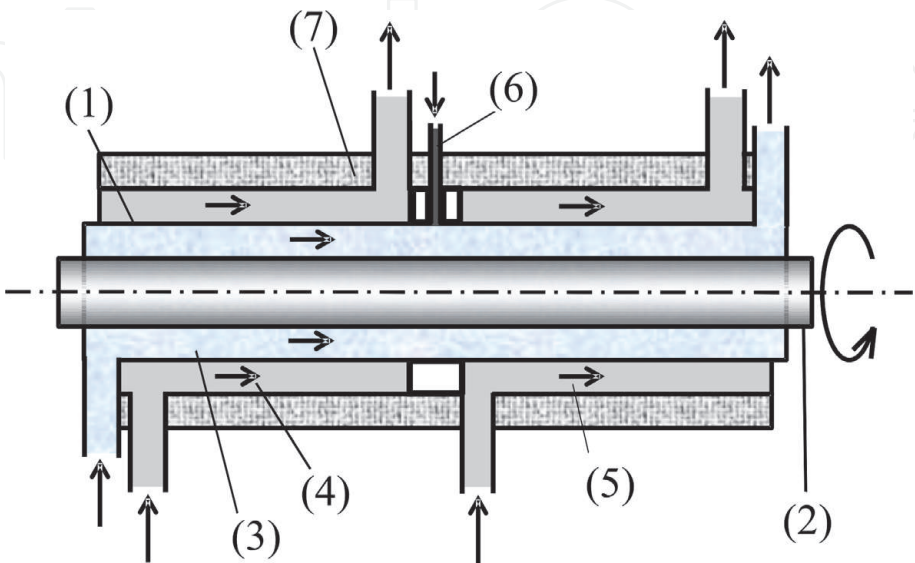


Figure 3. Taylor–Couette flow reactor used for starch processing [35]: (1) stationary outer cylinder, (2) rotational inner cylinder, (3) starch suspension, (4) hot water for gelatinization, (5) variable temperature water for enzymatic reaction, (6) enzyme injection port, (7) insulator.

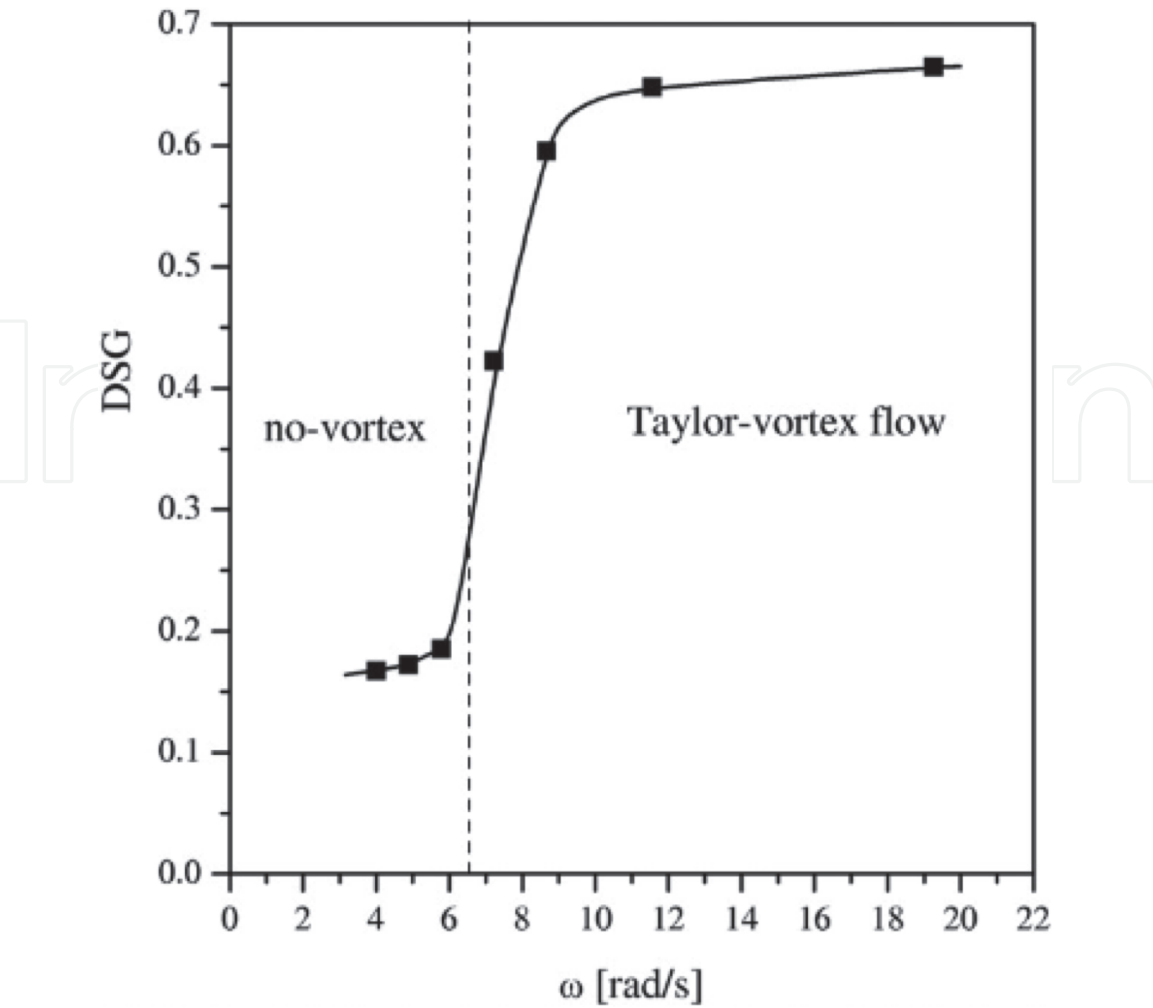


Figure 4. Dependence of DSG (degree of starch gelatinization), obtained via two-dimensional simulation, on the rotational speed of inner cylinder (ω) [36]. The water jacket temperature, T_{hj} , was assumed to be 65°C.

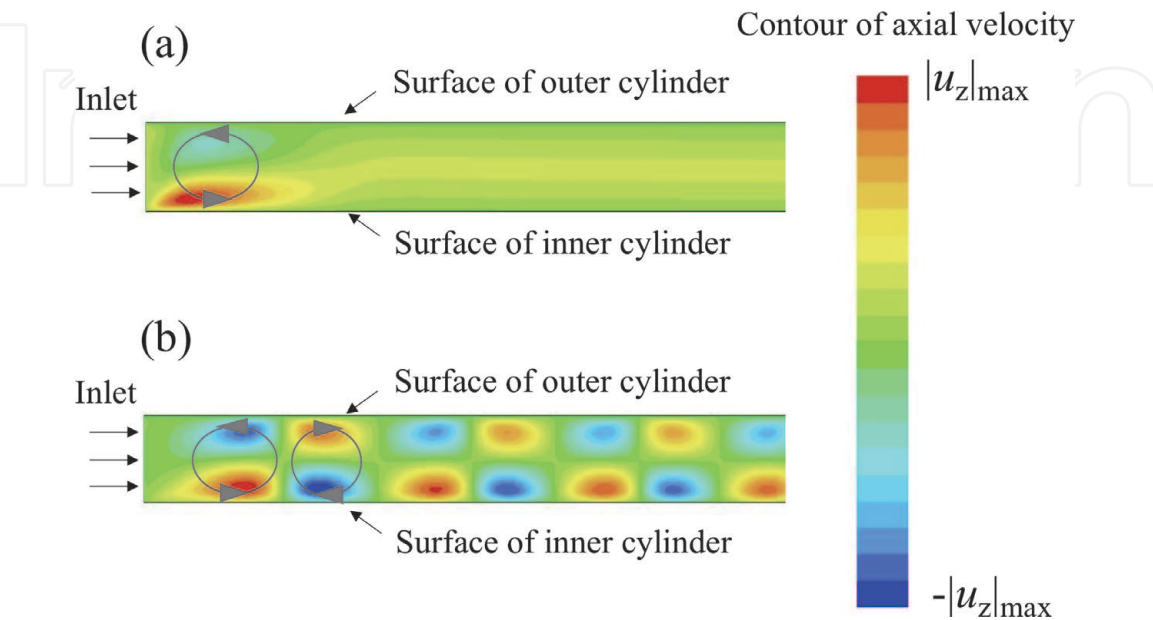


Figure 5. Velocity distribution near the inlet during gelatinization at $C_o = 50$ g/L, $\omega =$ (a) 10 rad/s and (b) 22 rad/s. The circles in the figures denote vortex motion.

are no Taylor vortices, except near the inlet because of the lower centrifugal force. Therefore, the rheological model is reasonably advantageous for the practical design of the starch gelatinization process based on Taylor–Couette flow. In addition, as Van Den Einde et al. [40] indicated, starch granule degradation by thermomechanical treatment should also be considered. Hubacz et al. [36] confirmed that, as shown in **Figure 6**, there was no mechanical destruction of starch granules, and thermal degradation was not visible. Therefore, Taylor–Couette flow is suitable for the intensification of starch gelatinization owing to the efficient heat transfer without violent shear force.

The Taylor–Couette flow reactor intensifies starch gelatinization and liquefaction/saccharification. **Figure 7** shows that the relationship between the concentration of reducing sugar and effective Reynolds number at $C_0 = 50, 150, \text{ and } 300 \text{ g/L}$ for the axial velocity u of 0.024 cm/s . It is noted that the flow condition was evaluated by the effective Reynolds number Re_{eff} because the apparent viscosity spatially changes due to the shear-thinning property of starch suspension. The detailed procedure for defining and calculating Re_{eff} is described in a paper by Masuda et al. [41]. As clearly shown in **Figure 7**, a higher yield of reducing sugar is obtained through the operation above Re_{cr} (dashed line in the figure) in all cases of C_0 . Remarkably, starch is continuously and efficiently hydrolyzed even at relatively high concentrations of the starch suspension. The maximum yield is comparable to that obtained using a stirred batch reactor. Therefore, the conversion from batch to continuous is possible for food process intensification. However, a slight decrease in the yield was observed at higher Re_{eff} values. This decrease is explained by the axial

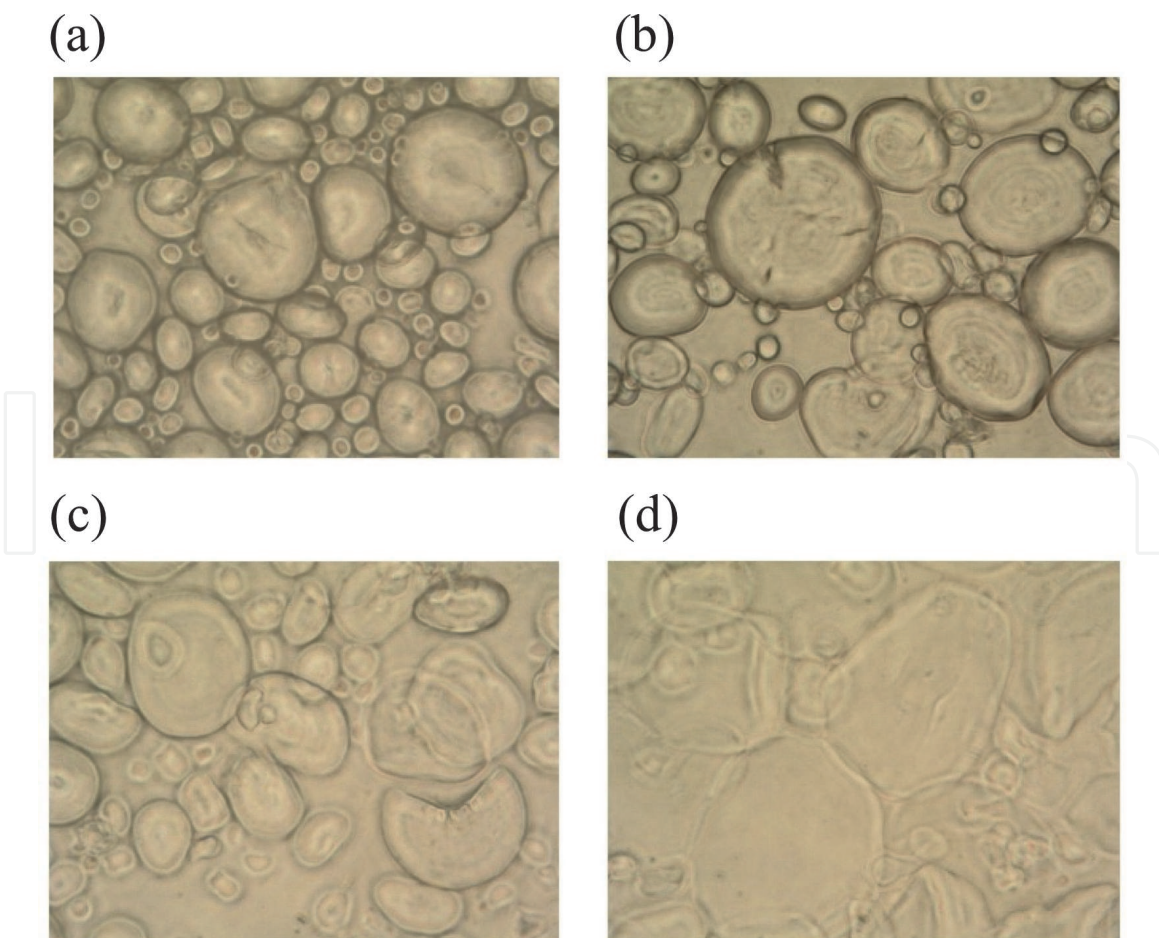


Figure 6.
Structure of starch observed using a light microscope: (a) native starch, gelatinized starch after treatment at (b) $u = 0.099 \text{ cm/s}$, $\omega = 11.56 \text{ rad/s}$, $T_{hj} = 60^\circ\text{C}$, (c) $u = 0.099 \text{ cm/s}$, $\omega = 19.56 \text{ rad/s}$, $T_{hj} = 65^\circ\text{C}$ and (d) $u = 0.099 \text{ cm/s}$, $\omega = 19.56 \text{ rad/s}$, $T_{hj} = 85^\circ\text{C}$ [36].

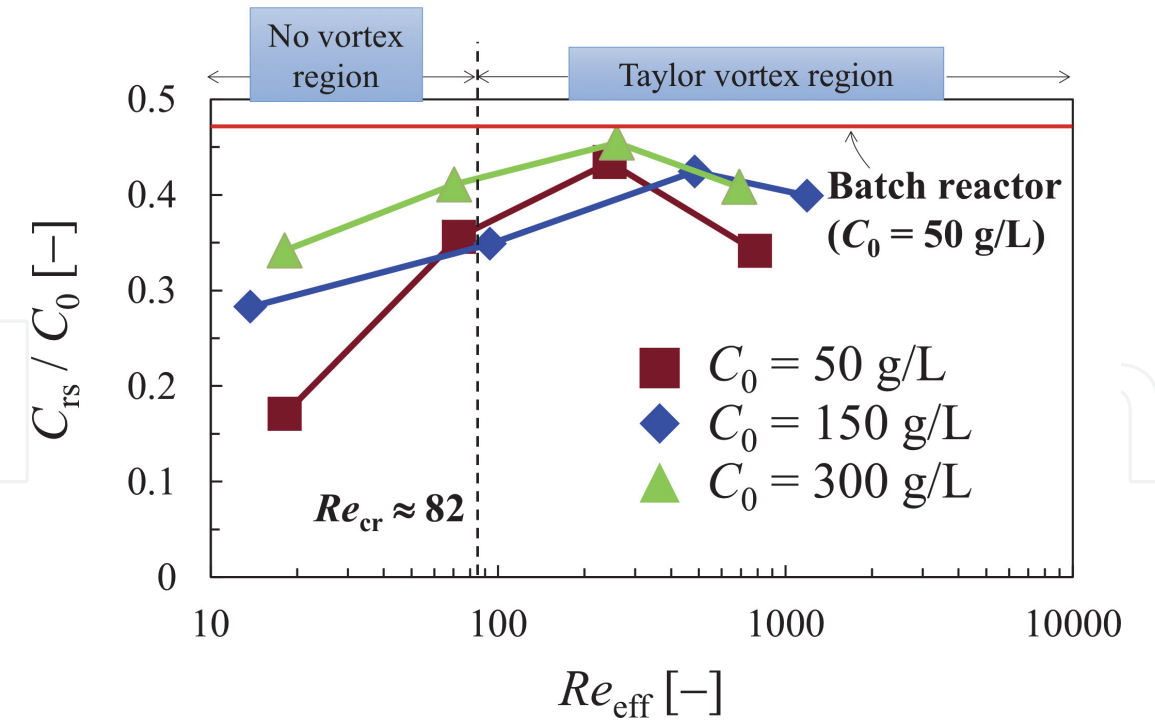


Figure 7. Relation between the yield of reducing sugar (C_{rs}/C_0) and effective Reynolds number (Re_{eff}) at $C_0 = 50, 150, 300$ g/L, $u = 0.024$ cm/s, $T_{hj} = 45^\circ\text{C}$ [39]. The dashed line denotes the critical Re (Re_{cr}) where Taylor vortices are fully formed.

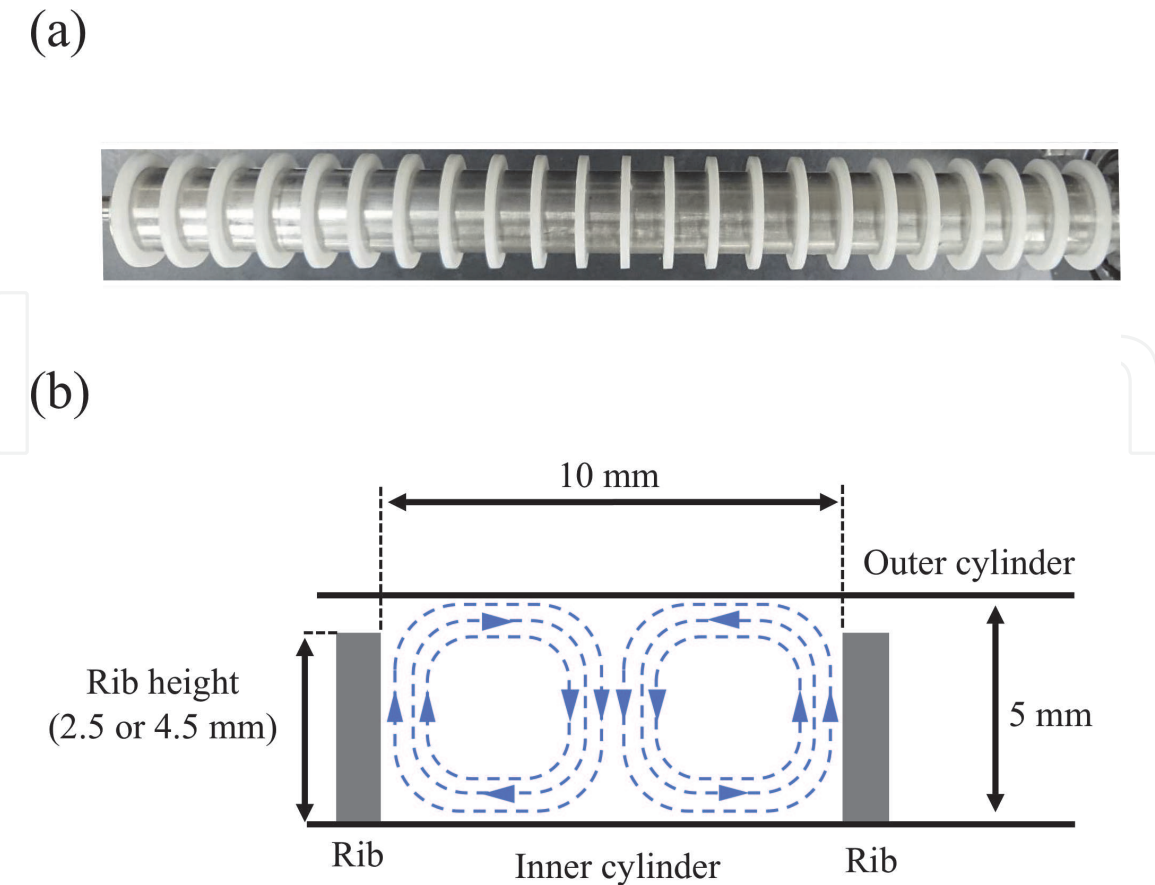


Figure 8. Ribbed inner cylinder system [27]: (a) picture and (b) cross-sectional view of a pair of Taylor vortices between ribs.

dispersion and destabilization of the vortex structure during the enzymatic reaction [27]. At higher Re , a wavy motion is observed (called the wavy Taylor vortex flow). The wavy vortex flow significantly enhances mixing and heat/mass transfer within Taylor cells; furthermore, this also leads to axial dispersion through by-pass flow [42]. According to Richter et al. [43, 44], Taylor vortices can be stabilized and immobilized by a ribbed inner cylinder, as shown in **Figure 8**.

Consequently, the axial dispersion was suppressed even at a higher Re . Masuda et al. [27] successfully showed that the decrease in the yield at a higher Re_{eff} is suppressed by the equipment of ribs in the inner cylinder, as shown in **Figure 9**. Furthermore, as shown in **Figure 10**, the yield of small saccharides (glucose, maltose, and maltotriose) was significantly enhanced by utilizing the ribbed inner cylinder. This is because the ribbed inner cylinder enables the enhancement of mixing,

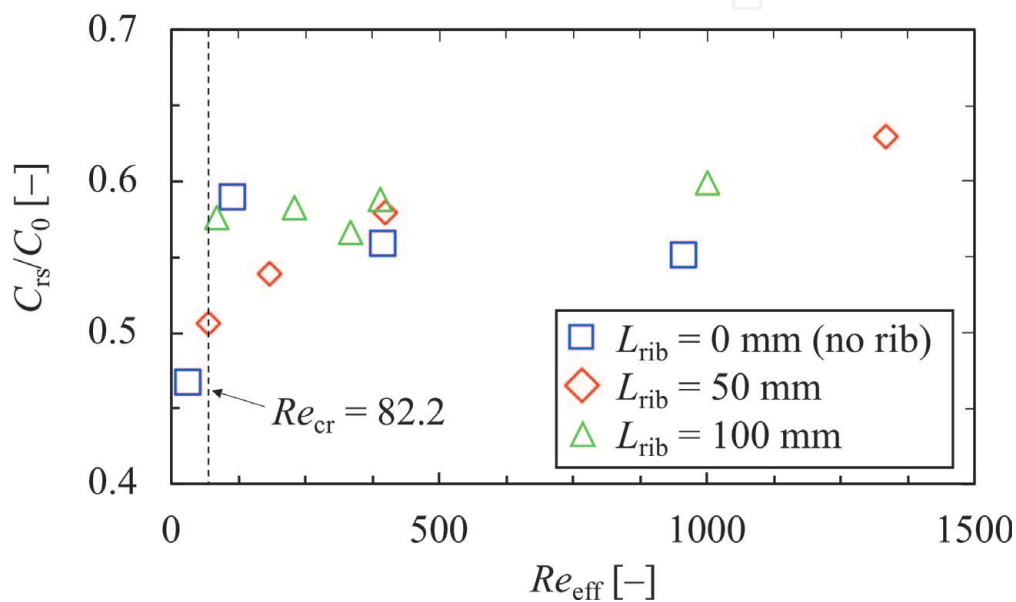


Figure 9. Effect of Re_{eff} on C_{rs}/C_0 with three types of cylinders ($L_{rib} = 0, 50, 100$ mm) at $u = 0.024$ cm/s in starch hydrolysis experiments [27]. L_{rib} refers to the length of the ribbed section from the outlet.

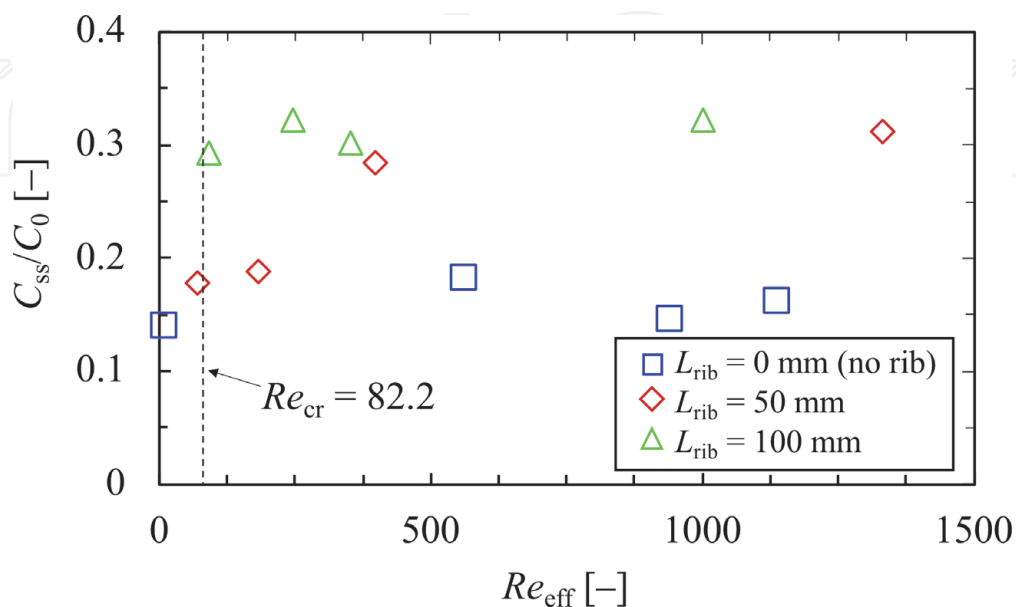


Figure 10. Effect of C_{ss}/C_0 on Re_{eff} with three types of cylinders ($L_{rib} = 0, 50, 100$ mm) at $u = 0.024$ cm/s [27]. C_{ss} refers to small saccharide concentration.

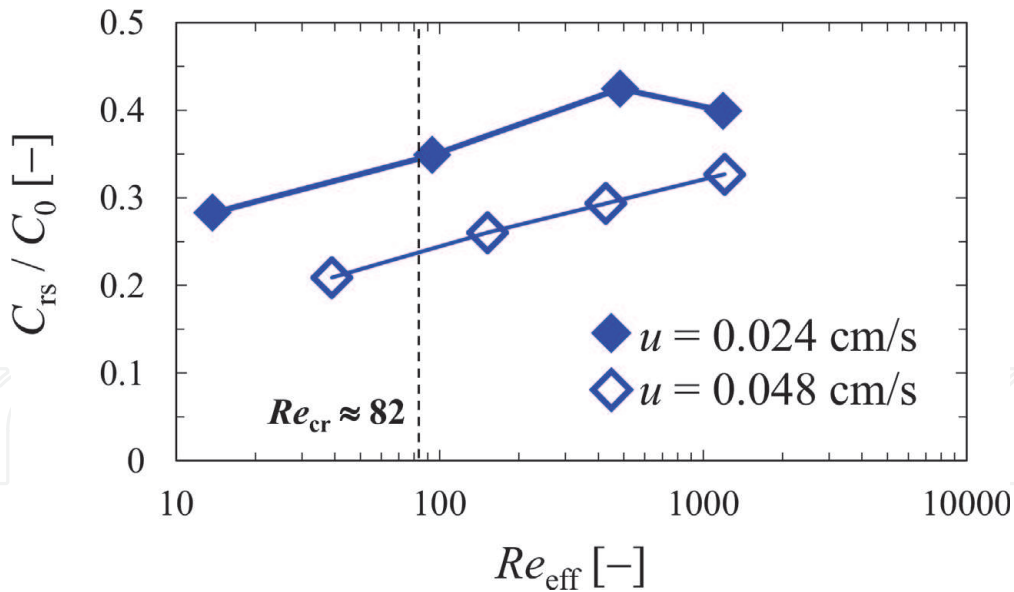


Figure 11.
Effect of axial velocity on C_{rs}/C_0 at $C_0 = 150$ g/L [39].

while the axial dispersion is suppressed at a higher Re . Finally, the effect of the axial velocity on the reducing sugar yield at $C_0 = 150$ g/L is shown in **Figure 11**.

At a higher axial velocity ($u = 0.048$ cm/s), the yield monotonically increases with Re_{eff} without a decrease at a higher Re_{eff} . Masuda et al. [39] explained that the transition from laminar Taylor vortex flow to wavy Taylor vortex flow occurs at a higher Re_{eff} than at a lower u because the axial flow enhances the stability of the Taylor vortex flow [45]. This should be investigated from the viewpoint of fluid mechanics. Nevertheless, the Taylor–Couette flow reactor promotes innovation in starch processing, for example, dramatic size reduction, high efficiency, and energy saving.

3.2 Intensification of heat sterilization processing

Heat sterilization is important for human health. Although novel technologies such as ultraviolet, ultrasonic, high-pressure, and cold plasma have been utilized [46], thermal sterilization plays a major role in the food industry. Recently, ohmic heating has recently been applied to heat sterilization processes [47]. However, the principle of scale-up for industries is under consideration. A traditional heat sterilizer, including a double-pipe, plate, and scrapped surface heat exchanger, faces problems such as clogging and high-pressure loss in the case of highly viscous liquid food. Therefore, heat sterilizers should be utilized for food process intensification. We consider the functions of an ideal sterilizer as follows:

1. High heat transfer performance in rapid heating;
2. Low shear force to avoid mechanical degradation of nutritional component;
3. Low pressure loss for saving energy.

These three functions are satisfied by adequately controlling the motion of liquid food. For example, chaotic advection and Dean vortex flow enable efficient and continuous heat sterilization [48, 49]. Taylor–Couette flow also offers a novel heat sterilization process. As described in the previous section, the Taylor–Couette flow

offers efficient and moderate heat transfer. In addition, the shear-thinning properties of many liquid foods should be considered. Another advantage is that a lower power is required for pumping because the apparent viscosity decreases owing to the rotation of the inner cylinder. The Taylor–Couette flow sterilizer has the potential for food process intensification. Masuda et al. [50–52] numerically investigated the performance of a Taylor–Couette flow sterilizer. They assumed the sterilization process of highly viscous liquid food such as mayonnaise or ketchup, including the thermal destruction of the spores of *Clostridium botulinum* and the retention of thiamine.

Figure 12 shows the computational domain used in [51]. To eliminate the effect of back flows through Taylor vortex flow at the outlet, an extended section is imposed where the inner cylinder is stationary. This attempt does not affect the simulation results. They have solved the conservation equations of mass, momentum, heat, and chemical species, as follows [51]:

$$\nabla \cdot \mathbf{u} = 0, \tag{2}$$

$$(\mathbf{u} \cdot \nabla)\mathbf{u} = -\frac{\nabla p}{\rho} + \frac{1}{\rho} \nabla \cdot (2\eta \mathbf{D}) - \mathbf{g}\alpha(T - T_{\text{ref}}), \tag{3}$$

$$\mathbf{u} \cdot \nabla T = \frac{\lambda}{\rho C_p} \nabla^2 T, \tag{4}$$

$$\mathbf{u} \cdot \nabla C = \nabla \cdot (D_c \nabla C) + S, \tag{5}$$

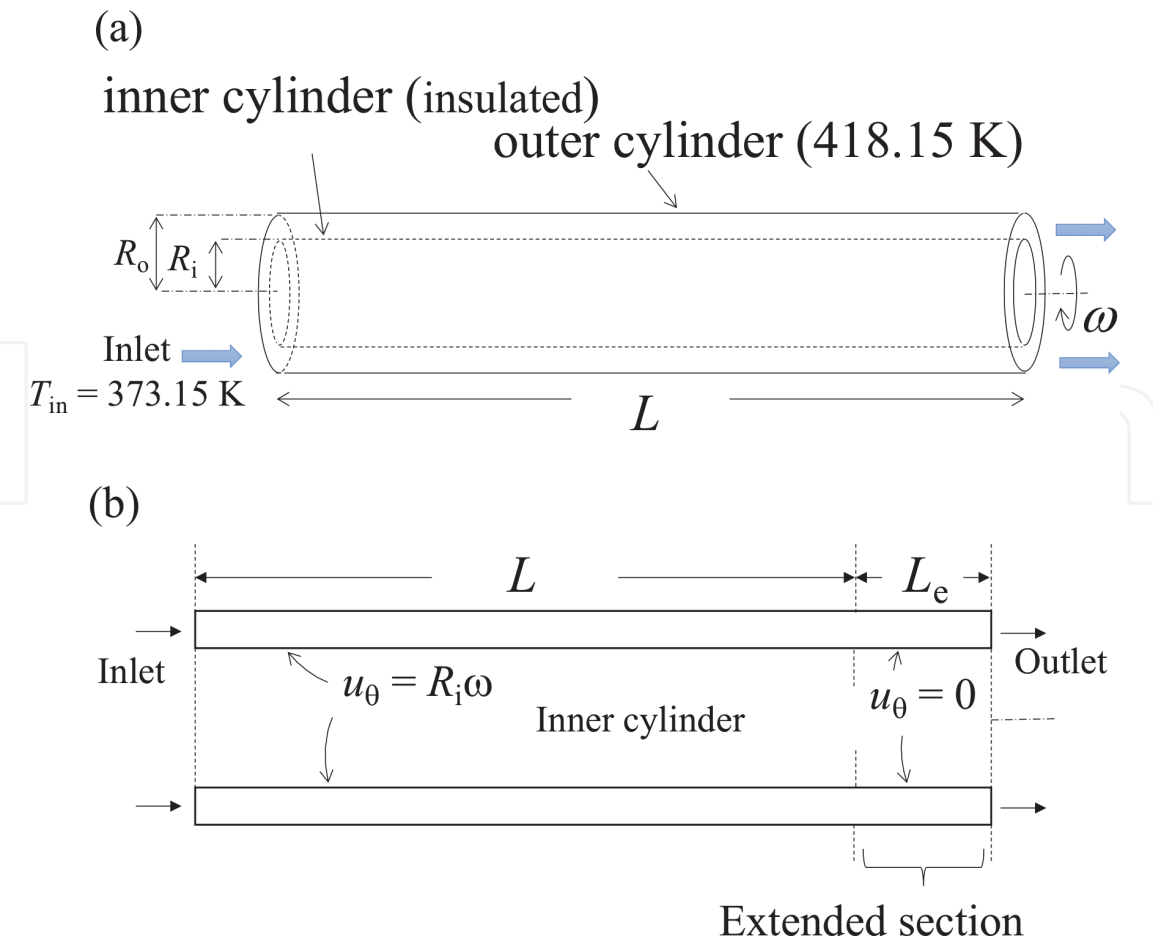


Figure 12.
Computational domain: (a) three-dimensional view without an extended section, (b) cross-sectional view with an extended section [51].

where \mathbf{u} is the velocity, p is the pressure, ρ is the density, η is the viscosity depending on the shear rate, $\mathbf{D} (= (\nabla \mathbf{u} + \nabla \mathbf{u}^T) / 2)$ 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. Because this simulation was assumed to be in a steady state, the time derivative term is omitted in Eqs. (2)–(5). It was assumed that the model fluid had a moderate shear-thinning property. According to Horak and Kessler [53], the thermal destruction of thiamine is followed by a second-order reaction model. The decrease in thiamine concentration due to destruction was included in the sink term, S , as shown in Eq. (5). Detailed information on the numerical procedure is described in [51]. The simulation code was validated.

Figure 13 shows the temperature distribution with the velocity vectors near the inlet at various values of Re_{eff} . In the case of $Re_{\text{eff}} = 101.1$ and 172.6 (**Figure 13(c)** and **(d)**), Taylor vortices were fully developed near the inlet, and consequently, heat transfer from the surface of the outer cylinder was significantly enhanced. This enhancement of the heat transfer is clearly confirmed from the bulk temperature distribution along the axis, as shown in **Figure 14**.

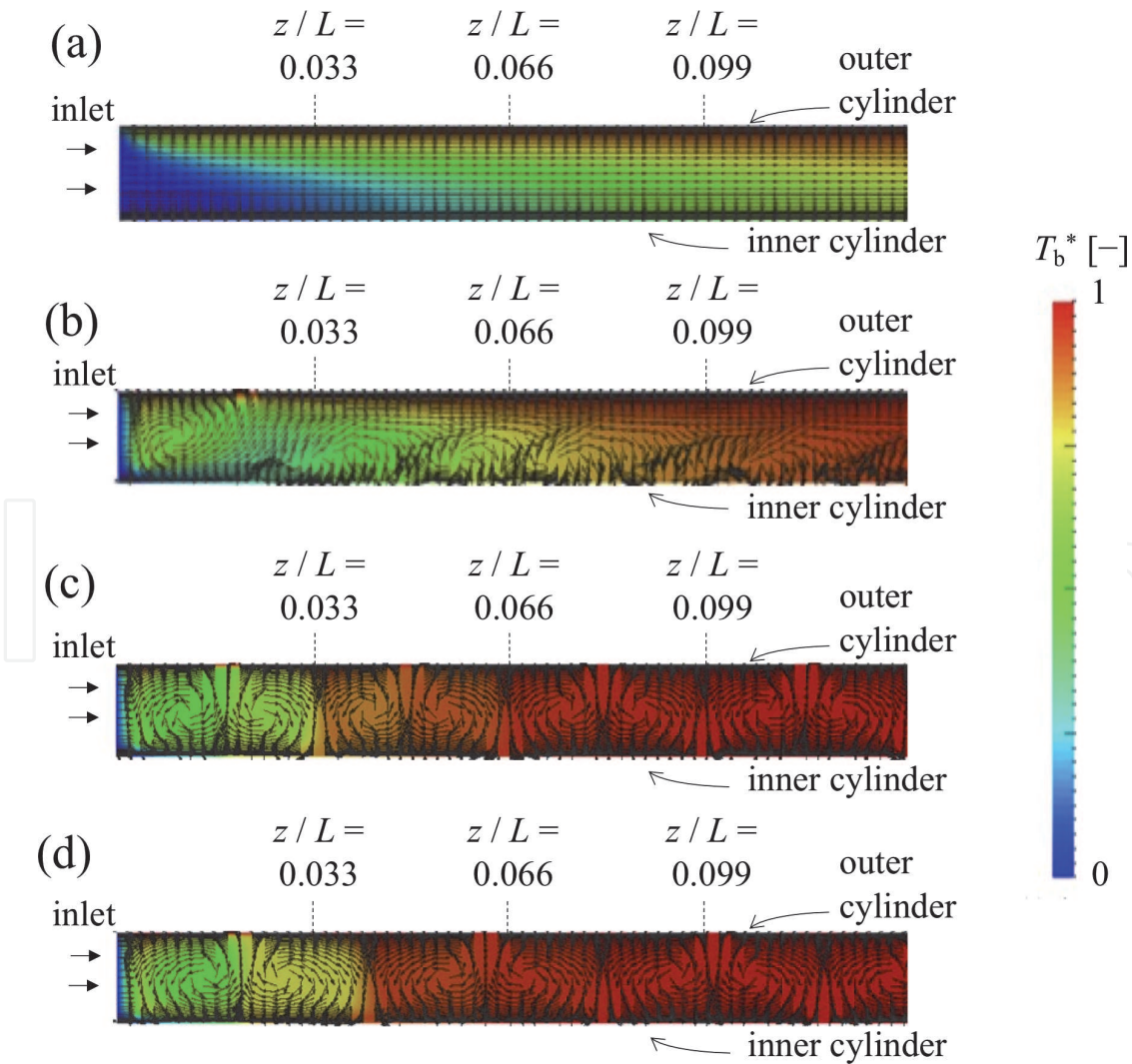


Figure 13. Normalized bulk temperature distribution with velocity vectors in r - z plane near the inlet at (a) $Re_{\text{eff}} = 0$ ($\omega = 0 \text{ rad/s}$), (b) $Re_{\text{eff}} = 43.7$ ($\omega = 20 \text{ rad/s}$), (c) $Re_{\text{eff}} = 101.1$ ($\omega = 35 \text{ rad/s}$), (d) $Re_{\text{eff}} = 172.6$ ($\omega = 50 \text{ rad/s}$) [51].

To investigate the performance of heat sterilization, the equivalent lethality, F_0 , was calculated from the temperature distribution. The value of F_0 is calculated as follows:

$$F_0 = \int_0^t \exp \left[\frac{E_a}{R} \left(\frac{1}{394.25} - \frac{1}{T(t)} \right) \right] dt, \tag{6}$$

where E_a is the activation energy for the destruction of *Clostridium botulinum*, and R is the gas constant. Finally, the local value of F_0 at an arbitrary axial position z is calculated as follows:

$$F_0(z) = \sum_{z=0}^z \Delta F_0 = \sum_{z=0}^z \Delta z \frac{dF_0}{dz} \Big|_{\min}, \tag{7}$$

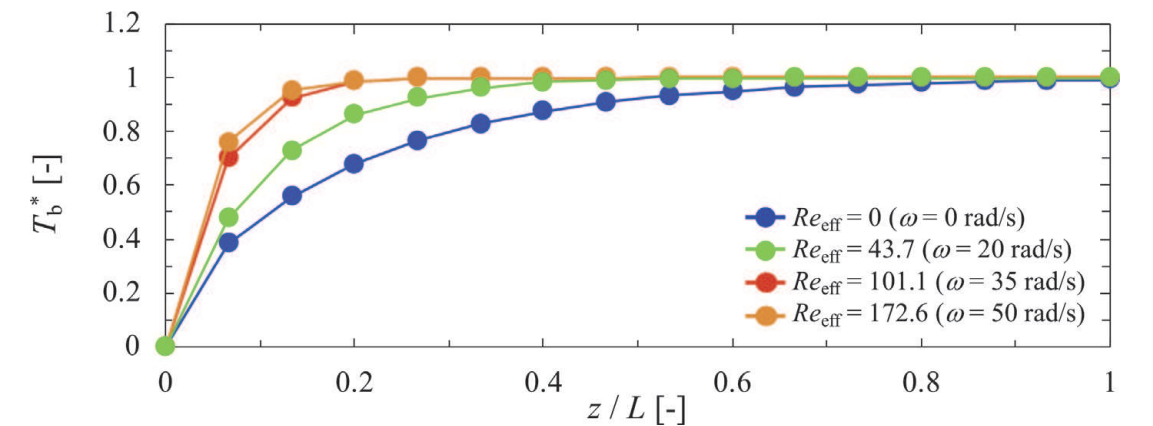


Figure 14.
Normalized bulk temperature distribution along the axis [51].

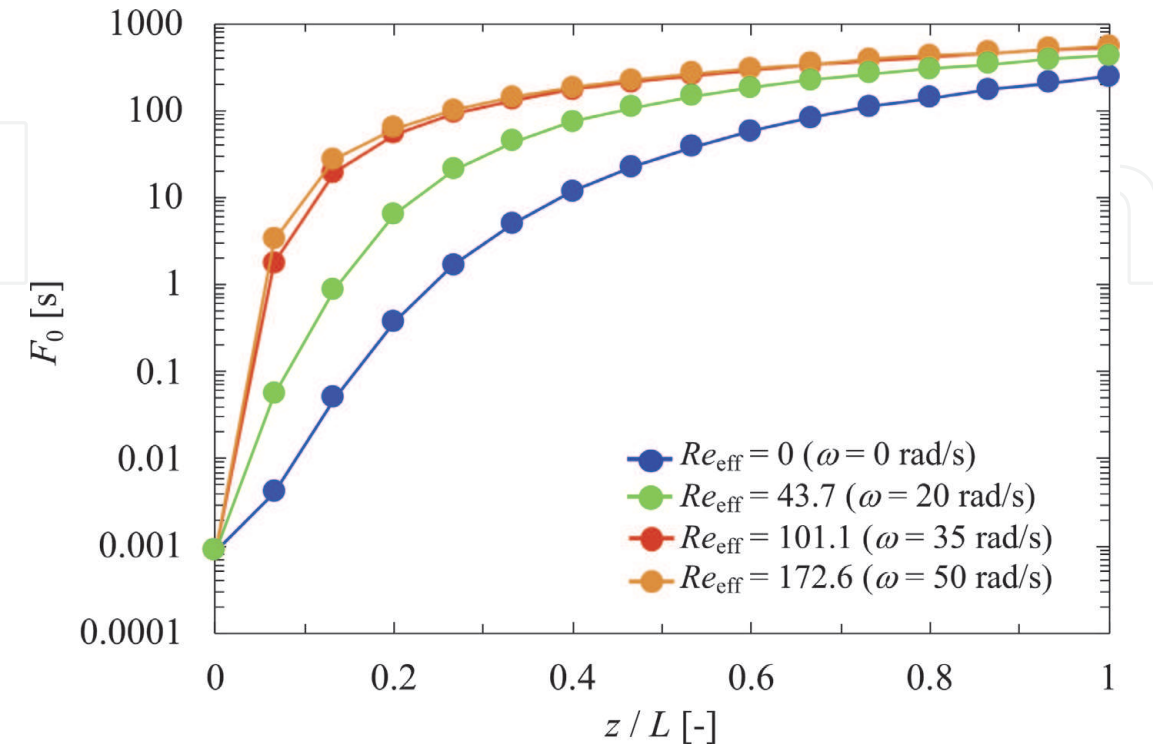


Figure 15.
Equivalent lethality distribution along the axis [51].

Figure 15 shows the axial distribution of F_0 along the axis. The significant increase in F_0 (higher than $F_0 = 500$ s) is observed under the condition at which Taylor vortices are developed ($Re_{eff} = 101.1$ and 172.6), as shown in **Figure 15**. This result indicates that Taylor–Couette flow has the potential to intensify the heat sterilization process. **Figure 16** shows the retention performance of thiamine during the sterilization process. Comparing the result at $Re_{eff} = 101.1$ with that at $Re_{eff} = 172.6$, it is confirmed from **Figure 15** that there is no clear difference in F_0 . In addition, a clear difference in the thermal destruction of thiamine is not observed in **Figure 16**. Nevertheless, Ilo and Berghofer [54] indicated the mechanical destruction of thiamine by shear force. Therefore, the operation at $Re_{eff} = 101.1$, is preferable because of the lower shear force. It is valuable to investigate the effect of shear force on thiamine destruction in the future.

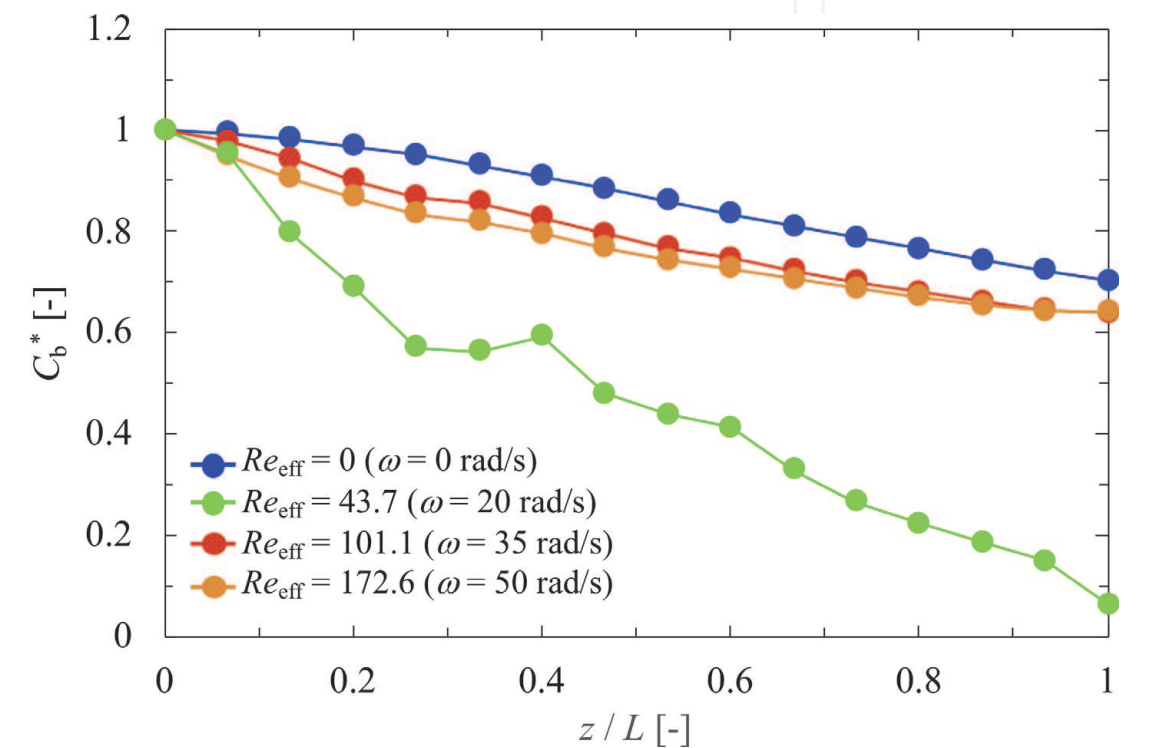


Figure 16.
Normalized thiamine concentration distribution along the axis [51].

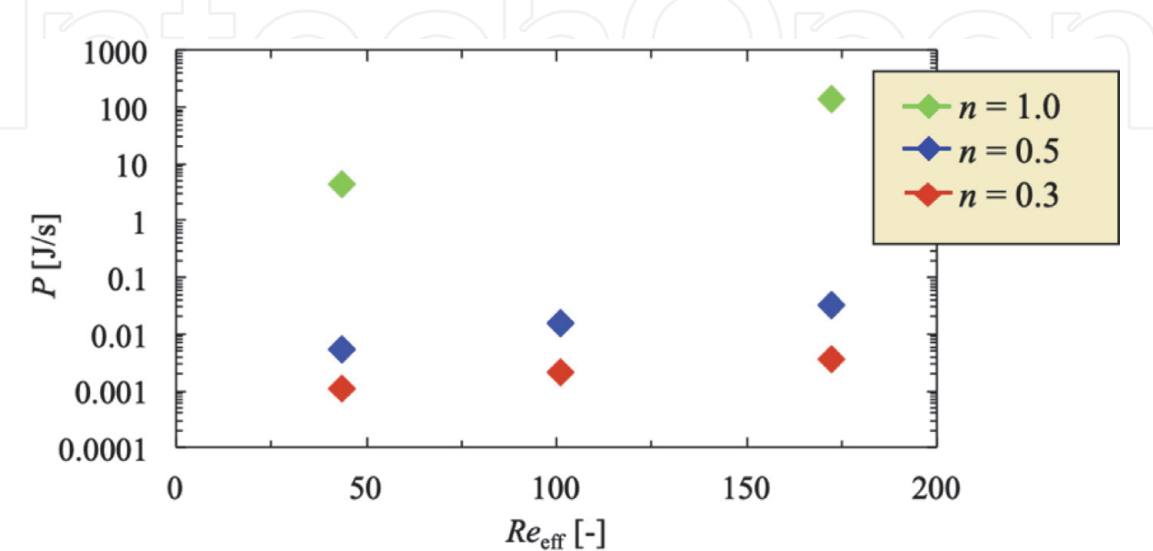


Figure 17.
Effect of power consumption on rheological properties in Taylor–Couette flow sterilizer.

Finally, the characteristics of energy consumption that are important for practical applications, are shown in **Figure 17**. In **Figure 17**, the energy consumption was calculated from the shear stress at the surface of the inner cylinder, as follows:

$$P = \omega R_i \iint \tau_{r\theta} dA, \quad (8)$$

where $\tau_{r\theta}$ is the component of the shear stress tensor at the surface of the inner cylinder, and dA is the differential surface of the inner cylinder. It is noted that the value of n indicates the strength of the shear-thinning property. For Newtonian fluids, n corresponds to 1. Remarkably, **Figure 17** shows that the power consumption significantly decreases with an increase in the shear-thinning property because the apparent viscosity decreases owing to the shear force generated by the rotation of the inner cylinder. Therefore, the Taylor–Couette flow sterilizer enables energy-saving sterilization processing of liquid foods with shear-thinning properties.

4. Conclusions

In this chapter, novel food processing utilizing Taylor–Couette flow was introduced for food process intensification. As examples, starch processing and heat sterilization processes were specifically selected. With respect to starch processing, continuous and efficient gelatinization/liquefaction/saccharification were successfully conducted even in the case of high-concentration starch suspension. In addition, no clear thermal degradation of the starch granules was observed. Therefore, in the future, Taylor–Couette flow could be practically utilized in industries. In heat sterilization processing, enhancement of heat transfer by Taylor–Couette flow significantly improved the thermal destruction of *Clostridium botulinum*. Actually, the sufficient value of F_0 (higher than $F_0 = 500$ s) was obtained due to Taylor vortices. Based on the lethality, thermal destruction of nutritional components such as thiamine and mechanical destruction by shear force, the optimum operational conditions were proposed.

Taylor–Couette flow has the potential to intensify other processes as well. For example, an appropriate mixing performance of Taylor vortices would facilitate the manufacturing of sophisticated emulsions, such as multiple emulsions. Furthermore, other fluid techniques, such as chaotic advection, could incorporate novel processing. This chapter provides all food engineers with new insights into food process intensification.

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Conflict of interest

The author declares no conflict of interest.

Nomenclature

C	thiamine concentration [mg/L]
C_p	specific heat capacity [kJ/kg·K]
C_{rs}	reducing sugar concentration [g/L]
C_{ss}	small saccharide concentration [g/L]
C_0	initial concentration of starch [g/L]
\mathbf{D}	rate of deformation tensor [1/s]
d	gap width [–]
D_c	diffusion coefficient [m ² /s]
E	activation energy [kJ/mol]
E_a	activation energy for destruction of spores [kJ/mol]
F_0	lethality [s]
\mathbf{g}	gravity acceleration [m/s ²]
L	length of cylinders [m]
L_e	length of extended section of cylinders [m]
L_{rib}	length of ribbed section from outlet [mm]
n	power index [–]
R	gas constant [J/mol·K]
r	radial position [m]
Re	Reynolds number [–]
R_i	outer diameter of inner cylinder [m]
R_o	inner radius of outer cylinder [m]
S	scalar source term [mg/L·s]
T	temperature [K]
T_{hj}	heat jacket temperature [K]
\mathbf{u}	velocity [m/s]
u	axial velocity [m/s]
p	pressure [Pa]
z	axial position [m]

Greek letters

α	coefficient of volume expansion [1/K]
β	characteristic time [s]
$\dot{\gamma}$	shear-rate [1/s]
η	fluid viscosity [Pa·s]
η_0	zero shear rate viscosity [Pa·s]
λ	Thermal conductivity [W/m·K]
ρ	fluid density [kg/m ³]
τ	residence time [s]
ω	angular velocity of inner cylinder [rad/s]

Subscripts

b	bulk
cr	critical
eff	effective
ref	reference

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