Doctoral Thesis

Study on a Homogenization Effect and a Scale-Up of Batch Rotor-Stator Mixers

(バッチ式ローター・ステーター型ミキサーの均質化効果とスケールアップに関する研究)

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Introduction

Main purpose of this study

Rotor-stator mixers are used in chemical, biochemical, food-processing, cosmetic, and pharmaceutical industries to improve process efficiency and product quality. Despite widespread use of these mixers, evaluation methods and scale-up criteria for this type of mixers are still unknown.

The purpose of this study is to propose a theoretical evaluation method of the homogenization effect for different stator configurations of internally and externally circulated batch rotor-stator mixers. Further, another aim of this study is to derive the scale-up factor in relation to the mixing time and to confirm the validity of the scale-up procedure proposed in this thesis.

Outline and scope of this study

This thesis is divided into five chapters as shown in **Figure I-1**. The Scheme image of this study is shown in **Figure I-2**. The outlines of each chapter are as follows:

Chapter 1 provides an explanation of the background of this study and the current knowledge about general rotor-stator mixers. The objectives of this study are described in this chapter. Further, problems related to the actual operation of rotor-stator mixers and necessities of a solution to these problems are discussed.

In **chapter 2**, a scale-up factor for the mean drop diameter in externally circulated batch rotor-stator mixers is proposed. The homogenization index (*H.I.*) is defined as the scale-up factor obtained from the local energy dissipation rate of turbulence and the circulation number. The local energy dissipation rate is calculated using the volume of the homogenization region, and the local power consumption is obtained from the measured net power consumption and the flow rate. The mean drop diameter using a certain time interval for different configurations of mixers and different operating conditions is also measured in order to evaluate the validity of the scale-up index using *H.I.* Experimental results show that *H.I.* could well account for the mean drop diameter under different rotor speed conditions (13–27 m/s), with a different gap width between the rotor and the stator (0.15–0.25 mm) and different sizes of mixers and production volumes (rotor diameters were 30 and 57 mm; production volumes were 1.5 and 9 L). These results indicate that *H.I.* can be used for predicting the mean drop diameter. The results also suggest that the scale-up criteria for the mean drop diameter in relation to the mixing time is based on *H.I.*, and not necessarily on geometrical similarities, same rotor tip speed, or gap width in the case of similar mixer configurations and the experimental production volume range (1 to 10 L) used for the model product, which is similar to typical dairy foods.

In chapter 3, a theoretical evaluation method of the homogenization effect for different stator configurations of internally circulated batch rotor-stator mixers is proposed. The homogenization effect has been evaluated indirectly using a homogenization coefficient (C_h) based on the measured power number, estimated flow number, and calculated shear frequency derived from the number of rotor blades and stator holes. As a result of the C_h evaluation during operation with water, it is inferred that the homogenization effect is considerably high when the stator hole diameter is small and the number of stator holes is large. The results also suggest that the clearance between the rotor and the stator has less influence on the homogenization effect than the hole diameter and the number of holes. In the case of operation with the model product, the same trend as that for the operation with water is obtained. On the basis of this fact, it has been considered that the performance estimation using C_h has a high degree of adequacy. The total energy dissipation rate that is contained in C_h can well account for the mean drop diameter in relation to the mixing time. The results demonstrate that the homogenization effect for different configurations of rotor-stator mixers can be compared and evaluated using the calculated C_h of the water mixing operation without actual product trials. This information can be useful for determining the optimum mixer design and the adequate mixer selection.

In **chapter 4**, the scale-up factor for the mean drop diameter in internally circulated batch rotor-stator mixers is proposed. The total energy dissipation rate (ε_t) is used as the scale-up factor for the mean drop diameter. ε_t is calculated from the power number, flow number, rotational speed, and the number of rotor blades and stator holes. Because it is difficult to directly measure the circulation flow rate of an internally circulated mixer, the flow rate of a production-scale mixer is estimated by measuring the time required for complete mixing—termed "completely mixed time" and the power number of the production- and pilot-scale mixers and the flow number of the pilot-scale mixer. The experimental results indicate that ε_t can account for the mean drop diameter. Theoretical verification suggests that ε_t includes information about differences in the mixer configuration (rotor diameter, stator hole diameter, stator wall thickness, stator opening ratio, and gap width) and manufacturing conditions (mixing time: t_m; rotational speed: N; and total product volume: V). The results show that the mean drop diameter decreases in proportion to t_m, N^4, and V^{-1}. Then, the mean drop diameter for the production-scale mixer is estimated from a model product experiment with the pilot-scale mixer. These results also indicate that the scale-up criteria for the mean drop diameter can be determined on the basis of ε_t in terms of the mixing time and not necessarily in terms of the geometric similarities between mixer configurations, constant rotor tip speed, or constant clearance between the rotor and the stator.

Chapter 5 presents a summary of the results and/or conclusions of this study and a discussion of the future work.

List of author's published papers

(1) Kamiya, T., M. Kaminoyama, K. Nishi and R. Misumi; "Scale-Up Factor for Mean Drop Diameter in Batch Rotor-Stator Mixers," *J. Chem. Eng. Japan*, **43**, 4, 326-332, (2010)

(2) Kamiya, T., H. Sasaki, Y. Toyama, K. Hanyu, M. Kaminoyama, K. Nishi and R. Misumi; "Evaluating Method of Homogenization Effect for Different Stator Configurations of Internally Circulated Batch Rotor-Stator Mixers," *J. Chem. Eng. Japan*, **43**, 4, 355-362, (2010)

(3) Kamiya, T., T. Sugawara, H. Sasaki, T. Tomita, K. Hanyu, M. Kaminoyama, K. Nishi and R. Misumi; "Scale-Up Factor for Mean Drop Diameter in Internally Circulated Batch Rotor-Stator Mixers," *J. Chem. Eng. Japan*, submitted (2010)

List of author's orally presented papers

(1) Guest lecture at Aalborg University (Invited from Professor Lasse Rosendahl) Kamiya, T., "Particle Size Reduction and Emulsification in High Shear Vacuum Mixers," November 7th 2008, at Aalborg University, Department of Energy Technology (Denmark).

(2) Kamiya, T., M. Kaminoyama, K. Nishi and R. Misumi; "Scale-Up Factor for Mean Drop Diameter in Batch Rotor-Stator Mixers," SCEJ Regional Meeting, Yonezawa, Japan (2009)

Patent

(1) Kamiya, T., T. Asou, T. Tomita and H. Echizen, "Production Method of liquid enteral formula" (in Japanese), Japanese Patent Disclosure No. 2007-046227

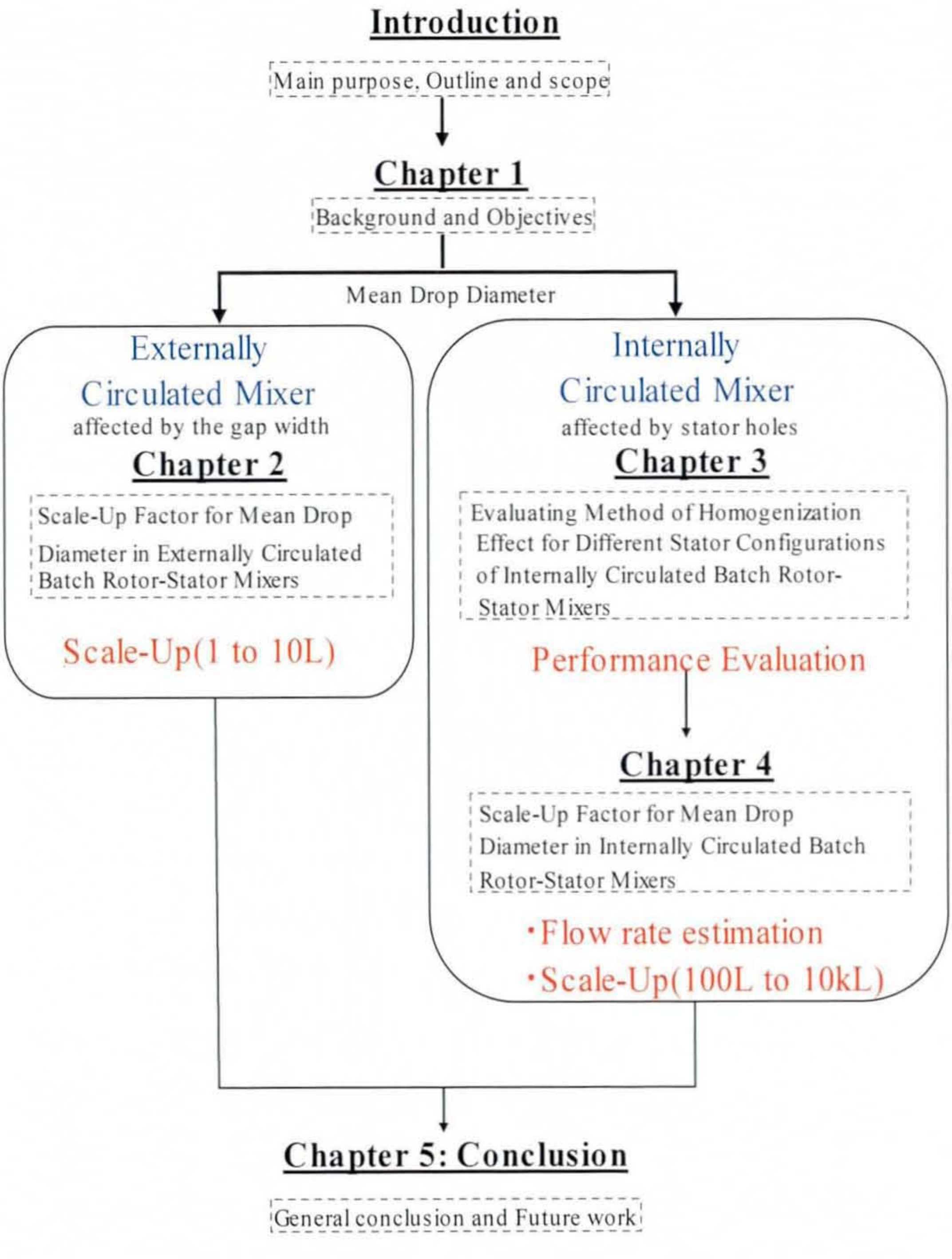

Fig. I-1 Flow scheme of this study

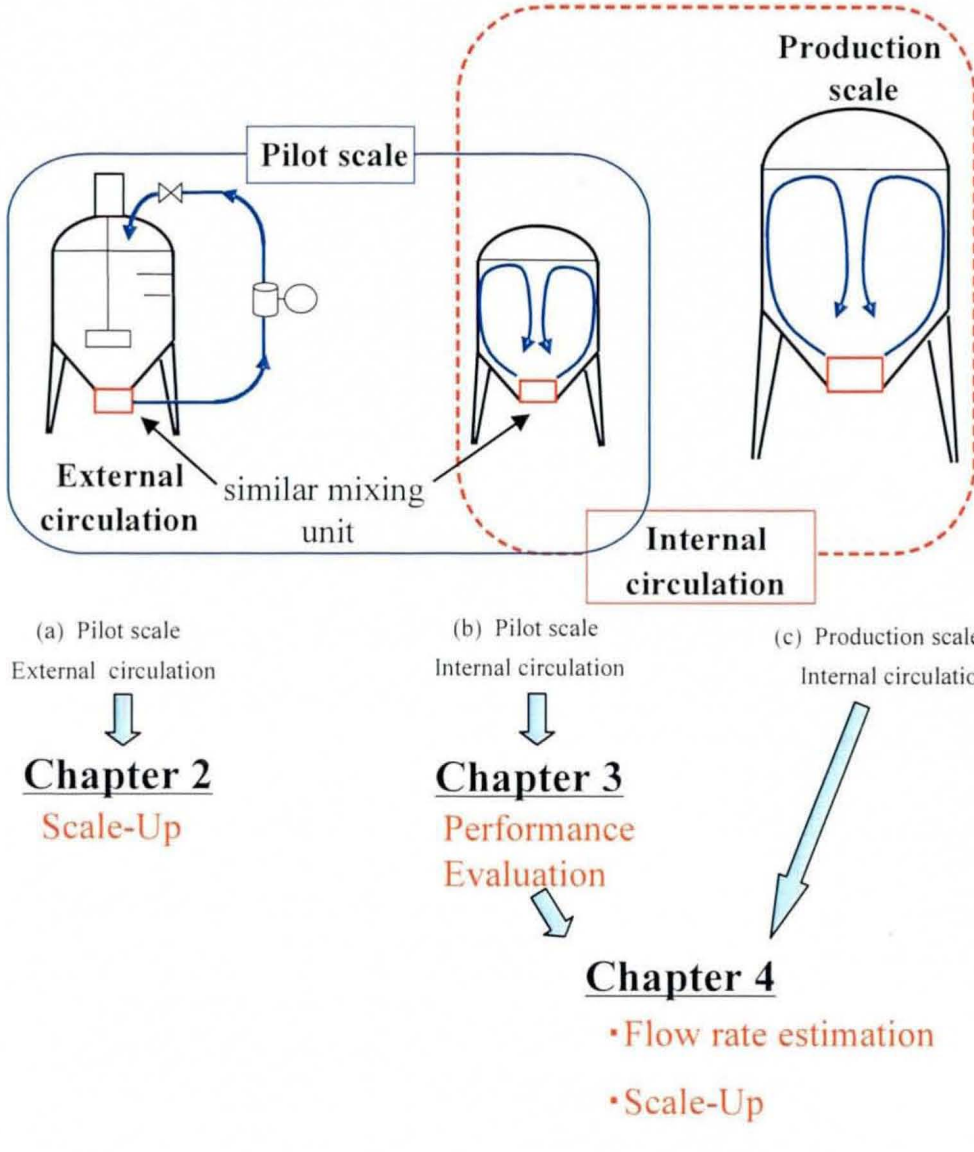

Fig. I-2 Scheme image of this study

Chapter 1 Background and motivation of this study

1.1 Background of this study

1.1.1 Characteristics of rotor-stator mixers

Rotor-stator mixers are used in chemical, biochemical, food-processing, cosmetic, and pharmaceutical industries to improve process efficiency and product quality. A distinguishing feature of rotor-stator mixers is that a high-speed rotor (a driven mixing element) operates in close proximity to a stator (a fixed mixing element). Typical rotor tip speeds range from 10 to 50 m/s. These mixing units generate a high shear rate that ranges from 20,000 to 100,000 s^{-1} (Atiemo-Obeng and Calabrese, 2004). Therefore, these devices are also called high-shear mixers. The local energy dissipation may be three orders of magnitude greater than that in a conventional mechanically agitated vessel. High speed, high shear, and high power are the main characteristics of rotor-stator mixers.

They are employed in many process operations that involve homogenization, dispersion, emulsification, grinding, dissolving, chemical reaction, and cell disruption.

1.1.2 Summary of current knowledge about rotor-stator mixers

Despite widespread use, the current understanding of rotor-stator mixer devices is not definitive. Over the past few decades, several studies on rotor-stator mixers have been conducted.

With regard to the maximum stable drop size, Davies (1985, 1987) reported that the drop size decreases with an increase in the energy dissipation rate per unit mass. This phenomenon has been confirmed in different types of emulsification devices (such as static mixers, turbine impellers, colloid mills, and fine valve homogenizers).

Davies (1985, 1987) also indicated that a turbulent fluctuation velocity, and not the shear rate, is responsible for drop breakup.

Calabrese *et al.* (2000, 2002) have reported further details of the drop breakup mechanism in a rotor-stator mixer. From their investigations, it was found that a shear gap between the rotor and the stator was not a major factor responsible for the drop breakup. It is more likely that breakup occurs in the stator slots or in the jet emanation from the stator slot. However, a narrow gap in the stator slot contributes to a high level of turbulent kinetic energy in it. Barailler *et al.* (2006) have also reported the importance of shear gap.

Maa and Hsu (1996) compared the equilibrium drop size between different sizes and configurations of rotor-stator sets (four-blade rotors with 12 rectangular slots and two-blade rotors with 8 slant slots). They also compared the trend in drop size reduction of the different sets.

Bourne and Garcia-Rosas (1986) studied the micro-mixing performance of different rotor-stator configurations in the same mixing device (six types of rotors and two types of stators). They concluded that there is an optimum combination of rotor-stator sets; however, the stators had a negligible effect on both the predicted energy dissipation and the measured product distributions in the mixing systems.

Urban (2006) reported the drop size for different types of emulsification devices (such as rotor-stator systems, disc systems, and high-pressure systems). Although he compared the mean drop diameter experimentally, he did not discuss the theoretical effects of differences in mixer configurations.

A study on the energy dissipation rate of a rotor-stator mixer was conducted by Utomo *et al.* (2008). From their results of complete three-dimensional computational fluid dynamics simulations, it was found that the highest energy dissipation rate occurred around the leading and trailing edges of the stator slots. They also indicated that a scale-up procedure should be based on the constant energy dissipation rate per unit mass and geometrical similarities, rather than the constant tip speed and constant gap width as proposed by other researchers (Bourne and Studer, 1992; Atiemo-Obeng and Calabrese, 2004).

In addition to the above-mentioned factors, another scale-up factor termed shear number derived from the shear frequency and shear rate has been proposed by Porcelli (2002). This proposal considered the number of rotor blades and stator openings.

Kowalski (2009) reported the power consumption of in-line rotor-stator devices.

1.1.3 Summary of current knowledge for mean drop diameter

Mechanisms of liquid-liquid dispersion and breakup of oil drops in agitating vessels were conducted by Ali *et al.* (1981), Chang *et al.* (1981), Tatterson and Stanford (1981). They reported that two different dispersion mechanisms, ligament stretching and turbulent fragmentation were observed to occur in the vortex systems of impeller discharge. And they also investigated the dispersion of low viscosity liquid into high viscosity liquid.

Clark (1988a, 1988b) explained that the local viscous effect in the breakup of droplets smaller than the Kolmogoroff micro-scale and inertial effects in the breakup of droplets larger than Kolmogoroff micro-scale.

With regard to the mean drop diameter, many researches have been carried out. Especially, many researchers were interested in the relationship between Weber number and drop size (Mlynek and Resnick (1972), Konno *et al.* (1977), McManamey (1979), Gnanasundaram *et al.* (1979), Konno *et al.* (1983), Konno and Saito (1987), Baldyga and Bourne (1993), Konno *et al.* (1993)). Generally, the average drop size in agitated liquid-liquid dispersion can be correlated as following equation.

$$\frac{d_{32}}{D} = C'(We)^{-0.6} \tag{1-1}$$

Here, d_{32}; Sauter mean diameter [m], D: impeller diameter [m], C': constant [-] and We: Weber number [-]. Zhou and Krestra (1998) reviewed results of many similar works.

For the scale-up, several index which estimate the mean drop diameter were proposed. These indexes are based on the energy dissipation rate. Average drop size in an agitated liquid–liquid dispersion can be correlated as

$$d_{32} = C_1 \varepsilon^{-2/5} (D / D_0)^{6/5} f(\phi) f(\mu) (\sigma / \rho)^{3/5} \tag{1-2}$$

or

$$d_{32} / D = C_2 We^{-3/5} N_p^{-2/5} f(\phi) f(\mu) \tag{1-3}$$

in the breakup-dominant region, and the average energy dissipation rate per unit mass of liquid ε and the Weber number in mixing vessel *We* are shown as follows.

$$\varepsilon = (4N_p / \pi) N^3 D^2 \left(D^3 / (D_0 H)\right) \tag{1-4}$$

$$We = N^2 D^3 \rho / \sigma \tag{1-5}$$

$f(\Phi)$ and $f(\mu)$ in these equations present the effect of volume fraction and the effect of liquid viscosity, respectively.

Average drop size in the coalescence region is also shown by the following equation.

$$d_{32} = C_1' \varepsilon^{-1/4} (D / D_0)^{3/4} f'(\phi) f(\mu) (\sigma / \rho)^{3/8} \tag{1-6}$$

or

$$d_{32} / D = C_2' We'^{-3/8} N_p^{-1/4} D^{-3/8} f'(\phi) f(\mu) \tag{1-7}$$

Then interfacial area of drops in dispersion, a, is obtained by

$$a = 6\phi / d_{32} \tag{1-8}$$

It has been reported by the presence authors from turbulent measurements using hot-film anemometry that the distribution pattern of the local energy dissipation rate in a mixing vessel is independent of vessel scale when geometrical similarity is preserved and that the average value throughout the vessel is shown by the following equation to give (2).

$$\varepsilon = P / (\rho \cdot V) \tag{1-9}$$

where P and V are agitation power consumption and product volume in the vessel.

Nishikawa *et al.* (1987) reported following index for scale-up.

$$\left(N^3 D^{\,2} D_0\right) \cdot \left(\frac{4 N_p}{\pi}\right) \tag{1-10}$$

Here, N: rotational speed [1/s], D_0: Vessel diameter [m] and N_p: Power number [-]. They also reported that the average energy dissipation rate, Weber number in the mixing vessel and Reynolds number is not a satisfying scale-up standard.

On the other hands, Pacek *et al.* (1999) indicated that the energy dissipation rate per swept volume was well account for the mean drop diameter in the agitated vessel.

Hong and Lee (1985) was developed a general correlation for the changes of the Sauter-mean droplet diameter with respect to mixing time during the initial period of liquid-liquid dispersions in agitated vessels as follows:

$$\frac{d_{32}-d_{32}^{*}}{d_{32}^{*}}=\alpha(N\cdot t_{m})^{-0.7} \tag{1-11}$$

Here, d_{32}^{*} : the steady-state drop size [m] α :constant [-] and t_{m}: mixing time [s].

Most researches were focused on normal agitated vessels, not on rotor-stator mixes. Thus far, the investigation of concerning about mean drop diameter for rotor-stator mixers has been required.

1.1.4 Main problem of rotor-stator mixers in production fields

Although a rotor-stator mixer is a highly efficient device, its drop-size distribution is generally considerably broader than that of a fine-clearance valve homogenizer. This is why rotor-stator mixers are usually used in pre-emulsification processes in an actual production line. From an engineering viewpoint, for the design of production lines, obtaining information about the decreasing trend of the mean drop diameter is more important than obtaining information about the maximum stable drop size, which is obtained over a long mixing time.

Thus far, researchers have focused on pilot-scale mixers and the maximum stable drop size that is obtained over a long mixing time. However, studies have not been conducted on the decreasing trend of the mean drop diameter and the correspondence between the scale-up factor and mixing time of a production-scale mixer.

Further, many studies have focused on the comparison of different types of emulsification devices under experimental conditions; however, a theoretical evaluation to address the effect of different configurations of rotor-stator mixers has not been carried out.

1.2 Objectives of this study

The objective of this study is to propose a theoretical evaluation method of a homogenization effect for different stator configurations of internally and externally circulated batch rotor-stator mixers. Another aim of this study is to derive the scale-up factor for the mean drop diameter in relation to the mixing time and to confirm the validity of the scale-up procedure proposed in this study.

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Chapter 2 Scale-Up Factor for Mean Drop Diameter in Externally Circulated Batch Rotor-Stator Mixers

2.1 Introduction

Rotor-stator mixers are widely employed in the chemical, food, cosmetic, and pharmaceutical industries to produce emulsions and liquid–liquid dispersions. A typical feature of these mixers is the presence of a high-speed rotor (which drives the mixing process) in close proximity to a stator (a fixed element with slots). These mixing units generate a high shear rate that ranges from 20,000 to 100,000 s^{-1} (Atiemo-Obeng and Calabrese, 2004). Therefore, these devices are also called high-shear mixers.

Although a rotor-stator mixer is a highly efficient device, its drop size distribution is generally much broader as compared to that of a fine clearance valve homogenizer. This is why rotor-stator mixers are usually used in pre-emulsification processes in actual production. From an engineering viewpoint, obtaining information about the decreasing trend of the mean drop diameter is more important than obtaining that about the maximum stable drop size, which is obtained over a long mixing time, for the design of production lines.

Over the past few decades, several studies have been conducted on rotor-stator mixers. With regard to the maximum stable drop size, Davies (1985, 1987) reported that the drop size decreases with an increase in the energy dissipation rate per unit mass. This phenomenon has been confirmed in different types of emulsification devices (static mixers, turbine impellers, colloid mills, and fine valve homogenizers). Davies (1985, 1987) also indicated that a turbulent fluctuation velocity is responsible for drop breakup, and not the shear rate.

Calabrese *et al.* (2000, 2002) have reported further details of the drop breakup mechanism in a rotor-stator mixer. From their investigations, it was found that a shear gap between the rotor and the stator was not a major factor responsible for the drop breakup. It is more likely that breakup occurs in the stator slots or in the jet emanation from the stator slot. A narrow gap in the stator slot, however, contributes to a high level of turbulent kinetic energy in it. From this fact, they deduced that this narrow gap is necessary for efficient dispersion. Maa and Hsu (1996) and Barailler *et al.* (2006) reported the importance of shear gap.

A study on the energy dissipation rate of a rotor-stator mixer was conducted by Utomo *et al.* (2008). From their results of complete three-dimensional computational fluid dynamics simulations, it was found that the highest energy dissipation rate occurred around the leading and trailing edges of the stator slots. However, the energy dissipated in the slot region is 7.6% of the total energy supplied by the rotor. They also reported that the high energy dissipation rate could be found on the stator wall. This result suggests that the gap between the rotor and the stator cannot be disregarded in the processes of dispersion and emulsification.

Utomo *et al.* (2008) also indicated that a scale-up procedure should be based on the constant energy dissipation rate per unit mass and geometrical similarities, rather than the constant tip speed and constant gap width, which have been proposed by other researchers (Bourne and Studer, 1992; Atiemo-Obeng and Calabrese, 2004). In addition to the above factors, another scale-up factor termed shear number derived from the shear frequency and shear rate has been proposed by Porcelli (2002). This proposal considered the number of rotor blades and stator openings; however, the associated scale-up accuracy and coverage were not known.

Thus far, studies have focused on the maximum stable drop size that is obtained over a long mixing time, however, studies on the decreasing trend of the mean drop diameter and the scale-up index correspondence with mixing time have still not been conducted.

In this chapter, we derive the scale-up index in relation to the mixing time. This index can also explain the mean drop diameter for different configurations of rotor-stator mixers as well as different operating conditions and production scales.

2.2 Theory

2.2.1 Power consumption for homogenization

In order to intensify a homogenization effect, power consumption must be increased. This then requires that we consider the structure of power consumption and determine the power consumption which contributed to homogenization. The net power consumption P_n [W] is calculated by Eq. (2-1).

$$P_{\mathrm{n}} = \eta(P_{\mathrm{g}} - P_{\mathrm{a}}) \tag{2-1}$$

Here, η is the motor efficiency [-], P_g is the gross electrical power [W], and P_a is the power loss [W] as determined by running the mixer in air (Kowalski, 2009). Although η is normally a function of different motor power and rotor speeds, we assumed that the motor power and rotor speed are relatively high and that η is fairly constant (in this study, η is 1.0). P_g and P_a are measured values. Power consumption is usually measured by strain gauges or torque transducers. In this study, we determined motor power consumption through direct measurement of the electrical current. We understand that this method is not generally recommended, particularly on a small scale, as losses tend to be greater than the power delivered to the fluid (Brown *et al.*, 2004). However, for a mixer in large-scale production, it is difficult to attach strain gauges and torque transducers to the mixer driving shaft. Thus, even as the method introduces a certain margin of error, using the measurements of electrical current enables us to practically estimate the power consumption of actual mixers.

On the other hand, P_n can also be described as follows with Eq. (2-2).

$$\begin{aligned} P_n &= Q \cdot H_t \\ &= Q \cdot (H_k + H_{pr} + H_{pt}) \end{aligned} \quad (2\text{-}2)$$

The total energy loss H_t [kg/m/s^2] is correlated with three factors: the kinetic energy loss H_k [kg/m/s^2], the pressure energy loss H_{pr} [Pa] (= pressure), and the potential energy loss H_{pt} [kg/m/s^2] (= 0).

The flow rate is represented by Q [m^3/s]. For all others, the kinetic energy loss H_k is separated into two losses shown by Eq. (2-3).

$$H_{\mathrm{k}} = H_{\mathrm{k,avg}} + H_{\mathrm{k,fluc}} \tag{2-3}$$

Here, $H_{k,avg}$ is the average velocity loss [$kg/m/s^2$] and $H_{k,fluc}$ is the fluctuation velocity loss [$kg/m/s^2$]caused by turbulence (Yamaguchi, 1984). From Eqs. (2-2) and (2-3), P_n is given by Eq. (2-4).

$$P_{\mathrm{n}} = Q \cdot (H_{\mathrm{k,ave}} + H_{\mathrm{k,fluc}} + H_{\mathrm{pr}}) \tag{2-4}$$

In these energy losses, it is surmised that $H_{k,fluc}$ and H_{pr} are the main factors contributing to homogenization, and the power consumption which contributed to homogenization P_h [W] is defined by Eq. (2-5).

$$P_{\mathrm{h}} = Q \cdot (H_{\mathrm{k,fluc}} + H_{\mathrm{pr}}) \tag{2-5}$$

On the other hand, the pumping power consumption P_p [W] is also defined by the conservation of angular momentum as Eq. (2-6).

$$\begin{aligned} P_{\mathrm{p}} &= Q \cdot H_{\mathrm{k,ave}} \\ &= 2\pi N \rho Q \left(\frac{D}{2}\right)^2 \varpi \\ &= \rho Q (\pi D N)^2 \end{aligned} \tag{2-6}$$

Here, N is the rotational speed [1/s], ρ is the density [kg/m^3], D is the rotor diameter [m], and ω is the angular velocity [rad/s]. The purpose is to know the P_h, but both energy losses in Eq. (2-5) are difficult to measure directly. Therefore, P_h is estimated by subtracting P_p from P_n as shown in Eq. (2-7).

$$P_h = P_n - P_p$$
$$= \eta(P_g - P_a) - \rho Q(\pi D N)^2 \qquad (2\text{-}7)$$

All variables in Eq. (2-7) can be derived from experiments.

2.2.2 Homogenization volume and circulation number

According to Utomo *et al.* (2008), the highest energy dissipation rate occurs around the leading and trailing edges of the stator slot due to the stagnation of fluid on these edges. A high energy dissipation rate was also predicted on the stator wall. From these results, the volume that contributed to homogenization v_h [m^3] is defined as the entire slot volume on the stator v_s [m^3] and the gap in the volume between the rotor and the stator v_g [m^3], which was calculated by subtracting the swept-out volume of the rotor diameter from the swept-out volume of the stator diameter.

$$v_h = v_g + v_s \qquad (2\text{-}8)$$

The circulation number N_c [-] is defined as follows by Eq. (2-9).

$$N_c = \frac{Q}{V} \cdot t_m \tag{2-9}$$

Here, V is the total product volume [m^3], and t_m is the mixing time [s]. N_c signifies how many times the product passed through the homogenization unit during the time it was operating.

2.2.3 Homogenization index

In past experimental results, it is difficult to explain the mean drop diameter by N_c, except for at the same rotational speed condition. This means it is required to evaluate the homogenization intensity for a single pass through a batch-mixing unit. Davies (1985, 1987) reported that the drop size decreases with an increase in the energy dissipation rate per unit mass. Sumi and Kamiwano (2000) indicated that the power consumption per unit volume and the circulation time affect the drop breakup. From these facts, it is supposed that main factors affecting homogenization are energy dissipation rate per unit mass and N_c. Based on this hypothesis, the homogenization index $H.I.$ [m^2/s^3] (=[W/kg]) is defined by Eq. (2-10).

$$\begin{aligned} H.I. &= \left(\frac{P_h}{\rho \cdot v_h} \right) \cdot (N_c) \\ &= \varepsilon_l \cdot N_c \end{aligned} \tag{2-10}$$

Here, ε_l is the local energy dissipation rate of turbulence [m^2/s^3] (the energy dissipation rate per unit mass of the homogenization region). The ε_l signifies how much power the product received in the homogenization region. In other words, *H.I.* was obtained from the circulation number weighted with the local energy dissipation rate of turbulence.

2.3 Experimental

2.3.1 Experimental apparatus

The mixer head used for this study is shown in **Figure 2-1**. Two sizes of rotor-stator mixers were employed. In order to compare the effect of different rotor-stator configurations, we used two rotors with two different gap widths in the small mixer (Magic Lab, IKA Works Inc.). The diameter of the standard mixer was 30.1 mm and the gap width was 0.15 mm. In the wide gap mixer, the diameter and the gap width were 29.9 mm and 0.25 mm, respectively. Both the standard and the wide gap mixers were used with the same diameter stator (30.4 mm). The diameter and the gap width of the large mixer (MP-10, IKA Works Inc.) were 57 mm and 0.25 mm, respectively. More details on the mixer configuration are shown in **Table 2-1**.

Figure 2-2 shows the apparatus of the batch rotor-stator mixing unit. Small and large scales of rotor-stator mixers were installed at the bottom of a vessel and the throughput from the mixer was circulated to the vessel. Total volume of each vessel were 1.5 L and 9 L, respectively.

2.3.2 Materials

In order to simulate the emulsion of food products, milk protein concentration powder (MPC-80, DMV International bv.) and rapeseed oil (Cocolin rapeseed oil, Taiyo Yushi Corp.) were used for the model product. Their composition and properties are presented in **Table 2-2.** The composition ratios of protein to water, oil to protein, and oil to water were similar to those found in typical dairy products.

2.3.3 Preparation and Evaluation Methods

The preparation procedure was as follows. First, hot water (40–50°C) and rapeseed oil (15–25°C) were added to a mixing pail (10 L). Then, a vertical mixer (IKA-ROTOTRON, IKA Works Inc.) was turned on in order to obtain a rough dispersion of the oil and water. After pre-mixing, the milk protein powder was added to the mixing pail, and was mixed for ten min. After this preparation, the model product was moved to the batch mixing unit. The decreasing trend of the mean drop diameter was evaluated in drop size measurement increments (mean drop diameter: d_{50} [m]) using a laser diffraction particle size analyzer (SALD-2000, Shimadzu Corp.).

The time at which the rotor reached full speed was considered the start of the mixing time. Samples were taken at certain time intervals for measurement of the mean drop diameter.

2.4 Results and Discussion

2.4.1 Mean drop diameter

All experimental conditions and calculated values are summarized in **Table 2-3**. Discussion of the accuracy of the scale-up factor is based on *H.I.* shown Table 2-3 and the results of drop size measurement.

Figure 2-3 shows the mean drop diameter under different operating conditions and with rotors of different diameters in the small rotor-stator mixer. The drop size decrease much faster at a high rotor speed, narrow gap width, and long mixing time.

With regard to the effect of the gap width, Calabrese *et al.* (2000, 2002) indicate that the shear gap between the rotor and the stator is not a major factor that is responsible for the drop breakup. However, in the model product and the mixer, it was confirmed that gap width strongly affects the mean drop diameter.

Figure 2-4 shows the relationship between the circulation number and the drop size under different operating conditions and with rotors of different diameters, as obtained by Magic Lab. All data are the same as those shown in Figure 2-3. From this figure, it can be inferred that the circulation number is not necessarily responsible for the mean drop diameter under different rotational speed conditions or different gap widths. This result also indicates that it is necessary to evaluate the homogenization intensity for a single pass through a mixer unit.

2.4.2 Influence of rotor speed

In order to confirm the validity of the scale-up index using *H.I.*, comparisons of the mean drop diameter obtained under different operating conditions were carried out.

Figure 2-5 shows the mean drop diameter, which is ordered by the *H.I.,* under different rotor speed conditions. It is found that the tendency varies, even as changes in drop size show a similar slope under different operating conditions. This result suggests that *H.I.* can be used to describe the mean drop diameter in terms of the influence of the rotor speed.

2.4.3 Influence of the gap

Figure 2-6 shows the mean drop diameter, which is arranged by the *H.I.*, for different gap widths. By comparing Figures 2-6, 2-3, and 2-4, it is found that, although it is difficult to correlate the mean drop diameter with the mixing time and the circulation number, *H.I.* can account suitably for the mean drop diameter, considering the influence of the gap. This result also suggests that *H.I.* can be used to predict the effect of different rotor-stator configurations.

2.4.4 Influence of the mixer size and batch volume

Figure 2-7 shows the mean drop diameter, which is ordered by the *H.I.*, for different-sized mixers. As shown in Figures 2-5 and 2-6, the mean drop diameter is in good agreement with both the mixer sizes and the different rotor speed settings.

The ratio of the rotor diameter between Magic Lab (29.9–30.1 mm) and MP-10 (57 mm) is approximately 1.9. Further, the volume ratio of Magic Lab (1.5 L) to MP-10 (9 L) is 6. We can explain the mean drop diameter using *H.I.* by considering the influence of the mixer size and the batch volume. However, the large mixer produced a wider drop size distribution. As shown in **Figure 2-8**, the standard deviation of the production scale mixer was much higher (σ = 0.188 μm) compared with the standard deviation of the pilot scale (σ = 0.128 μm) although the mean drop diameter of the production scale mixer was smaller than the pilot scale mixer (Production scale mixer d_{50}= 0.499 μm, Pilot scale mixer d_{50}= 0.578 μm).

We then plotted all results onto the same graph, which are shown in **Figure 2-9**. These results clearly indicate that *H.I.* is a good index for estimating the mean drop diameter for different product volumes, different rotor speeds, and different mixer configurations (diameter and gap). In other words, *H.I.* can be applied to a wide range of operating conditions. This implies *H.I.* can be used to evaluate the homogenization intensity for a single pass through a mixing unit, adequately using the local energy dissipation rate. From the result, it can be inferred that the scale-up procedure should be based on *H.I.*, which is calculated from the local energy dissipation rate and circulation number.

In the production scale, it is difficult to satisfy the same conditions as in the laboratory scale, such as constant dissipation rate per unit mass, geometrical similarities, constant tip speed, and constant gap width. The results suggest that these constant conditions and geometrical similarities are not necessary for achieving successful scale-up for mean drop diameter in the pre-homogenization process carried out in the mixers for the model product. In Figure 2-8, the data correspond well with Eq. (2-11).

$$d_{50} \propto H.I.^{-0.328} \qquad (2\text{-}11)$$

The coefficient of variation is R = 0.926. If the stress on the drop is inertial, as shown from the results of Calabrese *et al.* (2002), the correlation of d_{32} and ε in low viscosity liquid is given by Eq. (2-12).

$$d_{32} \propto \sigma^{1/3}\rho^{-2/3}\varepsilon^{-1/3}\mu^{1/3} \qquad (2\text{-}12)$$

Here, d_{32} is the Sautar mean diameter [m], μ is the viscosity [Pa・s], ε is energy dissipation rate [m^2/s^3] and σ is the surface tension [N/m]. The fitted coefficient of ε_l in the study is the same coefficient of ε that was reported by Calabrese *et al.* (2000). If we were to assume that d_{32} and ε have a proportional relationship with d_{50} and ε_l, respectively, the result could be explained by the theory of Calabrese *et al.* (2000). It is assumed the mechanism for the breakup of drops is based on the interaction of inertial sub-range eddies, which could take place either on a similar scale or on the smaller Kolmogorov microscale.

The Power consumption that was calculated from the electrical current, however, contains some measurement errors; therefore, it might not be applicable to all types of rotor-stator mixer. Further studies to confirm the coverage of scale-up using *H.I.* are required.

2.5 Conclusions

In this chapter, a scale-up factor (homogenization index: *H.I.*) was proposed for the mean drop diameter in batch rotor-stator mixers. This index is based on the concept that the circulation number and local energy dissipation rate of turbulence could well account for the mean drop diameter at different rotor speeds, with different mixer configurations (gap width and rotor diameter), and for different volumes of production. In other words, mean drop diameter could be estimated by using *H.I.* This result also suggested that *H.I.* accurately corresponds with the homogenization intensity for a single pass through a batch-mixing unit. The scale-up criteria for the mean drop diameter in terms of mixing time should be based on *H.I.*, and not necessarily on geometrical similarities, same rotor tip speed, or the same gap width in the case of similar mixer configurations and the experimental range (1 to 10 L) used for the model product.

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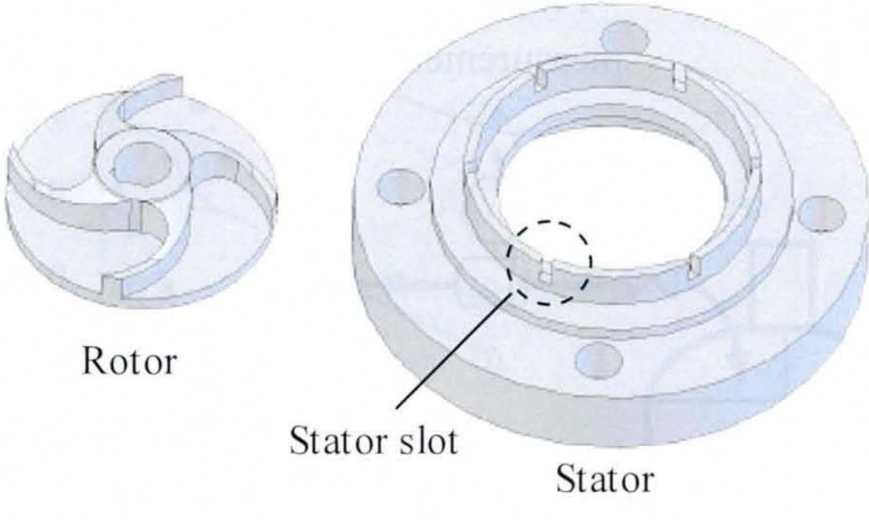

Fig. 2-1 Schematic representation of the rotor and the stator

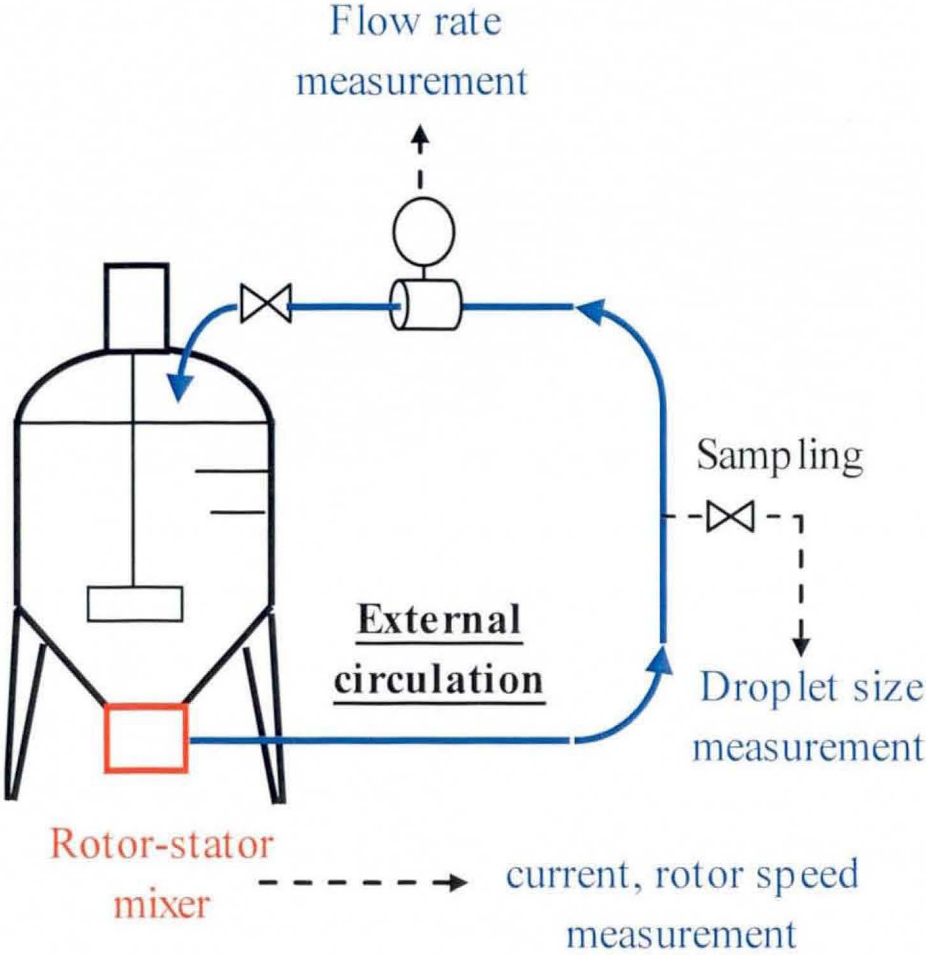

Fig. 2-2 Flow diagram of the batch mixing unit

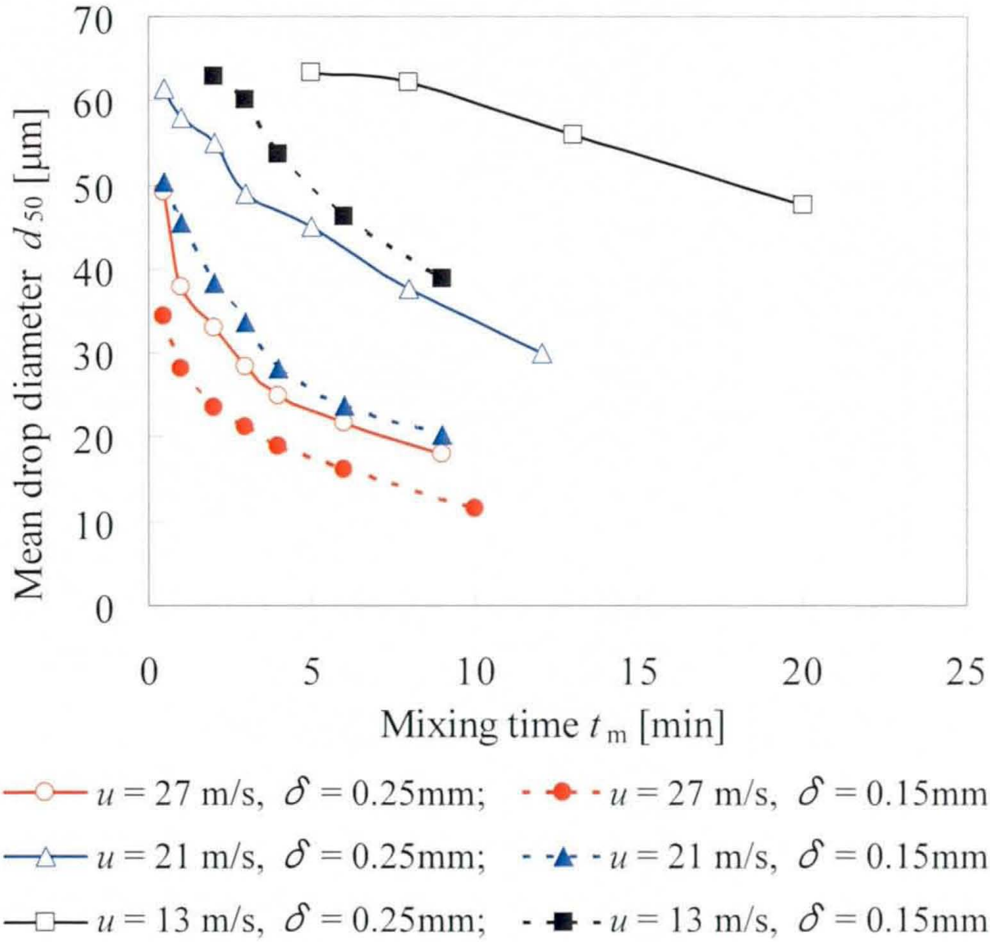

Fig. 2-3 Profiles of the mixing time vs. the mean drop diameter by Magic Lab

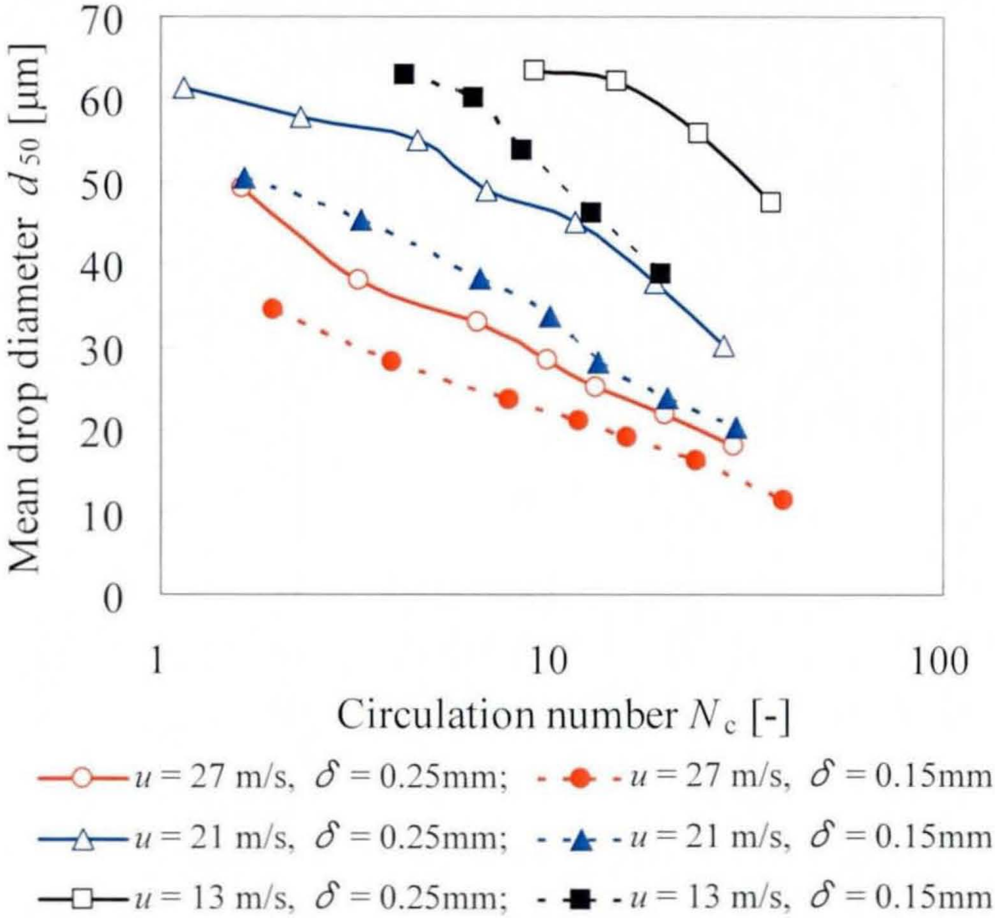

Fig. 2-4 Profiles of the circulation number vs. the mean drop diameter by Magic Lab

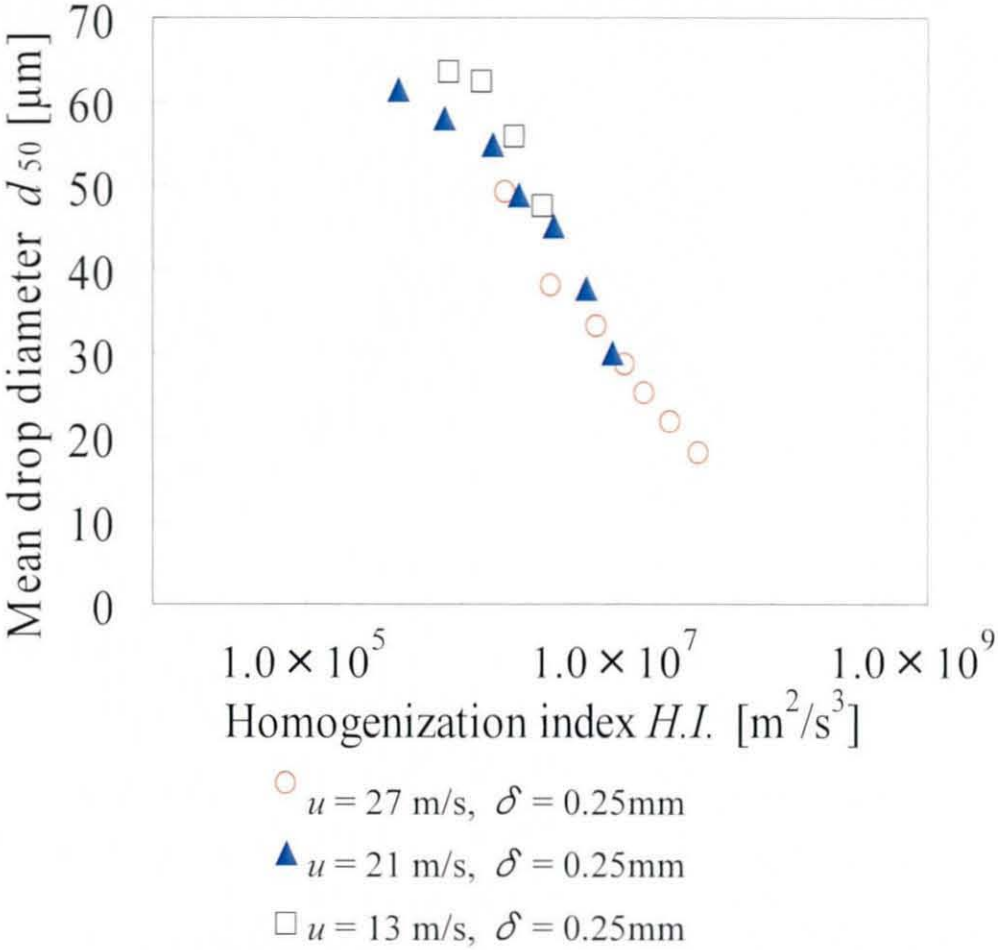

Fig. 2-5 Profiles of the homogenization index vs. the mean drop diameter in different rotor speed by Magic Lab

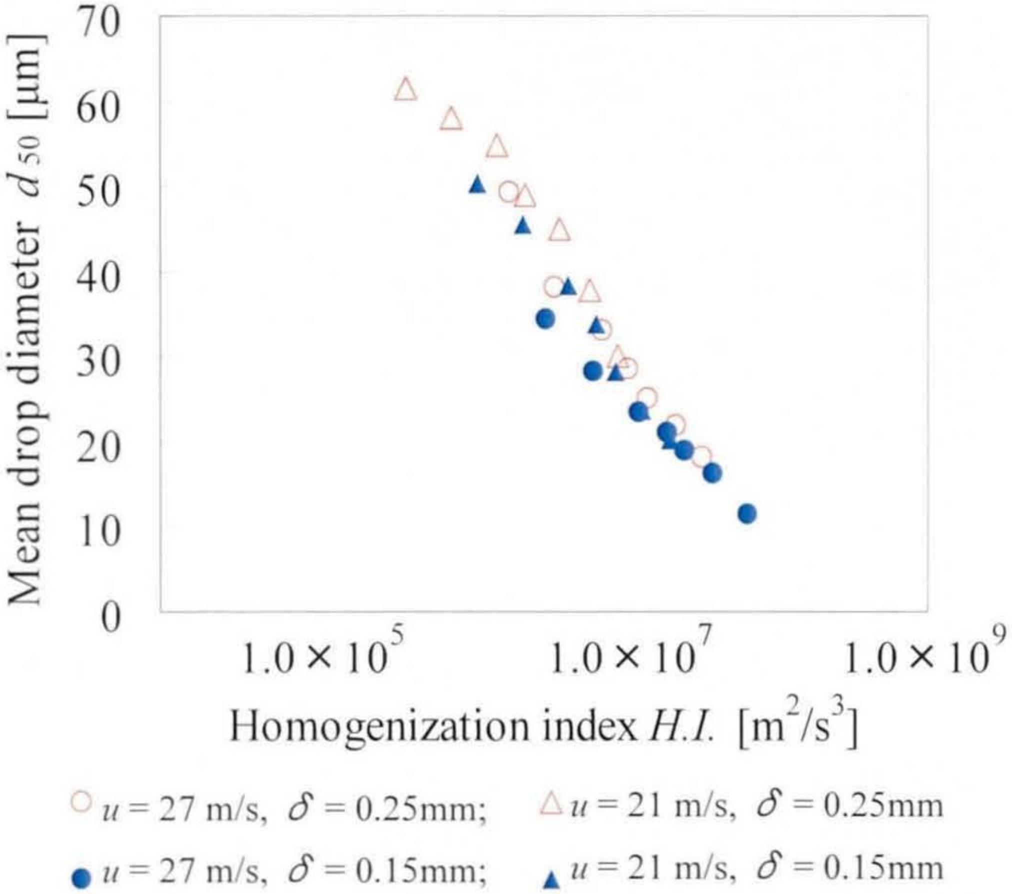

Fig. 2-6 Profiles of the homogenization index vs. the mean drop diameter in different gap width by Magic Lab

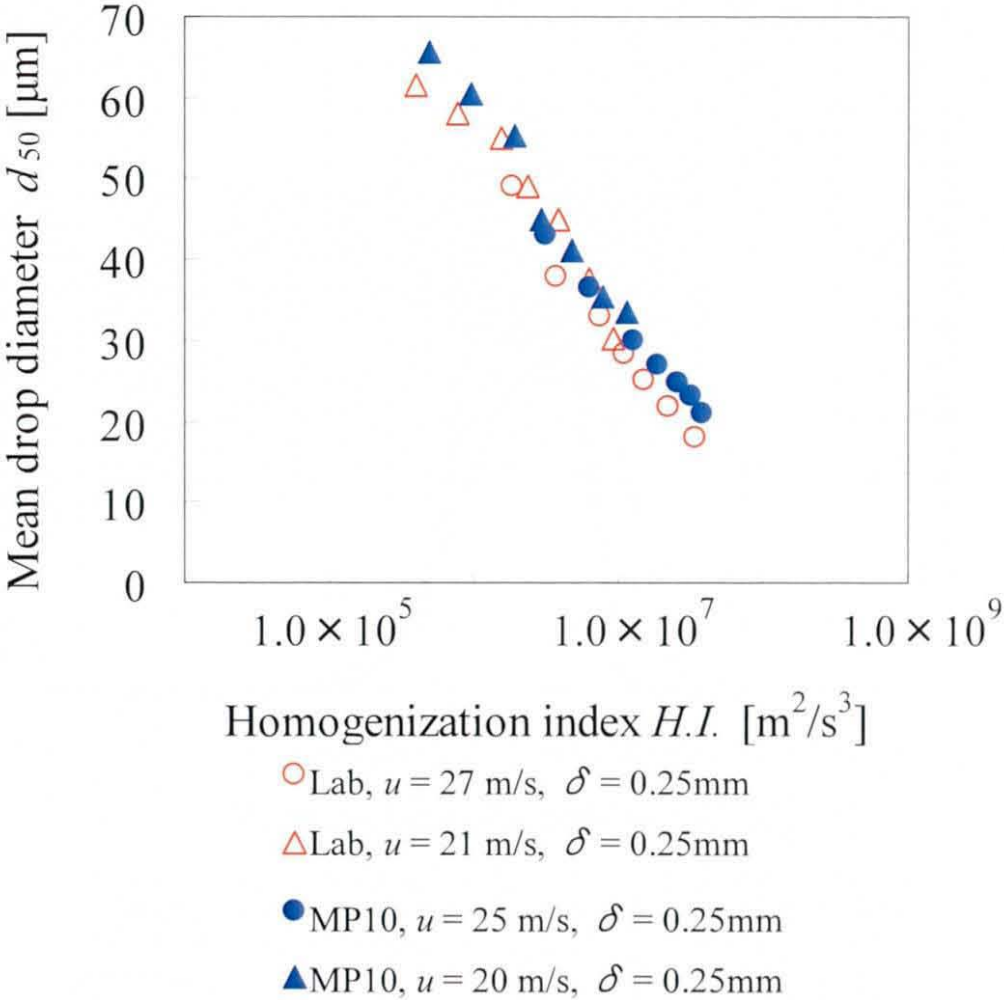

Fig. 2-7 Profiles of the homogenization index vs. the mean drop diameter in different mixer size

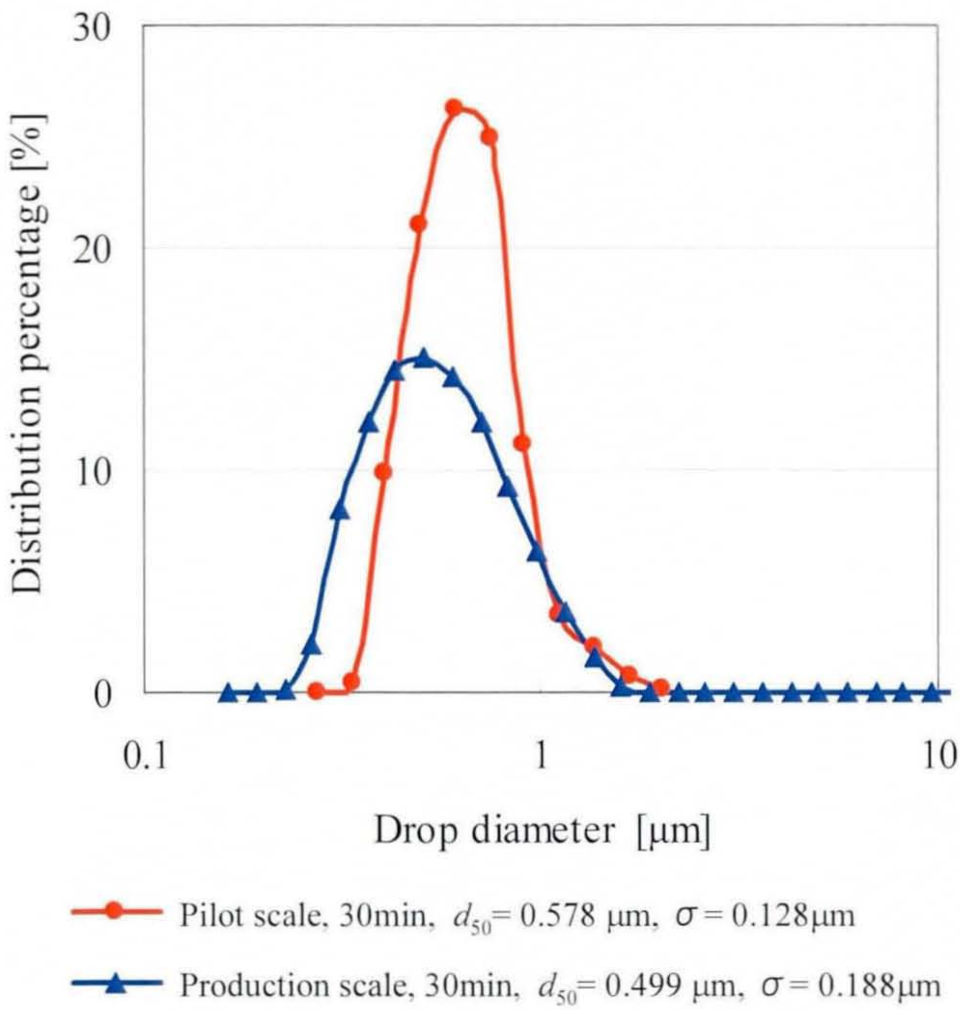

Fig. 2-8 Comparison of drop size distribution between the pilot scale and the production scale

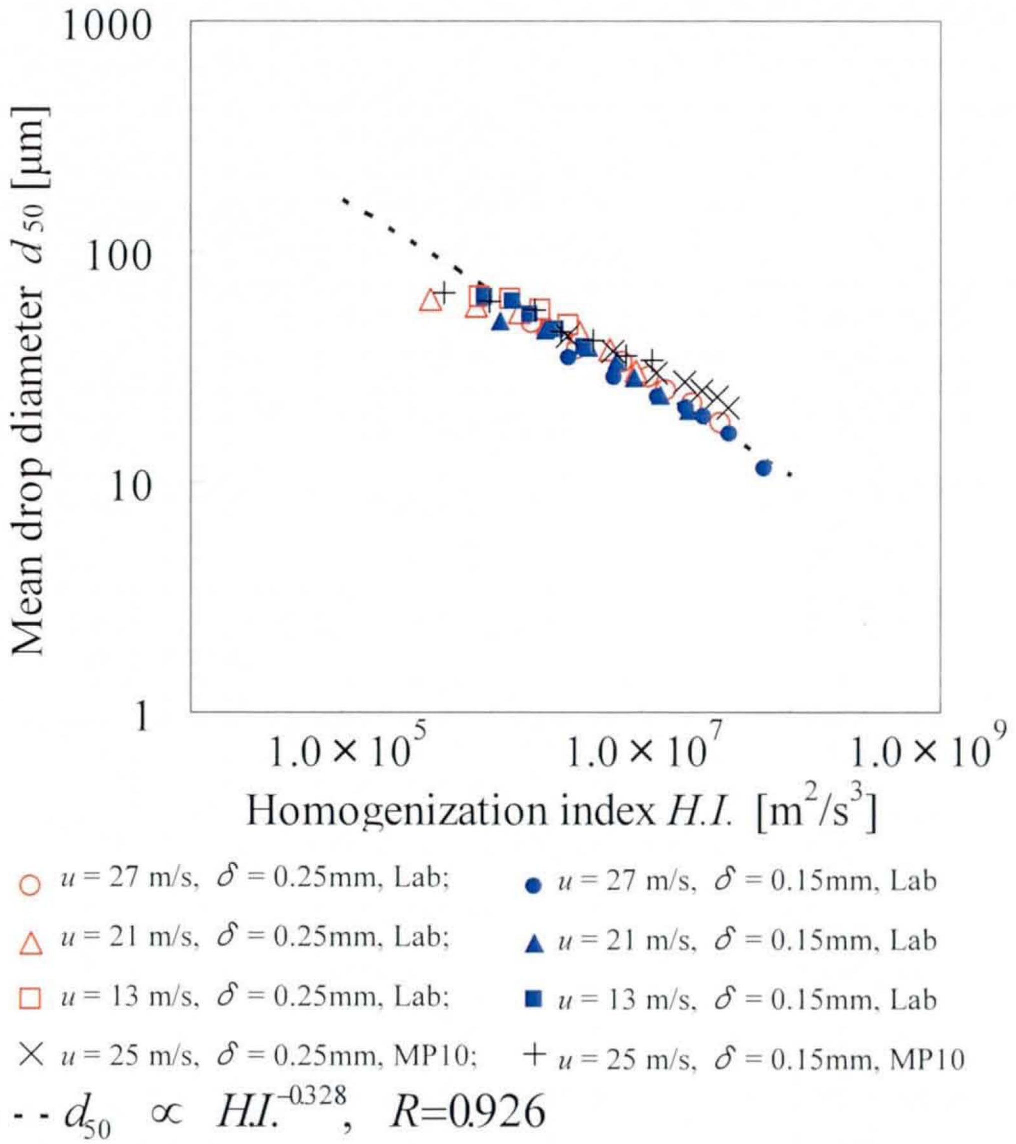

Fig. 2-9 Profiles of the homogenization index vs. the mean drop diameter in all experimental data

Table 2-1 General information of mixing unit

		Magic Lab (Small mixer)		MP-10 (Large mixer)
		Standard gap	Wide gap	
Maximum motor power [kW]	$P_{g,max}$	0.9		1.5
Maximum speed [rpm]	N_{max}	26000		8400
Rotor diameter [mm]	d	30.1	29.9	57
Stator diameter [mm]	d_s	30.4	30.4	57.5
Gap width [mm]	δ	0.15	0.25	0.25
Number of stator slots [-]	n_s	6	6	5
Volume of homogenization region [m^3]	v_h	6.08×10^{-8}	8.44×10^{-8}	4.24×10^{-7}

Table 2-2 Composition and properties of the model product

Composition	Milk protein concentrate	8%
	Rape seed oil	4.5%
	Water	87.5%
	Total	100%
Ratio	Protein / Water	9.1%
	Oil / Protein	56.3%
	Oil / Water	5.1%
Properties	Density	1028 kg/m^3
	Viscosity	15 mPa·s

Table 3 Experimental conditions and calculated values

			Magic Lab V = 1.5 L						MP-10 V = 9 L	
			δ = 0.25 mm			δ = 0.15 mm			δ = 0.25 mm	
Rotational speed	N	[rpm]	17000	13600	8400	17000	13600	8400	8400	6720
Rotor tip velocity	u	[m/s]	26.6	21.3	13.2	26.8	21.4	13.2	25.1	20
Flow rate	Q	[m^3/h]	0.291	0.215	0.164	0.352	0.295	0.19	2.86	2.13
Circulation number per minute	N_c / min	[1/min]	3.23	2.39	1.82	3.91	3.28	2.11	5.29	3.95
Net power consumption	P_n	[W]	158	55.5	15.8	176	81.2	22.9	1026	346
Homogenization power consumption	P_h	[W]	101	28.5	8.0	106.0	43.5	13.6	527	107
Ratio of contributed to homogenization	P_h.P_n	[-]	0.64	0.51	0.51	0.60	0.54	0.59	0.51	0.31
Homogenization index per minute	$H.I.$	[m^2/s^3] at 1mm	3.77×10^6	7.84×10^5	1.67×10^5	6.63×10^6	2.28×10^6	4.60×10^5	6.39×10^6	9.75×10^5

Chapter 3 Evaluating Method of Homogenization Effect for Different Stator Configurations of Internally Circulated Batch Rotor-Stator Mixers

3.1 Introduction

High-speed rotor-stator mixers have been broadly used in process industries as a process intensification tool to accelerate mixing, dissolution, homogenization, dispersion, and emulsification. In a typical configuration, these mixers consist of a high-speed rotor (that drives the mixing process) in close proximity to a stator (a fixed element with slots). These mixing units generate a high shear rate that ranges from 20,000 to 100,000 s^{-1} (Atiemo-Obeng and Calabrese, 2004). Therefore, these devices are also called high-shear mixers.

Many manufacturers have developed and provided a variety of rotor-stator mixers that have, for the most part, a different design. However, methods of comparing emulsification and homogenization from different rotor-stator configurations have not been developed. Therefore, a quantitative evaluation of the homogenization performance with different types of rotor-stator mixers has been difficult thus far. In order to predict the mean drop diameter on a production-scale, a method to evaluate the homogenization effect from different rotor-stator configurations is required.

Over the last few decades, many studies have focused on the homogenization or emulsification process with different types of high-shear devices. Bourne and Garcia-Rosas (1986) studied the micro-mixing performance of different rotor-stator configurations in the same mixing device (six types of rotors and two types of stators). They concluded that there is an optimum combination of rotor-stator set; however, the stators had a negligible effect on both the predicted energy dissipation and the measured product distributions in their mixing system.

Davies (1987) reported on the maximum stable drop size for different types of emulsification devices (static mixers, turbine impellers, colloid mills, and fine-valve homogenizers). He concluded that the drop size decreases with an increase in the energy dissipation rate per unit mass. Maa and Hsu (1996) compared the equilibrium drop size between different sizes and configurations of rotor-stator sets (four-blade rotors with 12 rectangular slots and two-blade rotors with 8 slant slots). They also compared the trend in drop size reduction of the different sets; however, they did not discuss the effects of the differences in mixer configurations theoretically.

Calabrese *et al.* (2000, 2002) reported the effect of different clearance gaps between the rotor and the stator (standard clearance: 0.5 mm, wide clearance: 1.0 mm). They found that the drop size for wide clearance geometry is smaller than that for standard clearance geometry. While the reason for this is not apparent, they concluded that the mechanical shear force created in the shear clearance does not control the ultimate drop size.

With regard to the theoretical effect of different mixer configurations, Porcelli (2002) reported an evaluation index called the shear number that was derived from the shear frequency and shear rate. Porcelli (2002) considered the number of rotor blades and stator openings; however, the scale-up accuracy and the scope of their theories were unknown.

Urban (2006) reported the drop size for different types of emulsification devices (rotor-stator system, disc system, and high-pressure system). Although he compared the mean drop diameter experimentally, he did not discuss the theoretical effects of differences in mixer configurations.

Kamiya *et al.* (2009) proposed a homogenization index to scale-up and estimated the mean drop diameter in relation to the mixing time for externally circulated batch rotor-stator mixers. However, this index is not applicable to various mixer designs and stator configurations.

As noted above, many studies have focused on the comparison of different types of emulsification devices under experimental conditions; however, a theoretical evaluation to address the effect of different configurations of rotor-stator mixers has not been carried out.

In this chapter, a theoretical evaluation method of the homogenization effect from different stator configurations of internally circulated batch rotor-stator mixers is proposed. This evaluation method allows a comparison and assessment of the homogenization effect for different configurations of rotor-stator mixers by water mixing operations without actual product operation.

3.2 Theory

3.2.1 Calculation methods of power consumption, average shear stress, and average force

Kamiya *et al.* (2009) defined the power consumption that contributed to a homogenization as P_h [W]. They assumed that the homogenization effect was related to P_h. P_h is calculated by subtracting the net power consumption P_n [W] from the pump power consumption P_p [W] as follows:

$$P_n = N_p \rho N^3 D^5 \quad (3\text{-}1)$$

$$P_p = \rho \pi^2 N^2 D^2 Q$$

$$= N_{qd} \pi^2 \rho N^3 D^5 \quad (3\text{-}2)$$

$$P_h = P_n - P_p$$

$$= (N_p - \pi^2 N_{qd}) \rho N^3 D^5 \quad (3\text{-}3)$$

where N is the rotational speed [1/s]; N_p, the power number [-]; N_{qd}, the flow number [-]; ρ, the density [kg/m^3]; Q, the flow rate [m^3/s]; and D, the rotor diameter [m]. All variables in Eq. (3-3) can be derived experimentally.

According to Tatterson (2002), the power consumption was calculated by multiplying the flow rate (impeller pumping) by the shear stress (head). From this relationship, the average shear stress at a stator hole τ_a [N/m^2] is calculated by Eqs. (3-1)– (3-3) as follows:

$$\tau_a = \frac{P_h}{Q}$$

$$= \rho N^2 D^2 \left(\frac{N_p}{N_{qd}} - \pi^2 \right) \qquad (3\text{-}4)$$

Figure 3-1 shows the schematic diagram of the rotor-stator mixing unit and the details of a stator hole.

According to Utomo *et al.* (2008), the energy dissipation rate in the rotor swept volume was low. The energy dissipation rate around the leading and trailing edges of the stator holes was higher than that in the other parts due to stagnation of fluid on these edges.

From these facts, it is assumed that the area subjected to the shear stress S_s [m^2] is the sum of the area of the side wall S_l [m^2] and the area of a stator hole cross section S_d [m^2].

$$S_s = S_d + S_l$$

$$= (\pi d l + \frac{\pi}{4} d^2) \qquad (3\text{-}5)$$

Here, d is the stator hole diameter [m] and l, the thickness of the stator wall [m].

Therefore, the average force at a stator hole F_a [N] is calculated by multiplying the shear stress (Eq. (3-4)) by the area subjected to the shear stress (Eq. (3-5)) as follows:

$$F_a = \tau_a \cdot S_s$$
$$= \rho N^2 D^2 \left(\frac{N_p}{N_{qd}} - \pi^2 \right) (\pi d l + \frac{\pi}{4} d^2) \qquad (3\text{-}6)$$

3.2.2 Calculation methods of total energy dissipation rate and homogenization coefficient

Davies (1987) reported that the drop size decreases with an increase in the energy dissipation rate per unit mass. Utomo *et al.* (2008) also suggested that the energy dissipation rate is the highest when the blade overlaps with the leading edges. It is considered that the energy dissipation rate to be one of the key factors for homogenization. And it is also considered that the energy dissipation rate is the homogenization intensity in a single pass through a stator hole. From the result of the dimension analysis to lead an energy dissipation rate, the energy dissipation rate at a local volume ε_l [m^2/s^3] is calculated by the average force (Eq.(3-6)), rotor tip velocity U [m/s], density ρ, and volume of stator hole v_s as follows:

$$\varepsilon_l = \frac{F_a U}{\rho v_s}$$

$$= \frac{\pi^4 d N^3 D^3}{v_s} \left(l + \frac{d}{4} \right) \left(\frac{N_p}{N_{qd} \pi^2} - 1 \right) \qquad (3\text{-}7)$$

As the other key factor for homogenization with rotor-stator mixers, Porcelli (2002) defined the shear frequency f_s [1/s]. This factor expresses the frequency of overlaps with a rotor blade and a stator hole as follows:

$$f_s = n_r n_s N \tag{3-8}$$

where n_r is the number of rotor blades [-] and n_s, the number of stator holes [-]. When the opening ratio of the stator is defined as A [-], n_s can be expressed as follows:

$$n_s = A\frac{4(D+2\delta)h}{d^2} \tag{3-9}$$

where δ is the clearance between the rotor and the stator [m] and h, the height of the stator [m].

In this study, Porcelli's shear frequency theory for a unit hole was modified. The number of holes n_v in the total volume V [-] is calculated as follows.

$$n_v = \frac{V}{v_s} \tag{3-10}$$

In order to estimate the number of times the product receives the shear stress at a hole, the shear frequency for a unit hole $f_{s,h}$ [1/s] is calculated by dividing f_s by n_v.

$$
\begin{aligned}
f_{\mathrm{s,h}} &= \frac{n_{\mathrm{s}} n_{\mathrm{r}} N}{n_{\mathrm{v}}} \\
&= A \frac{4(D+2\delta)h}{d^2} \frac{v_{\mathrm{s}}}{V} n_{\mathrm{r}} N
\end{aligned}
\tag{3-11}
$$

Davies (1987) experimentally indicated that the mean drop diameter depends on the energy dissipation rate per unit mass. Utomo *et al.* (2008) numerically suggested that the energy dissipation rate around the leading and trailing edges of the stator holes was higher than that at the other parts. Porcelli (2002) theoretically reported the importance of the shear frequency for the mean drop diameter in rotor-stator mixers. From these facts, it is assumed that the main factor for homogenization is the total energy dissipation rate ε_{t} [m^2/s^3], which contains information about the local energy dissipation rate ε_{l}, shear frequency of a unit hole $f_{\mathrm{s,h}}$, and mixing time t_{m} [s]. t_{m} is added to the equation used in the dimension analysis. ε_{t} is expressed as follows:

$$
\begin{aligned}
\varepsilon_{\mathrm{t}} &= \varepsilon_{\mathrm{l}} f_{\mathrm{s,h}} t_{\mathrm{m}} \\
&= \left[\frac{\pi^4 d N^3 D^3}{v_{\mathrm{s}}}\left(l+\frac{d}{4}\right)\left(\frac{N_{\mathrm{p}}}{N_{\mathrm{qd}}\pi^2}-1\right)\right]\left(A\frac{4(D+2\delta)h}{d^2}\frac{v_{\mathrm{s}}}{V}n_{\mathrm{r}}N\right)t_{\mathrm{m}} \\
&= \left[A\pi^4 n_{\mathrm{r}}(D+2\delta)D^3 h\left(\frac{4l}{d}+1\right)\left(\frac{N_{\mathrm{p}}}{N_{\mathrm{qd}}\pi^2}-1\right)\right]\left(\frac{N^4}{V}t_{\mathrm{m}}\right)
\end{aligned}
$$

$$= C_{\mathrm{h}} \frac{N^4}{V} t_{\mathrm{m}} \tag{3-12}$$

$$C_{\mathrm{h}} = A\pi^4 n_{\mathrm{r}} (D + 2\delta) D^3 h \left(\frac{4l}{d} + 1 \right) \left(\frac{N_{\mathrm{p}}}{N_{\mathrm{qd}} \pi^2} - 1 \right) \tag{3-13}$$

where C_{h} is the homogenization coefficient [m^5]. As this coefficient depends on the rotor-stator configurations, it is possible to evaluate the stator performance from C_{h}.

3.3 Experimental

3.3.1 Experimental apparatus

The rotor-stator mixer investigated in this study is Turbo Mixer (SPM-100V, Tetra Pak Scanima A/S). The mixer head is shown in **Figure 3-2**.

The stator, which is installed at the bottom of a tank, is a dynamic one. It can be moved up and down while being operated. In the up state, the stator is in the circulation mode, and in the down state, it is in the homogenization mode.

In order to compare the effect of different rotor-stator configurations, 5 different configuration stators for the internally circulated batch rotor-stator mixer were used. Details about the mixer specifications and configurations are listed in **Table 3-1**. Rotor-stator mixers generally have external and internal circulation systems. The schematic diagrams of both circulation systems are shown in **Figure 3-3**. Over the last few decades, batch mixing systems that employ external circulation have been extensively used in various fields. More recently, in the chemical, food, and pharmaceutical fields, users have preferred an internally circulated batch mixing system because it is possible to build a less complex system and the system exhibits good performance on a large production scale. Therefore, this study mainly focused on an internal circulation system; however, it is difficult to directly measure the circulated flow rate in an internal circulation system. Thus, the flow rate of the external circulation system with a similar mixing head as the internal circulation system is used.

3.3.2 Materials

In order to simulate the emulsion of food products, milk protein concentration powder (MPC-80, DMV International bv.) and rapeseed oil (Cocolin rapeseed oil, Taiyo Yushi Corp.) were used for the model product. Their composition and properties are listed in **Table 2-2**. The composition ratios of protein to water, oil to protein, and oil to water were similar to those found in typical dairy products.

3.3.3 Preparation and evaluation methods

The preparation procedure was as follows. First, hot water (40–50°C) and rapeseed oil (15–25°C) were added to the mixing tank. Then, the mixer was turned on at low rotational speed and the dynamic stator was set to the up state (circulation mode) in order to obtain a rough dispersion of oil and water. After premixing, the vacuum pump was turned on and the milk protein powder was vacuum-sucked into the mixing tank. Finally, the dynamic stator was set to the down state (homogenization mode) and the rotational speed was increased to the setting value. The mean drop diameter was evaluated in drop size measurement increments (mean drop diameter d_{50} [m]) using a laser diffraction particle size analyzer (SALD-2000, Shimadzu Corp.). The time at which the rotor speed reached the setting value was considered as the start of the mixing time. Samples were taken at certain time intervals to measure the mean drop diameter.

3.4 Results and Discussion

All measured and calculated values for the operation with the model product are summarized in **Table 3-2**. The discussion of the adequacy of the mixer performance estimation is based on C_h shown in Table 3-2 and the results of the drop size measurement.

3.4.1 Mean drop diameter for different stators

Figure 3-4 shows the mean drop diameters for different stators under the same rotational speed conditions for the model product. Homogenization effects of stators No. 3 and No. 4 are more or less equivalent, and stator No. 5 is confirmed to be the most efficient stator (narrow clearance and smaller hole diameter) in the experiment. Table 3-2 lists the stators in order of the homogenization effect based on C_h.

It is clear from Fig. 3-4 that the mean drop diameter of the model product decreases with C_h. From this result, it is considered that C_h could be used to predict the mean drop diameter in relation to the different stator configurations.

3.4.2 Influence of stator hole diameter

In order to explain the effect of the stator hole diameter, the influence of each hole diameter was examined.

Figure 3-5 shows the relationship between the stator hole diameter and $C_h/C_{h,\ std}$, which is obtained by dividing each stator C_h from the standard stator (No. 4) $C_{h,\ std}$ under the same operating conditions.

All the plotted trials were carried out using an externally circulated batch mixer that has four different hole diameter stators (d = 1, 2, 4, 6 mm) under the same opening ratio (A = 0.24) and clearance (δ = 1 mm). In the case of rotor-stator mixers of this study, $C_h/C_{h,\ std}$ increases when the stator hole diameter is small. For example, $C_h/C_{h,\ std}$ for 2 mm hole diameter is 1.75 times that for 4 mm hole diameter. This suggests that the stator hole diameter strongly affects the homogenization process. From Eq. (3-9), a smaller stator hole diameter implies a larger number of stator holes (n_s) for the same opening ratio.

In order to confirm the adequacy of quantity estimation by C_h, the measured and estimated values of the mean drop diameter for the model product were compared, as shown in **Figure 3-6**. The verification experiment using the model product was carried out using an internally circulated mixer that has two different hole diameter stators (d = 1 and 4 mm).

The estimated mixing time of stator No. 5, which has the same mean drop diameter as stator No. 4, was calculated by dividing the mixing time of stator No. 4 by $C_h/C_{h,\,std}$ of stator No. 5. The estimated decreasing trend of the mean drop diameter of stator No. 5 was the same as that obtained experimentally. This confirms that the quantity estimation using C_h for the homogenization effect has good adequacy.

3.4.3 Influence of stator opening ratio

In order to demonstrate the effect of the stator opening area, the influence of the different opening ratio is examined.

Figure 3-7 shows the relationship between the stator opening ratio and $C_h/C_{h,\,std}$ for the same stator hole diameter and rotor-stator clearance. All the plotted trials were carried out using an externally circulated batch mixer that has three different opening ratio stators (A = 0.12, 0.24, 0.36) under the same hole diameter (d = 4 mm) and clearance (δ = 1 mm). $C_h/C_{h,\,std}$ is much higher when the stator opening ratio is larger. For example, in the case of an opening of 0.36, the opening ratio is 1.5; however, $C_h/C_{h,\,std}$ increases to 1.74 for an opening of 0.24. This suggests that the stator opening ratio strongly influences the stator performance. With respect to the hole diameter, a large opening ratio also implies a larger number of stator holes (n_s), by Eq. (3-9). From these results, it is clear that the number of stator holes is an important factor for assessing the stator performance. In order to confirm the adequacy of the quantity estimation by C_h, the decreasing trend in the mean drop diameter for the measured and estimated values were compared. The verification experiment using the model product was carried out using an internally circulated mixer that has three different opening stators (A = 0.11, 0.20, and 0.31).

Figure 3-8 shows the estimated decreasing trend of the mean drop diameters of stators No. 1 and No. 3, which were obtained by the experimental results of stator No. 2. The estimated mixing time of each stator, which has the same mean drop diameter as stator No. 2, was calculated by dividing the mixing time of stator No. 2 by $C_h/C_{h,\,std}$ values of stators No. 1 and No. 3. It was found that the performance estimation using C_h has a high degree of adequacy.

3.4.4 Influence of clearance between rotor and stator

In order to demonstrate the relationship between the rotor-stator clearance and $C_h/C_{h,\,std}$, the same comparison was carried out. In the case of 1 and 2 mm rotor-stator clearances, $C_h/C_{h,\,std}$ was slightly large (1.07 times) when the rotor-stator clearance was reduced by half (2 mm to 1 mm). This suggests that the clearance influences the stator performance; however, the effect is lesser than that of the hole diameter and the stator opening ratio.

With regard to the effect of the clearance, Calabrese *et al.* (2000, 2002) and Utomo *et al.* (2008) indicated that the shear clearance between the rotor and the stator is not a major factor responsible for drop breakup. It is more likely that breakup occurs in the stator slots or in the jet emanation from the stator slot. A narrow clearance in the stator slot, however, contributes to a high level of turbulent kinetic energy. Therefore, they deduced that this narrow clearance is necessary for efficient dispersion. Results of this study could be similarly explained.

3.4.5 Total energy dissipation rate and mean drop diameter

Figure 3-9 shows the mean drop diameter as a function of the total energy dissipation rate ε_t. All data are the same as those shown in Fig. 3-4. The mean drop diameter is similar when ε_t is the same regardless of the stator configuration and mixing time. As indicated in Eq. (3-12), ε_t contains information about the mixer configuration, power consumption, flow rate, and mixing time. The mean drop diameter, therefore, can be determined using ε_t in relation to the mixing time and stator configuration.

This implies that ε_t can be adequately used to evaluate the homogenization intensity for a single pass through a stator hole, suggesting that ε_t can be applied to a wide range of different stator configurations for estimating the mean drop diameter.

This information could be useful for determining the optimum mixer design and the adequate mixer selection.

3.5 Conclusions

In this chapter, a method of evaluating the homogenization effect for different stator configurations of batch rotor-stator mixers with internal circulation was proposed. The homogenization effect for different stator configurations was evaluated by the homogenization coefficient (C_h) based on the power number, flow number, and shear frequency derived from the number of rotor blades and stator holes. Using a water mixing operation, it was found that the homogenization effect was much higher in the case of a smaller stator hole diameter and larger number of stator holes. Based on the C_h evaluations, it was also found that the clearance between the rotor and the stator had less influence on the homogenization effect than the hole diameter and number of holes. It is verified that the adequacy of the mean drop diameter estimation by C_h using model product trials. The total energy dissipation rate that was contained by the C_h could well account for the mean drop diameter in relation to the mixing time and the stator configuration differences. Results of this study indicate that we can compare and evaluate the homogenization effect for different configurations of rotor-stator mixers using C_h by a water mixing operation without actual product trials.

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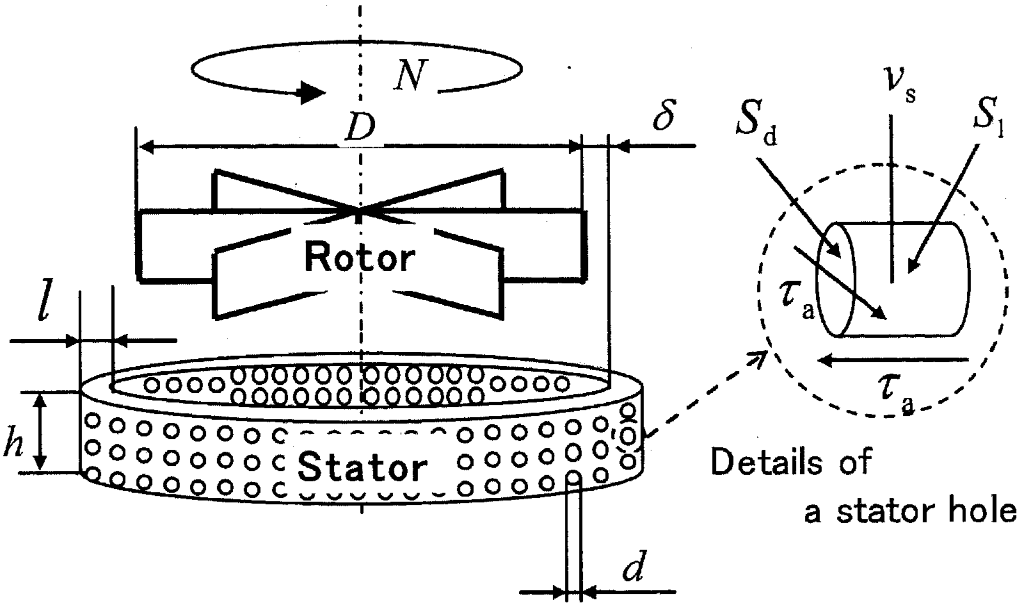

Fig. 3-1 Schematic diagram of the mixing unit

Top view of rotor Side view of rotor Top view of stator

Fig. 3-2 Photographs of the rotor and the stator

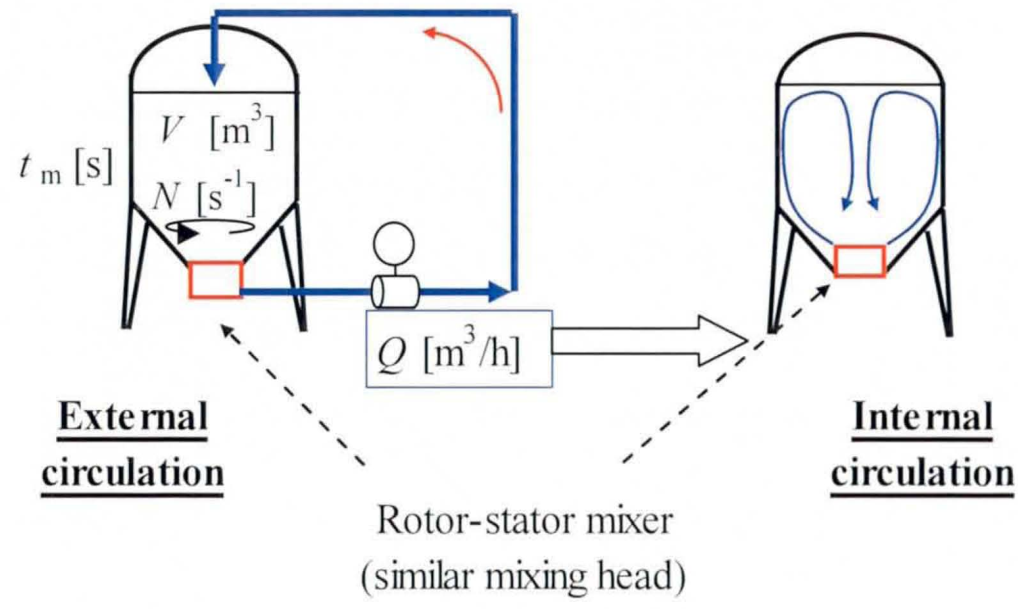

Fig. 3-3 Flow diagram of external and internal circulation system

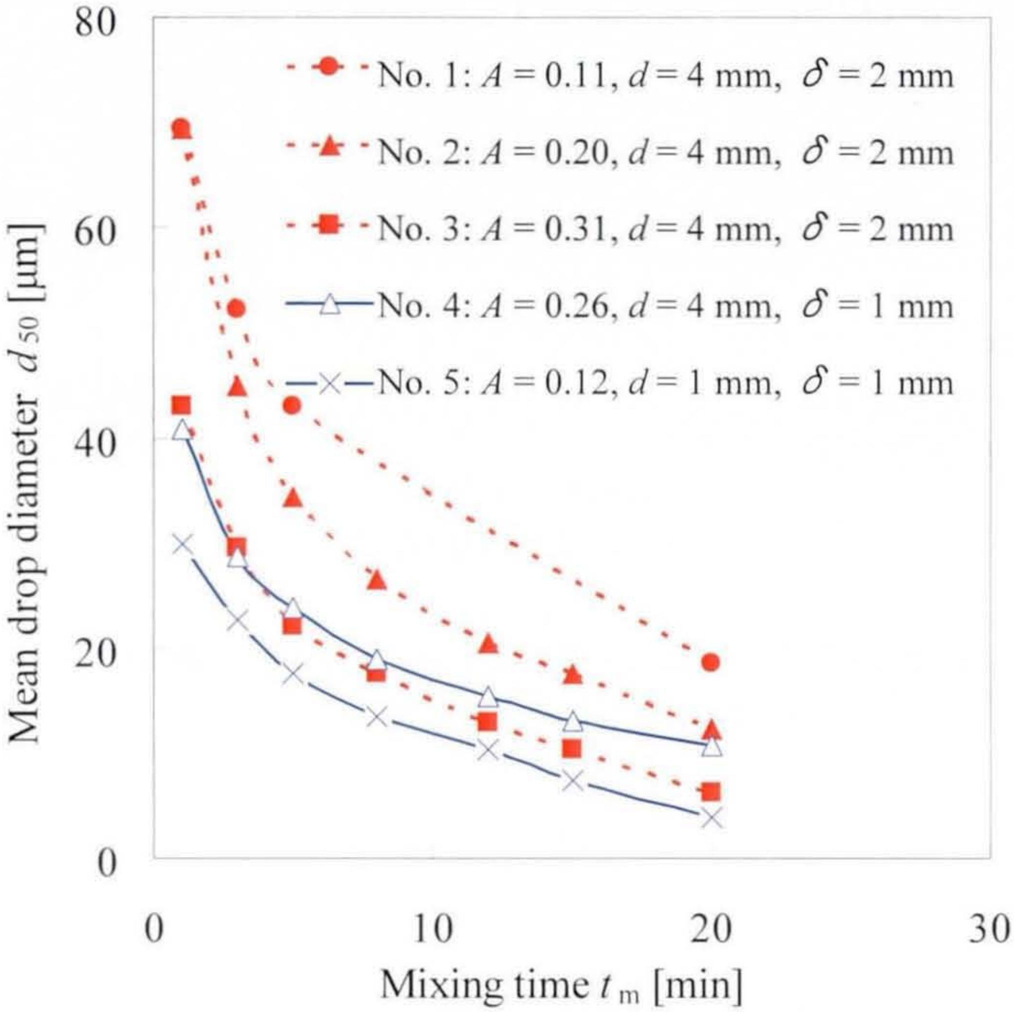

Fig. 3-4 Profiles of mixing time vs. mean drop diameter for all experimental

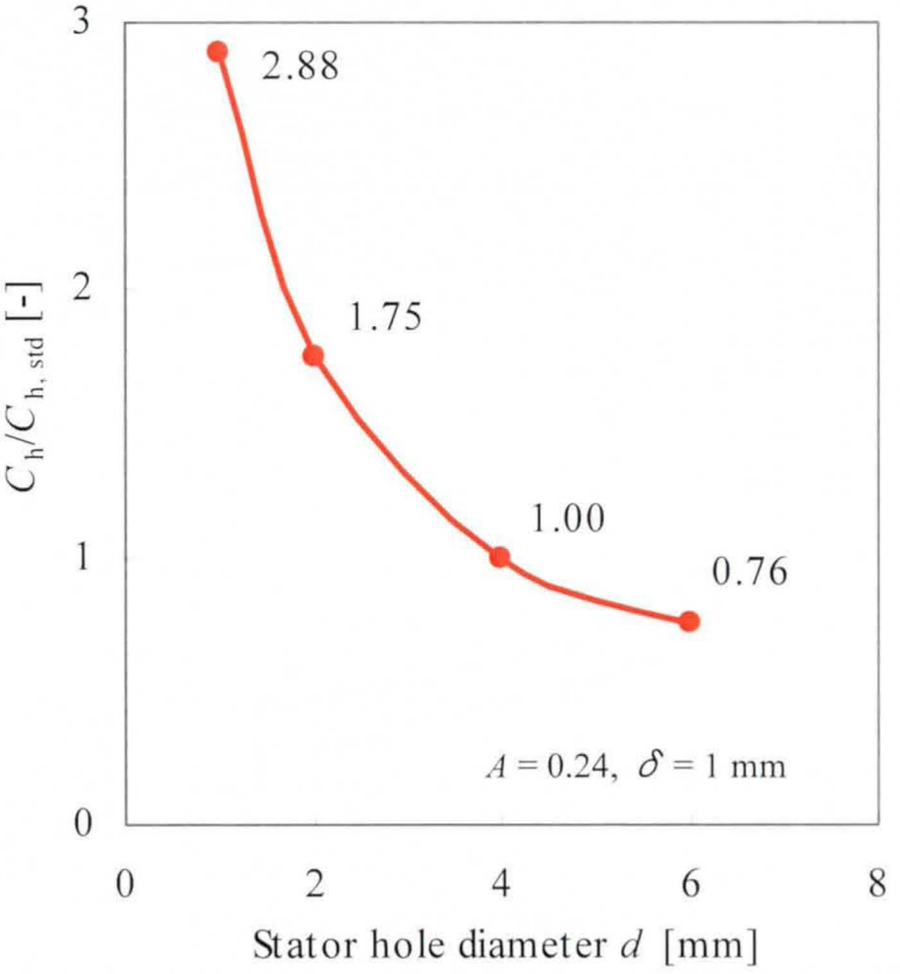

Fig. 3-5 Influence of the stator hole diameter evaluated by the ratio of homogenization coefficient (Externally circulated mixer)

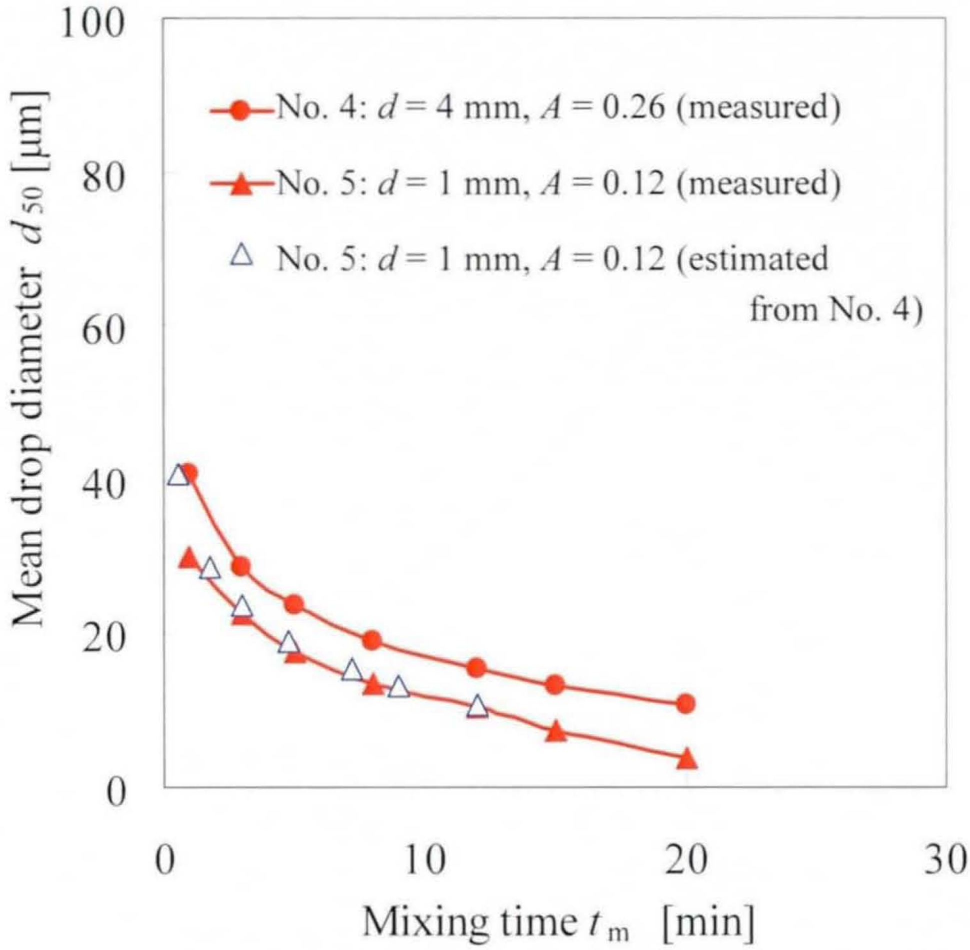

Fig. 3-6 Comparison between experimental and estimated drop size profiles of stator No. 5 and those of stator No. 4 (Internally circulated mixer)

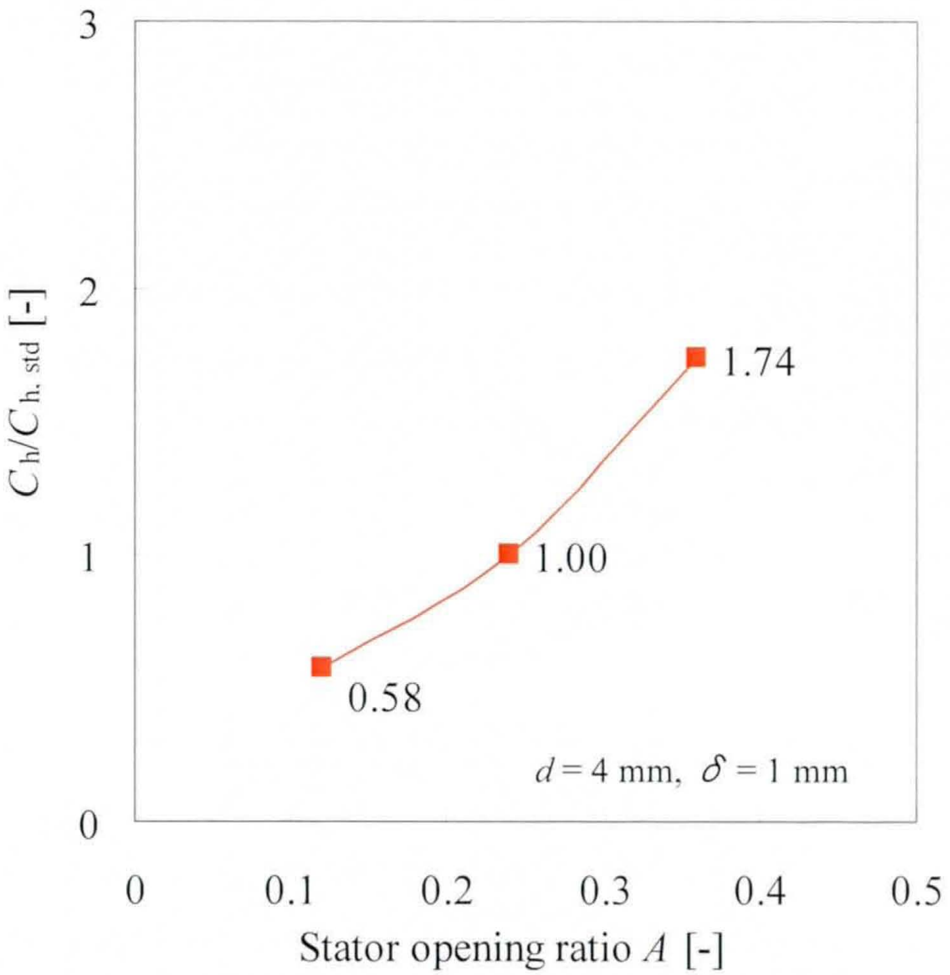

Fig. 3-7 Influence of the stator opening ratio evaluated by the ratio of homogenization coefficient (Externally circulated mixer)

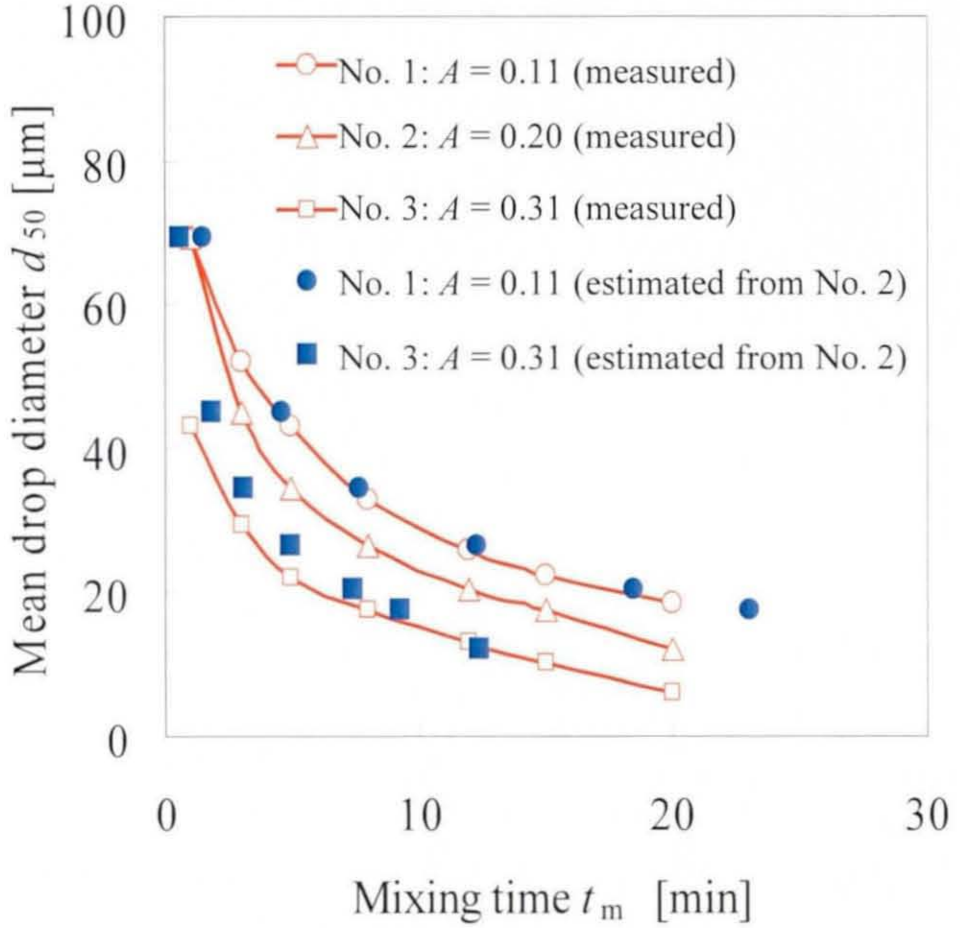

Fig. 3-8 Comparison between experimental and estimated drop size profiles of stator No. 1 and No. 3 and those of stator No. 2 (Internally circulated mixer)

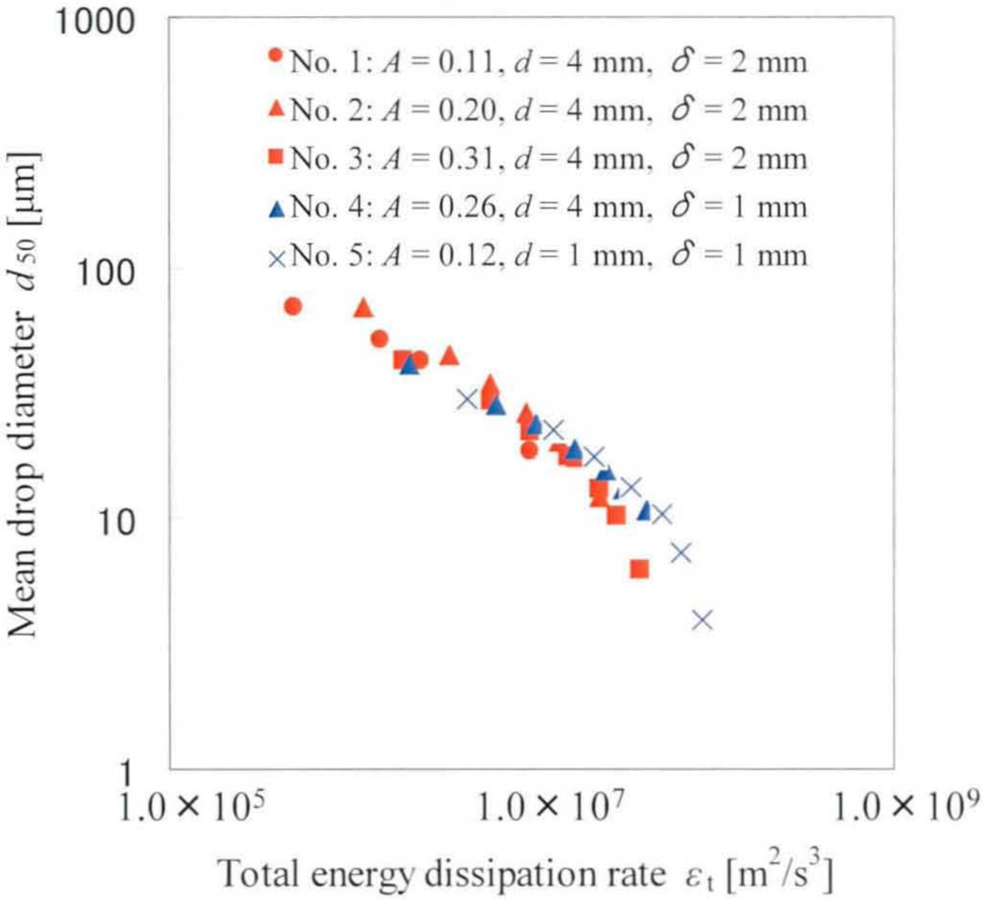

Fig. 3-9 Profiles of total energy dissipation rate vs. mean drop diameter for all experimental data

Table 3-1 Details of mixer specifications and configurations

Mixer type			Internally circulated batch mixer				
Stator No.			1	2	3	4 (Standard)	5
Stator hole diameter	d	[mm]	4	4	4	4	1
Opening ratio	A	[%]	0.11	0.20	0.31	0.26	0.12
Number of stator holes	n_s	[-]	173	316	500	411	3090
Thickness of stator wall	l	[mm]	2	2	2	2.5	2.5
Clearance between rotor and stator	δ	[mm]	2	2	2	1	1

Rotor diameter D:198 mm
Number of rotor blades n_r: 6
Stator height h: 32 mm

Table 3-2 Measured values for calculation of homogenizaiton coefficient(C_h) and energy dissipation ratio (ε_t)

Material: Model product (MPC-80 and Rape seed oil) N = 1317 [rpm], V = 0.1 [m^3]

Stator No.			1	2	3	4 (Standard)	5
Net power consumption	P_n	[kW]	2.52	3.10	3.24	3.37	3.45
Power number	N_p	[-]	0.76	0.94	0.98	1.02	1.04
Flow rate measured from external circulated mixer	Q	[m^3/h]	34.5	39.0	39.9	39.8	35.7
Flow number	N_{qd}	[-]	0.056	0.064	0.065	0.065	0.058
Power consumption for pumping	P_p	[kW]	1.84	2.08	2.12	2.12	1.90
Power consumption for homogenization	P_h	[kW]	0.69	1.03	1.12	1.25	1.55
Ratio of contributed to homogenization	P_h/P_n	[-]	0.27	0.33	0.34	0.37	0.45
Average shear stress	τ_a	[N/m^2]	7.16×10^4	9.48×10^4	1.01×10^5	1.13×10^5	1.56×10^5
Shear frequency per unit volume	$n_s n_r N/V$	[1/(s·m^3)]	2.28×10^5	4.16×10^5	6.59×10^5	5.41×10^5	4.07×10^6
Shear area	S_s	[m^2]	3.77×10^{-5}	3.77×10^{-5}	3.77×10^{-5}	4.40×10^{-5}	8.64×10^{-6}
Total energy dissipation ratio at 1min	ε_t	[m^2/s^3]	4.90×10^5	1.19×10^6	1.99×10^6	2.14×10^6	4.38×10^6
Homogenization coefficient	C_h	[m^5]	3.52×10^{-3}	8.51×10^{-3}	1.43×10^{-2}	1.54×10^{-2}	3.14×10^{-2}
Ratio of homogenization coefficient	$C_h/C_{h,std}$	[-]	0.23	0.55	0.93	1.00	2.04

Chapter 4 Scale-Up Factor for Mean Drop Diameter in Internally Circulated Batch Rotor-Stator Mixers

4.1 Introduction

Rotor-stator mixers are used in chemical, biochemical, food-processing, cosmetic, and pharmaceutical industries to produce emulsions and liquid–liquid dispersions. The distinguishing feature of rotor-stator mixers is that a high-speed rotor (a driven mixing element) operates in close proximity to a stator (a fixed mixing element). These mixing units generate a high shear rate that ranges from 20,000 to 100,000 s^{-1} (Atiemo-Obeng and Calabrese, 2004). Therefore, these devices are also called high-shear mixers.

Although a rotor-stator mixer is a highly efficient device, its drop-size distribution is generally much broader than that of a fine-clearance valve homogenizer. This is why rotor-stator mixers are usually used in pre-emulsification processes in an actual production line. From an engineering viewpoint, obtaining information about the decreasing trend of the mean drop diameter is more important than obtaining information about the maximum stable drop size, which is obtained over a long mixing time, for the design of production lines.

Over the past few decades, externally circulated batch mixing systems have been extensively used in various fields. However, in recent times, internally circulated batch mixing systems are preferred, especially in the chemical, food, and pharmaceutical industries, because these systems are less complex and they show good performance on a large production-scale. For these reasons, this study has mainly focused on internally circulated mixing systems.

Over the last several decades, a number of studies on the rotor-stator mixer have been carried out. Davies (1985, 1987) investigated the maximum stable drop size and reported that it decreases with an increase in the energy dissipation rate per unit mass. This phenomenon has been observed in different types of emulsification devices (static mixers, turbine impellers, colloid mills, and fine-valve homogenizers). Davies (1987) also indicated that the turbulent fluctuation velocity and the shear rate are not responsible for drop breakup.

Calabrese *et al.* (2000, 2002) studied the drop breakup mechanism in a rotor-stator mixer in detail. Their investigations revealed that a shear gap between the rotor and the stator does not play a significant role in drop breakup. Breakup is more likely to occur in the stator slots or during jet emanation from the stator slots. A narrow gap in the stator slots, however, contributes to the turbulent kinetic energy produced therein. From this observation, Calabrese *et al.* (2000, 2002) deduced that this narrow gap is necessary for efficient dispersion.

Utomo *et al.* (2008) conducted a study on the energy dissipation rate of a rotor-stator mixer by performing complete three-dimensional computational fluid dynamics simulations, and they found that the energy dissipation rate was the maximum around the leading and trailing edges of the stator slots. However, the energy dissipated in the slot region was 7.6% of the total energy supplied by the rotor. They also found that energy dissipation rate on the stator wall was high, suggesting that the gap between the rotor and the stator cannot be disregarded in the processes of dispersion and emulsification.

Utomo *et al.* (2008) also indicated that the scale-up procedure for mixers should be based on the constant energy dissipation rate per unit mass and the geometrical similarities rather than constant tip speed and constant gap width, as proposed by other researchers (Bourne and Studer, 1992; Atiemo-Obeng and Calabrese, 2004).

In addition to the abovementioned scale-up factors, another factor, termed shear number, which is derived from the shear frequency and the shear rate, has been proposed by Porcelli (2002). This proposed scale-up factor takes into account the number of rotor blades and stator openings; however, the adequacy of scale-up and scope of their theories are unknown.

Kamiya *et al.* (2009a) proposed a homogenization index for scaling up and estimated the mean drop diameter in terms of the mixing time for pilot-scale externally circulated batch rotor-stator mixers. However, this index is not applicable to internally circulated mixers and mixers that are less affected by the clearance between the rotor and the stator.

Thus far, researchers have focused on pilot-scale mixers and the maximum stable drop size that is obtained over a long mixing time. However, studies have not been conducted on the decreasing trend of the mean drop diameter and the correspondence between the scale-up factor and mixing time of a production-scale mixer.

In this chapter, the scale-up factor in terms of the mixing time is derived. This factor can also be used to explain the mean drop diameter in relation to the mixing time for different configurations of rotor-stator mixers as well as under different operating conditions and production scales.

4.2 Theory

4.2.1 Estimation method of internal circulation flow rate for production-scale mixers

Figure 4-1 shows the estimation method of circulation flow rate for production-scale mixers. In general, it is difficult to estimate the internal circulation flow rate of a conventional mixing tank. However, in the case of the pilot-scale rotor-stator mixer, an inline type of mixing pump (externally circulated mixing pump) is used; the mixing unit of this pump is similar to that of an internally circulated batch rotor-stator mixer. Therefore, the circulation flow rate of the pilot-scale rotor-stator mixer can be estimated using the inline type of mixing pump (Fig. 4-1(a) and (b)).

The diameter of the mixing unit of the production-scale mixer is in the range of 300–400 mm and it were unable to use an inline type of mixing pump, such as that used in the pilot-scale mixer. Thus, it was impossible to estimate the flow rate of the production-scale mixer. Hence, the flow rate of the production-scale mixer was estimated using the time required for complete mixing—termed "completely mixed time", which is given in Eq. (4-1). This equation was proposed by Kamiwano *et al.* (1967).

$$\frac{1}{T_{\mathrm{M}} \cdot N} = k\left(\left(\frac{D}{D_{\mathrm{t}}}\right)^{3} \cdot N_{\mathrm{qd}} + 0.21\left(\frac{D}{D_{\mathrm{t}}}\right) \cdot \sqrt{\frac{N_{\mathrm{p}}}{N_{\mathrm{qd}}}}\right) \cdot \left(1 - \exp\left(-13\left(\frac{D}{D_{\mathrm{t}}}\right)^{2}\right)\right)$$

(4-1)

Here, T_M [s] denotes the completely mixed time; N [s^{-1}], the rotational speed; k [-], a constant that depends on the method of the measurement system; D [m], the rotor diameter; D_t [m], the tank diameter; N_{qd} [-], the flow number; and N_p [-], the power number.

Except for N_{qd}, all values can be obtained from the experiment of the completely mixed time and measurement of the power consumption. The flow rate Q [m^3/h]: is a function of N_{qd} ($Q = N_{qd}ND^3$); thus, the flow rate of the production-scale mixer could be estimated experimentally (Fig. 4-1 (b) and (c)).

In the case of normal agitating vessels, the circulation flow rate Q_c [m^3/h] is suitable for the calculation of ε_t. Q_c is the function of N_{qc} ($Q_c = N_{qc}ND^3$). But N_{qc} is difficult to estimate directly. In this study, we assume Q_c is nearly equal to Q. Hence, it is considered that Q could be used for the calculation of ε_t, alternatively.

4.2.2 Calculation method of total energy dissipation rate

Figure 3-1 shows a schematic diagram of the rotor-stator mixing unit. According to Utomo *et al.* (2008), the energy dissipation rate around the leading and trailing edges of the stator holes was of a higher order of magnitude owing to the stagnation of the fluid therein.

Davies (1987) indicated that the mean drop diameter depends on the energy dissipation rate per unit mass. In chapter 3 it was stated that the mean drop diameter can be determined from the total energy dissipation rate ε_t [m^2/s^3] in terms of the mixing time for pilot-scale batch rotor-stator mixers. From these results, it is assumed that the main factor influencing homogenization is the total energy dissipation rate ε_t. ε_t was derived as follows.

$$\varepsilon_{\mathrm{t}} = C_{\mathrm{h}} \frac{N^4}{V} t_{\mathrm{m}} \tag{4-2}$$

Here, t_m [s] is the mixing time, V [m^3] is the total product volume, and C_h [m^5] is a homogenization coefficient, which depends on the rotor-stator configuration. C_h is calculated from Eq. (4-3). More details have been provided by Chapter 3.

$$C_{\mathrm{h}} = A\pi^4 n_{\mathrm{r}} (D + 2\delta) D^3 h \left(\frac{4l}{d} + 1 \right) \left(\frac{N_{\mathrm{p}}}{N_{\mathrm{qd}} \pi^2} - 1 \right) \tag{4-3}$$

Here, A [-] denotes the opening ratio of the stator; n_r [-], the number of rotor blades; δ[m], the width of the gap between the rotor and stator; h [m], the stator height; l [m], the thickness of the stator wall; and d [m], the stator hole diameter.

4.3 Experimental

4.3.1 Experimental apparatus of internally circulated batch

rotor-stator mixers

The internally circulated batch rotor-stator mixer investigated in this chapter is the Turbo Mixer; the pilot-scale mixer (SPM-500V) and the production-scale mixer (SPV-10000V) were sourced from Tetra Pak Scanima A/S. The mixer head is shown in **Figure 3-2**. The stator, which was installed at the bottom of the tank, was a dynamic stator: it could be moved up and down during operation. In the "up" position, the stator operated in the circulation mode, and in the "down" position, it operated in the homogenization mode. More detailed information about the mixer specifications and configurations are given in **Table 4-1**.

4.3.2 Materials for the emulsification experiment

In order to simulate the emulsion of food products, a mixture of milk protein concentrate powder (MPC-80, DMV International) and rapeseed oil (Cocolin rapeseed oil, Taiyo Yushi Corp.) was used as a model product. Their composition and properties are listed in **Table 2-2**. The composition ratios of protein to water, oil to protein, and oil to water were similar to those found in typical dairy products.

4.3.3 Measurement of completely mixed time and estimation procedure of the flow rate

The completely mixed time (the criterion for sufficient mixing) was measured by adding saturated KCL solution until the concentration of the mixture became 0.1% (conductivity: 1.343 mS/cm^2) at final consistency.

The saturated KCL solution was quickly poured into the tank from the top. The consistency was measured using an electrical conductivity meter (Smartec S CLD 132, Endress+Hauser), which was installed on a side wall of the tank (Fig. 4-1 (b) and (c)).

The completely mixed time was defined as the deviation from the normalized concentration difference. In this study, the time at which the deviation value of the normalized concentration difference reduced below 0.5% was defined as the completely mixed time.

The estimation procedure of the flow rate is as follows. T_M, N, N_{qd}, and N_p were measured using the pilot-scale mixer. The only unknown value in Eq. (4-1), k, was calculated from Eq. (4-1) for the pilot-scale mixer. Because k is a constant that depends on the type of measuring system, it was considered that k was not influenced by the measurement scale. In this study, it was assumed that k for the production-scale mixer was the same as that for the pilot-scale mixer. Thus, by measuring T_M, N, and N_p for the production-scale mixer and using k from the pilot-scale measurement, N_{qd} could be obtained from Eq. (4-1). The flow rate Q is a function of N_{qd} ($Q = N_{qd}ND^3$); thus, the flow rate of the production-scale mixer could be estimated experimentally.

4.3.4 Preparation procedure of emulsification experiment and evaluation of the mean drop diameter

The preparation procedure was as follows. First, hot water (40–50°C) and rapeseed oil (15–25°C) were added to the mixing tank. Then, the mixer was turned on at a low rotational speed and the dynamic stator was set to the "up" position (circulation mode) in order to obtain a coarse dispersion of oil and water. After premixing, a vacuum pump was turned on and the milk protein powder was vacuum sucked into the mixing tank. Finally, the dynamic stator was set to the "down" position (homogenization mode), and the rotational speed was increased to a setting value.

The mean drop diameter was evaluated in drop size increments (mean drop diameter d_{50}) using a laser diffraction particle size analyzer (SALD-2000, Shimadzu Corp.). The time at which the rotor speed reached the setting value was considered the start time of mixing. Samples were taken at certain time intervals to measure the mean drop diameter.

4.4 Results and Discussion

4.4.1 Completely mixed time and circulation flow rate of production-scale mixer

The measured completely mixed time and the estimated circulation flow rates are shown in **Table 4-2**. The value of k for the production-scale mixer, given in Table 4-2, was used as the average value for the pilot-scale mixer (0.033). The completely mixed time at the production-scale into the same experimental condition was 31 and 32 sec respectively. Thus the average value (31.5sec) was used for the flow rate calculation. Using average value of k and the completely mixed time, the circulation flow rate of the production-scale mixer was estimated as 234 m^3/h.

4.4.2 Influence of mixing time and production volume on mean drop diameter

All the experimental conditions and calculated values are summarized in **Table 4-3**. The adequacy of the scale-up factor based on ε_t is shown in Table 4-3, and the results of drop size measurements are discussed.

Figure 4-2 shows the relationship between the mean drop diameter and the mixing time at different rotational speeds and product volumes for the pilot-scale mixer. The drop size decreases rapidly at a high rotor speed, small product volume, and long mixing time. From the result of comparison between the stator No. 2 and 4, it is clearly indicated that the mean drop diameter is strongly affected by the rotor tip speed.

In order to confirm the influence of the product volume, the relationship between the circulation number and the drop size was examined, as shown in **Figure 4-3**. All data are the same as those shown in Figure 4-2. The circulation number N_c [-] is defined as follows:

$$N_c = \frac{Q}{V} \cdot t_m \qquad (4\text{-}4)$$

The circulation number includes information about the mixing time t_m and product volume V. From this figure, it can be seen that the mean drop diameter is the same at a given rotational speed, irrespective of the product volume

In the case of the same rotational speed, the mean drop diameter was determined by the circulation number. However, it was inferred that the circulation number did not necessarily influence the mean drop diameter at different rotational speeds. This result indicates that it is necessary to evaluate the homogenization intensity during a single pass through the mixing unit.

4.4.3 Relationship between the mean drop diameter and total energy dissipation rate

In order to confirm the validity of the evaluation method of the homogenization effect using ε_t, the mean drop diameters obtained under different operating conditions were compared.

Figure 4-4 shows the mean drop diameter, which is ordered by ε_t. All data are the same as those shown in Figures 4-2 and 4-3. It was found that the drop size showed a similar slope under different product volumes and rotational speeds.

This result suggests that ε_t can be used to describe the influence of the rotor speed and product volume on the mean drop diameter. This result also suggests that ε_t adequately corresponds with the homogenization intensity during a single pass through a batch-mixing unit. It is clear from Eqs. (4-2) and (4-3) that ε_t includes information about the difference in the mixer configurations (C_h), t_m, N, and V. It was found that the mean drop diameter reduced in proportion to C_h, t_m, N^4, and V^{-1}, in theory. Because ε_t can account for the mean drop diameter, it was considered the evaluation theory of the homogenization effect to be validated.

4.4.4 Validity of scale-up method for mean drop diameter using total energy dissipation rate

Figure 4-5 shows the mean drop diameter, ordered by ε_t, for different-sized mixers and at various rotational speeds. As shown in Figure 4-4, the mean drop diameter was in good agreement for both the mixers at different rotor speeds and product volumes. The ratio of the rotor diameter of the pilot-scale mixer (0.198 m) to the rotor diameter of the production-scale mixer (0.396 m) was approximately 2.

Further, the volume ratio of the pilot-scale mixer (200 L) to the production-scale mixer (7000 L) was almost 35. The mean drop diameter could be explained using ε_t, by considering the influence of the mixer size and the batch volume. However, the large mixer produced a wider drop-size distribution, although its mean drop diameter was the same as that of the small mixer. For example, the standard deviation of production-scale mixer is much higher value (σ = 0.19) compare with the pilot-scale mixer (σ = 0.11) at similar mean drop diameter (d_{50}= 0.50 μ m).

4.4.5 Estimation method of equivalent mixing time for production-scale mixer

From an engineering viewpoint, obtaining information about an equivalent mixing time, i.e., the time after which the mean drop diameter for both the pilot- and production-scale mixers will be the same, is more important than obtaining information about the maximum stable drop size, which is obtained over a long mixing time, for the design of production lines.

Figure 4-6 shows the relationship between the rotational speed and ε_t. This figure indicates that ε_t of the production-scale mixer was smaller than ε_t of the pilot-scale mixer at the same rotational speed. This implies that the production-scale mixer required a longer mixing time to obtain the same mean drop diameter as that obtained in the pilot-scale mixer.

Table 4-4 summarizes the estimated results of the equivalent mixing time for the production-scale mixer. The theoretically estimated equivalent mixing time for the production-scale mixer at 15 s^{-1} and 17 s^{-1} was 42 min and 18 min, respectively. These mixing times corresponded to a mixing time of 5 min at 27 s^{-1} for the pilot-scale mixer.

In order to confirm the adequacy of estimation using ε_t, the decreasing trend in the mean drop diameter for the measured and estimated values was compared.

Figure 4-7 shows the estimated mean drop diameters at 15 s^{-1} and 17 s^{-1} for the production-scale mixer, which were obtained from the experimental data for the pilot-scale mixer at 27 s^{-1}. The estimated mean drop diameter of the production-scale mixer showed a decreasing trend, as in the case of the measured values. It was found that the mean drop diameter estimated using ε_t showed a high degree of adequacy. This implies that it is possible to scale-up the mean drop diameter of production-scale mixers in terms of the mixing time. It is considered that the estimation method proposed in this study to be correct.

4.5 Conclusions

In this chapter, the total energy dissipation rate (ε_t) was proposed as a scale-up factor for the mean drop diameter in internally circulated batch rotor-stator mixers. This factor was selected on the basis of the concept that the shear frequency and the local energy dissipation rate of turbulence account for the mean drop diameter at different rotor speeds for mixers with different configurations (different gap widths, rotor diameters, and opening areas) and for different product volumes. In other words, the mean drop diameter could be estimated by using ε_t. Results of this study also suggested that ε_t accurately corresponded with the homogenization intensity during a single pass through a batch-mixing unit. The scale-up criteria for the mean drop diameter in terms of the mixing time should be based on ε_t and not necessarily on geometrical similarities, constant rotor tip speed, or constant gap width, in the case of similar mixer configurations and the experimental range (200–7000 L) used for model products.

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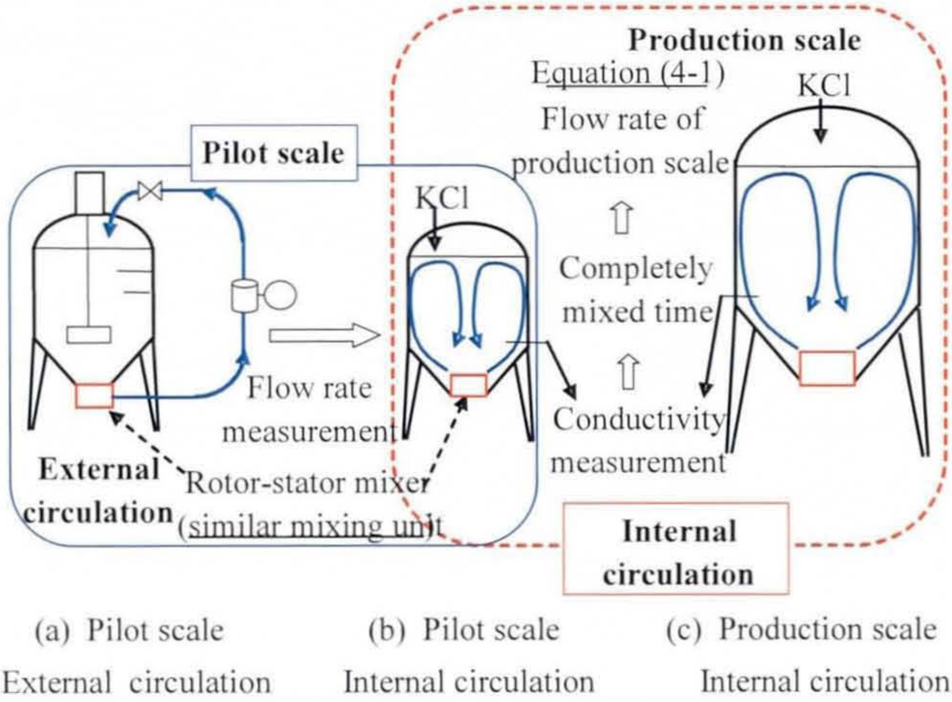

Fig. 4-1 Schematic diagram of circulation systems and the estimation method of the flow rate for the production-scale mixer

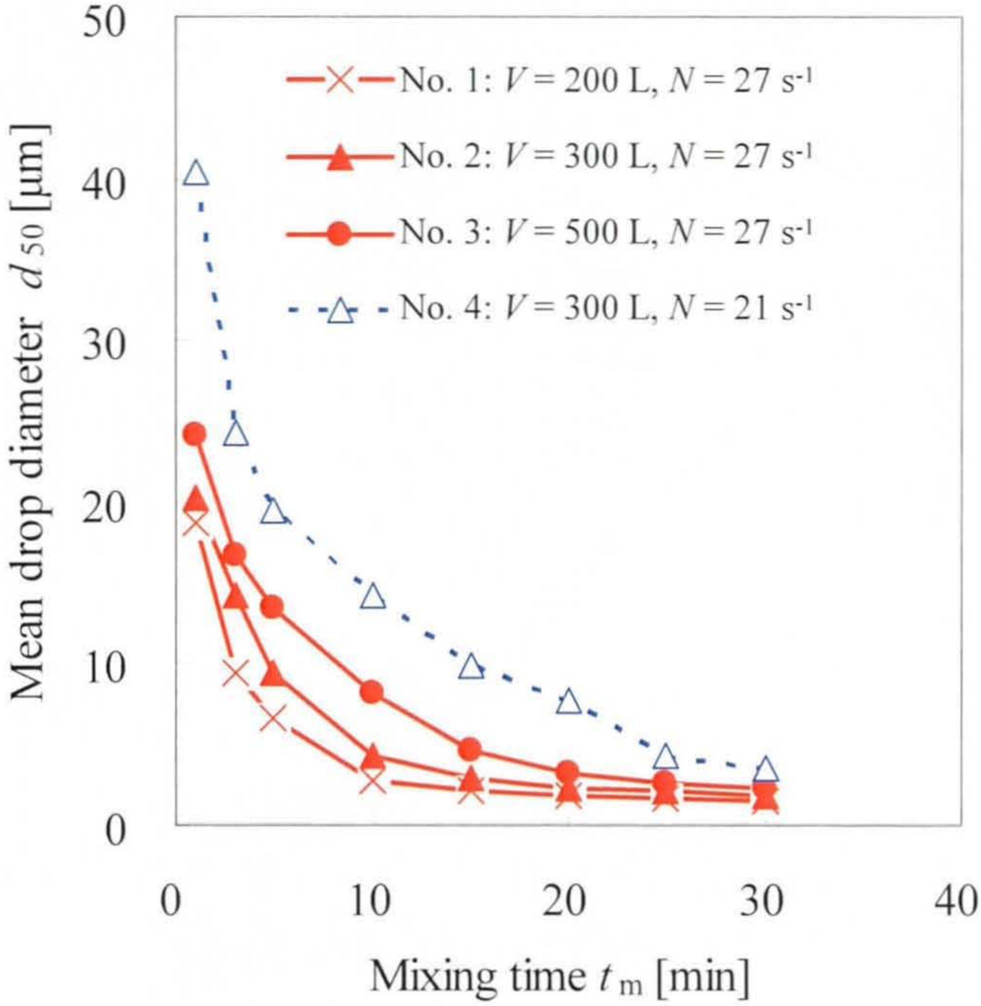

Fig. 4-2 Profiles of mixing time vs. mean drop diameter for the pilot-scale mixer

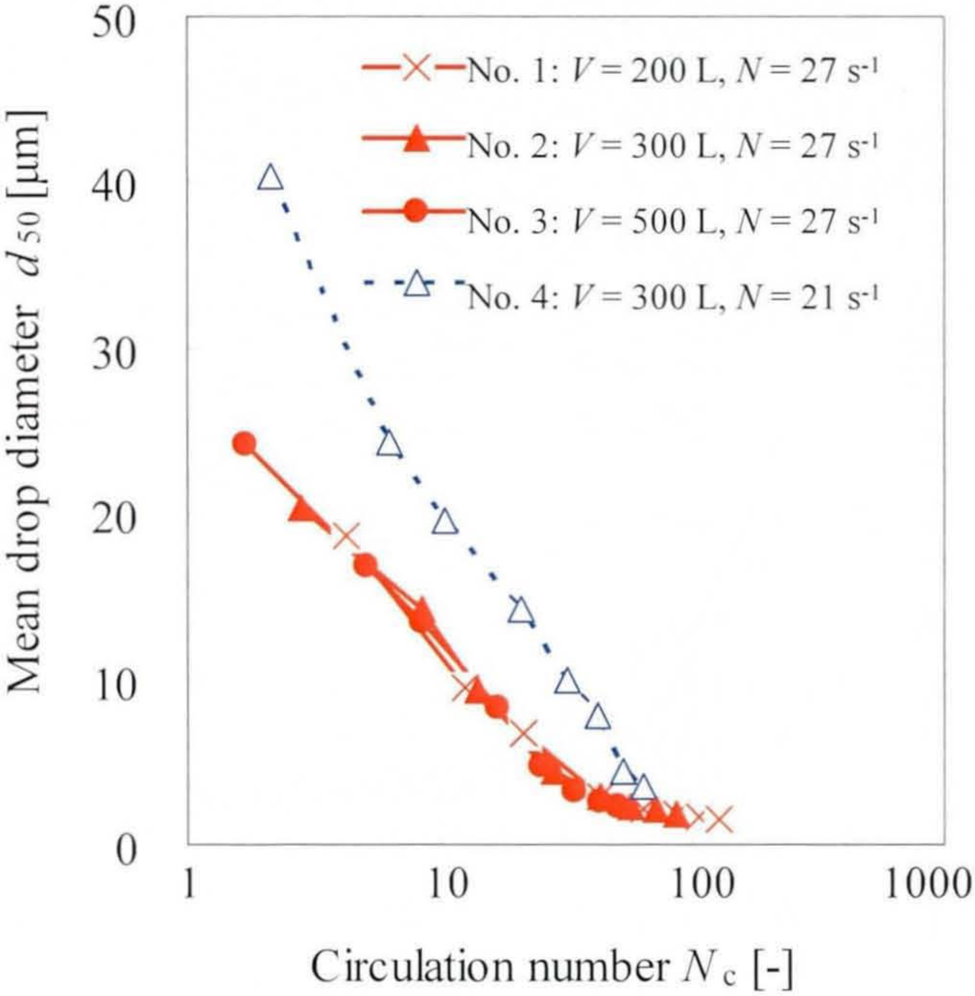

Fig. 4-3 Plot of circulation number vs. mean drop diameter for the pilot-scale mixer

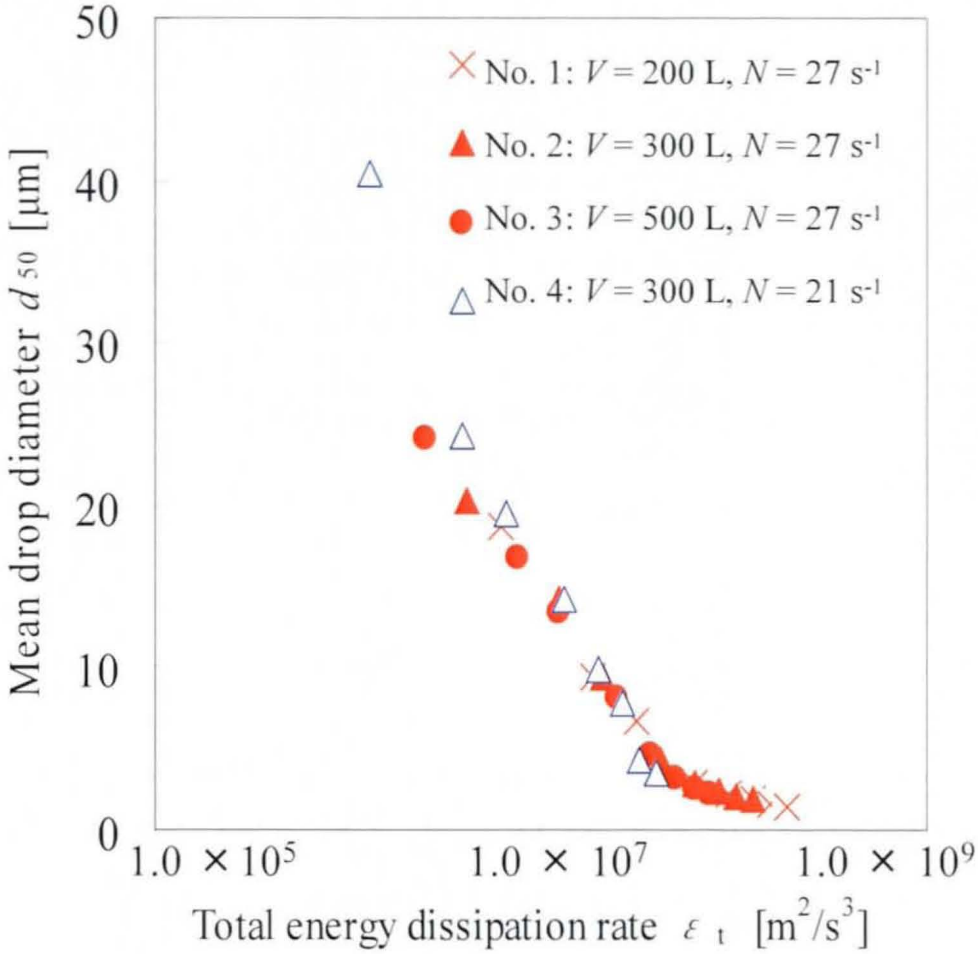

Fig. 4-4 Plot of total energy dissipation rate vs. mean drop diameter for the pilot-scale mixer

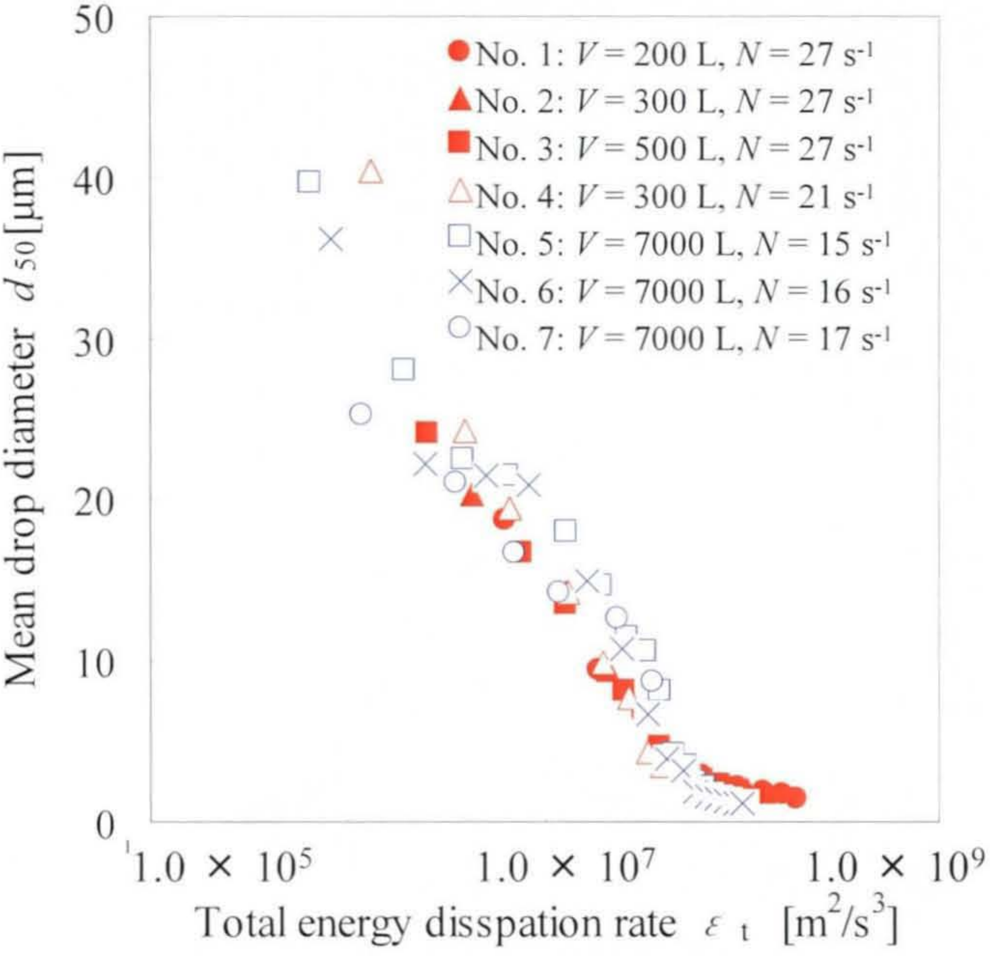

Fig. 4-5 Plot of total energy dissipation rate vs. mean drop diameter for the pilot- and the production scale mixer

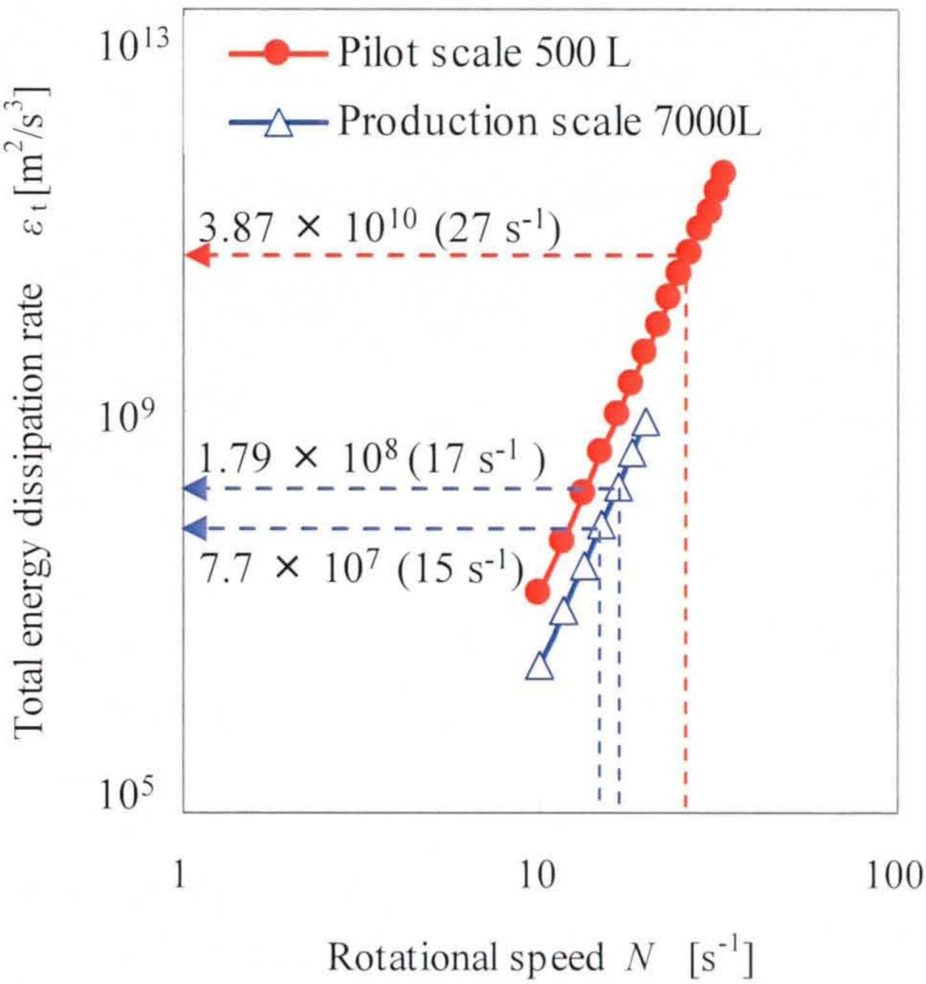

Fig. 4-6 Plot of rotational speed vs. total energy dissipation rate for the pilot and production mixer

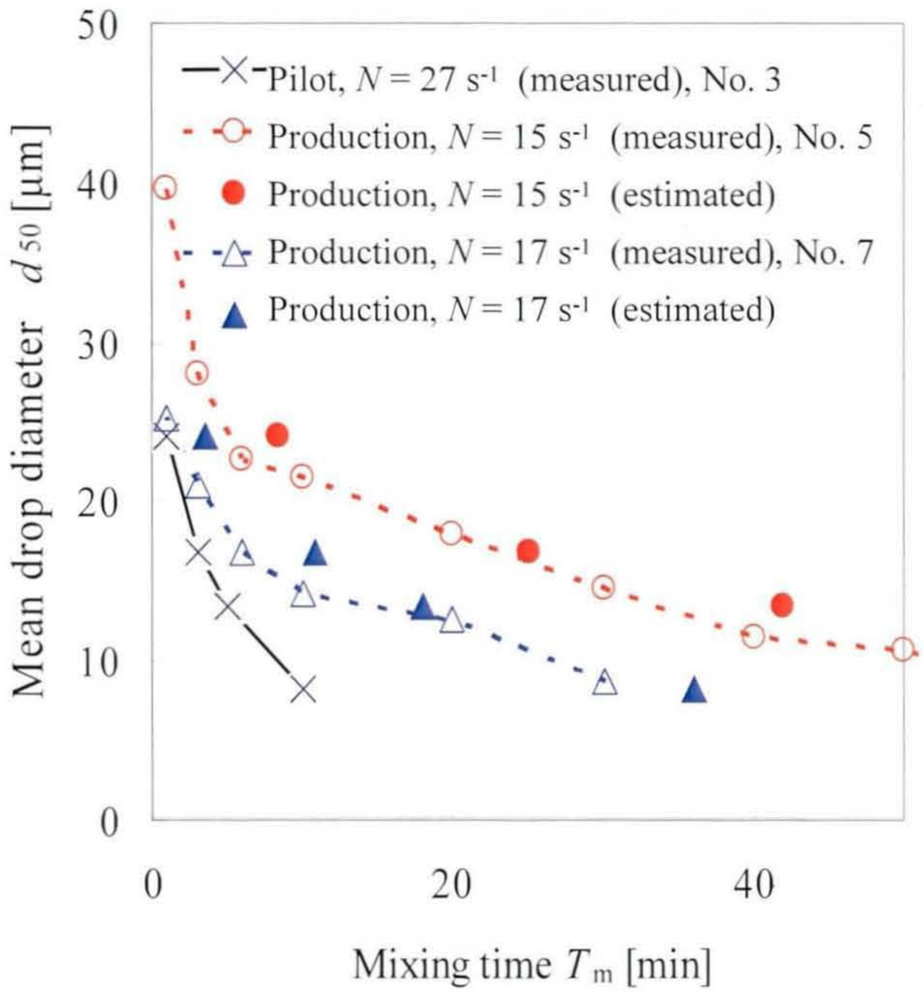

Fig. 4-7 Estimated mixing time for the production-scale mixer

Table 4-1 Specifications of mixing units

			Pilot scale φ200 mm unit	Production scale φ400 mm unit
Stator inner diameter	D_i	[m]	0.2	0.4
Rotor diameter	D	[m]	0.198	0.396
Tank diameter	D_t	[m]	0.95	2.5
Gap between rotor and stator	δ	[m]	0.001	0.002
Number of holes	n_s	[-]	414	1020
Stator height	h	[m]	0.032	0.058
Stator thickness	l	[m]	0.0025	0.005
Opening ratio	A	[-]	0.26	0.18
Maximum motor power	P_{max}	[kW]	30	160
Maximum speed	N_{max}	[1/s]	33.3	20.0

Stator hole diameter d: 4 mm
Number of stator blades n_r: 6

Table 4-2 Measured values and estimated flow rate of the production-scale mixer

			Pilot scale		Production scale
Rotational frequency	N	[1/s]	27	14	20
Power consumuption	P_{n}	[kW]	10.1	1,2	108
Power number	N_{p}	[-]	1.63	1.59	1.39
Completely mixed time	T_{M}	[s]	13	22	31.5
Nondimensional mixed time	$T_{M} \cdot N$	[-]	355	300	630
Flow number	N_{qd}	[-]	0.067	0.067	0.052
Flow rate	Q	[m^3/h]	51	26	234
Constant	k	[-]	0.030	0.036	0.033

Table 4-3 Experimental conditions, measured and calculated values of emulsification experiments

			Pilot scale				Production scale		
			1	2	3	4	5	6	7
Volume	V	[m^3]	0.2	0.3	0.5	0.3	7.0	7.0	7.0
Rotational speed	N	[1/s]	27.3	27.3	27.3	20.5	15.0	16.0	17.5
Rotor tip velocity	U	[m/s]	17.0	17.0	17.0	12.7	18.7	19.9	21.8
Net power consumption	P_n	[kW]	10.3	10.3	10.3	4.3	46.7	56.3	73.2
Power number	N_p	[-]	1.61	1.61	1.61	1.61	1.38	1.37	1.36
Estimated flow rate	Q	[m^3/h]	51.3	51.3	51.3	38.3	175.5	187.2	204.8
Flow number	N_{qd}	[-]	0.067	0.067	0.067	0.067	0.052	0.052	0.052
Pump power consumption	P_p	[kW]	4.1	4.1	4.1	1.7	16.9	20.6	26.9
Homogenization power consumption	P_h	[kW]	6.1	6.1	6.1	2.6	29.8	35.8	46.3
Ratio of cotributed to homogenization	P_h/P_n	[-]	0.60	0.60	0.60	0.60	0.64	0.63	0.63
Total energy dissipation ratio	ε_t	[m^2/s^3]	1.05×10^5	7.00×10^4	4.20×10^4	2.21×10^4	1.08×10^4	1.38×10^4	1.95×10^4

Table 4-4 Estimation result of equivalent mixing time for production-scale mixer

			Pilot scale 500 L	Production scale 7000 L	
Rotational speed	N	[1/s]	27	15	17
Rotor tip velocity	U	[m/s]	17	19	22
Total energy dissipation rate	ε_t	[m^2/s^3]	3.87×10^{10}	7.70×10^7	1.79×10^8
Equivalent mixing time	t_e	[min]	5	42	18

Chapter 5 Conclusion

5.1 General conclusion of this study

In this study, a theoretical evaluation method of the homogenization effect was proposed for different stator configurations of internally and externally circulated batch rotor-stator mixers. Further, the scale-up factor was derived in relation to the mixing time and the validity of the scale-up procedure proposed in this study was confirmed using a model product.

In **chapter 1**, the background of this study and the current knowledge was explained about general rotor-stator mixers. Further, the objectives of this study were described. Problems related to the actual operation of rotor-stator mixers and the necessity of a solution to these problems was also discussed.

In **chapter 2**, a scale-up factor (homogenization index: *H.I.*) for the mean drop diameter was proposed in externally circulated batch rotor-stator mixers. This index is based on the concept that the circulation number and local energy dissipation rate of turbulence could well account for the mean drop diameter at different rotor speeds, with different mixer configurations (gap width and rotor diameter), and for different production volumes. In other words, the mean drop diameter could be estimated by using *H.I.* This result also suggested that *H.I.* accurately corresponded with the homogenization intensity for a single pass through a batch-mixing unit. The scale-up criteria for the mean drop diameter in terms of mixing time should be based on *H.I.*, and not necessarily on geometrical similarities, the same rotor tip speed, or the same gap width in the case of similar mixer configurations and the experimental range of production volume (1 to 10 L) used for the model product.

In **chapter 3**, a method of evaluating the homogenization effect was proposed for different stator configurations of batch rotor-stator mixers with internal circulation. The homogenization effect for different stator configurations was evaluated using the homogenization coefficient (C_h) based on the power number, flow number, and shear frequency derived from the number of rotor blades and stator holes. Using a water mixing operation, it was found that the homogenization effect was considerably higher in the case of a small stator hole diameter and a large number of stator holes. Based on the C_h evaluations, it was also found that the clearance between the rotor and the stator had less influence on the homogenization effect than the hole diameter and the number of holes. the adequacy of the mean drop diameter estimation by C_h was verified using model product trials. The total energy dissipation rate that was contained by the C_h could well account for the mean drop diameter in relation to the mixing time and the stator configuration differences. The results indicated that it is possible to compare and evaluate the homogenization effect for different configurations of rotor-stator mixers using C_h in a water mixing operation without actual product trials.

In **chapter 4**, I proposed the total energy dissipation rate (ε_t) as a scale-up factor for the mean drop diameter in internally circulated batch rotor-stator mixers. This factor was selected on the basis of the concept that the shear frequency and the local energy dissipation rate of turbulence account for the mean drop diameter at different rotor speeds for mixers with different configurations (different gap widths, rotor diameters, and opening areas) and for different product volumes. In other words, the mean drop diameter could be estimated by using ε_t. The results also suggested that ε_t accurately corresponded with the homogenization intensity during a single pass through a batch-mixing unit. The scale-up criteria for the mean drop diameter in terms of the mixing time should be based on ε_t and not necessarily on geometrical similarities, constant rotor tip speed, or constant gap width, in the case of similar mixer configurations and the experimental production volume range (200–7000 L) used for the model products.

5.2 Future work

The use of rotor-stator mixers in various fields is expected to increase year after year. From an engineering viewpoint, it is considered that the necessity for an adequate evaluation of the rotor-stator mixer performance will also increase. Further, I believe that the results of this study can be adapted to various engineering needs.

In this study, in order to estimate the mean drop diameter, I proposed the use of *H.I.* for the mixer that is strongly affected by the gap between the rotor and the stator. On the other hand, I also proposed the use of ε_t for the mixer that is mainly affected by stator holes. However, I could not clarify the distinction criterion that can be used for categorizing mixers into various types. I think it will be useful if we can find the distinction criterion and develop a common index that can evaluate all types of mixers using the same theory.

At the end of this thesis, I mention the possibility of new index which merges both scale-up index *H.I.* and ε_t. The both index has same dimension (m^2/s^3). This dimension means energy dissipation rate.

The calculation theory of *H.I.* is simple, but it is difficult to be reflected the difference of mixer configurations directly. And ε_t is calculated under the ideal condition. Actually, the calculation of ε_t should be considered the leakage flow from gap between the rotor and stator. Based on these improvements, I look over the leading process of *H.I.* and ε_t again, and I propose a new scale-up and performance estimation index which connotes the concept of *H.I* and ε_t. Detail information of the leading process about new index is shown in appendix.

$$\varepsilon_a = \varepsilon_g + \varepsilon_s \tag{5-1}$$

$$\varepsilon_a = \left[\left(N_p - N_{qd}\pi^2\right)\cdot n_r\right]\cdot\left[D^3\left(K_g + K_s\right)\right]\cdot\left(\frac{N^4\cdot t_m}{V}\right) \tag{5-2}$$

$$K_g = \left(\frac{D^3 b}{\delta(D+\delta)}\right) \tag{5-3}$$

$$K_s = \frac{\pi^2 n_s^{\ 2} d(d+4\ell)}{4N_{qd}} \cdot \left(\frac{d^2}{n_s \cdot d^2 + 4\delta(D+\delta)} \right) \qquad (5\text{-}4)$$

ε_a [m^2/s^3] is overall energy dissipation rate [m^2/s^3], ε_g [m^2/s^3] is energy dissipation rate at gap which expresses similar effect of the *H.I.*, and ε_s [m^2/s^3] is energy dissipation rate at stator openings which has similar trend of ε_t. K_g [m^2] is the influence factor of gap, K_s [m^2] is the influence factor of stator openings.

I guess the reason why the *H.I.* and ε_t could well account for mean drop diameter in the definite type of mixers, using Eq. (5-2), to (5-4) as follows. In the mixer which was used at Chapter 2, K_g is dominant, K_s could be neglected. On the hands, it is considered that in the mixer which was used at chapter 3 and 4, K_s is dominant, the effect of K_g is small.

However, the new index ε_a have just led recently. The validity of the theory and accuracy of estimation and scale-up will confirm in near future.

I hope that results of this study will be used for a new mixer design that will improve the production efficiency. If we can obtain detail information of mixer configuration, power consumption, and flow rate, we can estimate the mixer performance and equivalent mixing time for production scale mixers.

Finally, this study proposes the basic idea for an evaluation method of mixer performance.

Appendix

In this appendix, we proposed a scale-up and evaluation method for estimating mean drop diameter for various batch rotor-stator mixers. We assumed that homogenization and emulsification occurs at the gap between the rotor and the stator and at the stator openings. The energy dissipation rate at the rotor tips and the stator openings is calculated experimentally using the local homogenization power consumption that is defined using the homogenization intensity of the liquid received in each area and the shear frequency, which is the number of times the product receives the shear stress in each area. We defined the overall energy dissipation rate ε_a in terms of the homogenization intensity and the shear frequency. This theoretical scale-up method has not confirmed the validity and accuracy for scale-up and performance estimation yet. It is just a concept of integration with *H.I.* and ε_t.

A-1 Theory

A-1.1 Calculation methods of the local energy dissipation rate at rotor tip

In chapter 2, authors defined the power consumption that contributed to a homogenization as P_h. They assumed that the homogenization effect was related to P_h. P_h is calculated by subtracting the net power consumption P_n from the pump power consumption P_p as given in Eqs. (A-1) to (A-3).

$$P_{\mathrm{n}} = N_{\mathrm{p}} \rho N^3 D^5 \tag{A-1}$$

$$\begin{aligned} P_{\mathrm{p}} &= \rho \pi^2 N^2 D^2 Q \\ &= N_{\mathrm{qd}} \pi^2 \rho N^3 D^5 \end{aligned} \tag{A-2}$$

$$\begin{aligned} P_{\mathrm{h}} &= P_{\mathrm{n}} - P_{\mathrm{p}} \\ &= (N_{\mathrm{p}} - \pi^2 N_{\mathrm{qd}}) \rho N^3 D^5 \end{aligned} \tag{A-3}$$

Here, N is the rotational speed; N_{p}, the power number; N_{qd}, the flow number; ρ, the density; Q, the flow rate; and D, the rotor diameter. All variables in Eq. (A-3) can be derived experimentally.

According to Tatterson (2003), the power consumption was calculated by multiplying the flow rate (impeller pumping) by the shear stress (head). From this relationship, the average shear stress at a stator hole τ_{a} is calculated by using Eqs. (A-1)– (A-3) as given in Eq. (A-4).

$$\begin{aligned} \tau_{\mathrm{a}} &= \frac{P_{\mathrm{h}}}{Q} \\ &= \rho N^2 D^2 \left(\frac{N_{\mathrm{p}}}{N_{\mathrm{qd}}} - \pi^2 \right) \end{aligned} \tag{A-4}$$

Figure A-1 shows a schematic diagram of the rotor tip. We assume that the area subjected to the shear stress S_b is the cross section of the tip of the rotor blade.

$$S_b = b \cdot h_b \tag{A-5}$$

Here, b is the thickness of the rotor blade [m], h_b is the rotor height [m]. Therefore, the average force at a stator hole F_b is calculated by multiplying the shear stress (Eq. (A-4)) with the area subjected to the shear stress (Eq. (A-5)) as given in Eq. (A-6).

$$\begin{aligned} F_b &= \tau_a \cdot S_b \\ &= \frac{\left(N_p - N_{qd}\pi^2\right)\rho N^2 D^2}{N_{qd}} \cdot b \cdot h_b \end{aligned} \tag{A-6}$$

The homogenization intensity at the tip of the rotor blade W_b is defined in terms of the average force F_b [N], velocity U [m/s], and number of rotors n_r [-] as shown in Eq. (A-7).

$$\begin{aligned} W_b &= F_b \cdot U \cdot n_r \\ &= \left(\frac{\left(N_p - N_{qd}\pi^2\right)\rho\pi \cdot n_r}{N_{qd}}\right) b \cdot h \cdot D^3 \cdot N^3 \end{aligned} \tag{A-7}$$

This factor indicates the homogenization intensity in a single pass through a product.

As the other key factor for homogenization with rotor-stator mixers, Porcelli (2002) defined the shear frequency f [1/s]. In order to estimate the number of times the product receives the shear stress at certain gap volume, the shear frequency for the gap volume f_g is calculated using Eq. (A-8). The gap volume shown in Figure 2 is calculated by subtracting the swept-out volume of the rotor diameter from the swept-out volume of the stator diameter.

$$f_g = \frac{N_{qd} N D^3}{\pi \cdot h_b \cdot \delta(D+\delta)} \qquad \text{(A-8)}$$

Here, δ is the clearance between the rotor and the stator and h_b is the height of the stator.

Davies (1987) experimentally indicated that the mean drop diameter depends on the energy dissipation rate per unit mass. Utomo *et al.* (2008) numerically suggested that the energy dissipation rate around the leading and trailing edges of the stator holes was higher than that at the other parts. Porcelli (2002) theoretically reported the importance of the shear frequency for the mean drop diameter in rotor-stator mixers. In chapter 3 and 4, authors also reported that the decreasing trend of the mean drop diameter could well account for the total energy dissipation rate. From these facts, we assume that the main factor for homogenization is the local energy dissipation rate ε_g, which contains information about the local homogenization intensity W_b, shear frequency at the rotor tip f_g and mixing time t_m. The local energy dissipation rate ε_g is expressed as follows in Eq. (A-9).

$$\varepsilon_g = \frac{W_b \cdot f_g \cdot t_m}{\rho \cdot V}$$

$$= \left[\left(N_p - N_{qd}\pi^2\right) \cdot n_r\right] \cdot \left(\frac{D^6 b}{\delta(D+\delta)}\right)\left(\frac{N^4 \cdot t_m}{V}\right) \quad \text{(A-9)}$$

A-1.2 Calculation of local energy dissipation rate at stator openings

The local energy dissipation rate at stator openings can be calculated in a manner similar to that mentioned in the above theories. The area subjected to the shear stress S_s is the sum of the area of the side wall S_w and the area of a stator-hole cross section S_d.

$$S_s = S_w + S_d$$

$$= (\pi dl + \frac{\pi}{4} d^2) \quad \text{(A-10)}$$

Here, d is the diameter of the stator hole and l is the thickness of the stator wall.

Therefore, the average force at a stator hole F_s is calculated by multiplying the shear stress (Eq. (A-4)) with the area subjected to the shear stress (Eq. (A-10)), as given in Eq. (A-11).

$$F_s = \tau_a \cdot S_s$$

$$= \frac{\left(N_p - N_{qd}\pi^2\right)\rho N^2 D^2}{N_{qd}} \pi \cdot d\left(\frac{d}{4} + \ell\right) \quad \text{(A-11)}$$

The homogenization intensity at stator openings W_s is defined in terms of average force F_s [N] and velocity U [m/s], as given in Eq. (12).

$$W_s = F_s \cdot U$$

$$= \left[\frac{\left(N_p - N_{qd}\pi^2\right)\pi^2}{N_{qd}}\right]\rho N^3 D^3 d\left(\frac{d}{4} + \ell\right) \quad \text{(A-12)}$$

The shear frequency f [1/s] at the stator openings is defined by Porcelli (2002) as follows;

$$f = n_s \cdot n_r \cdot N \quad \text{(A-13)}$$

In the case of actual mixers, there are some leakage flows at the gap between the rotor and the stator. It is considered that the leakage flows from the gap are in proportion to the ratio of the gap cross section S_g [m^2] to the total cross section of the stator wall openings S_h [m^2]. The leakage ratio α_L [-] is calculated as follows:

$$S_h = \frac{\pi}{4} d^2 \cdot n_s \quad \text{(A-14)}$$

$$S_g = \pi\delta(D+\delta) \quad \text{(A-15)}$$

$$\alpha_{\mathrm{L}} = \frac{S_{\mathrm{h}}}{S_{\mathrm{h}} + S_{\mathrm{g}}} \quad \text{(A-16)}$$

$$= \frac{n_s \cdot d^2}{n_s \cdot d^2 + 4\delta(D+\delta)} \quad \text{(A-17)}$$

Therefore, the shear frequency at the stator openings is calculated as given in. (A-17).

$$f_s = n_s^{\ 2} \cdot n_r \cdot N \cdot \left(\frac{d^2}{n_s d^2 + 4\delta(D+\delta)} \right) \quad \text{(A-18)}$$

The local energy dissipation rate at stator openings ε_{s}, which contains information about the local homogenization intensity W_{s}, shear frequency at stator openings f_{g} and mixing time t_{m} is expressed as follows in Eq. (A-18).

$$\varepsilon_s = \frac{W_s \cdot f_s \cdot t_m}{\rho \cdot V}$$

$$= \left[\frac{\left(N_p - N_{qd}\pi^2\right)\pi^2 n_s^{\ 2} \cdot n_r}{N_{qd}} \right] D^3 d \left(\frac{d}{4} + \ell \right) \left(\frac{d^2}{n_s d^2 + \delta(D+\delta)} \right) \left(\frac{N^4 \cdot t_m}{V} \right) \quad \text{(A-19)}$$

A-1.3 Calculation of the overall energy dissipation rate

We assumed that the homogenization and the emulsification take place at the gap between the rotor and the stator and at the stator openings. As the performance evaluation index and the scale-up index, we defined the overall energy dissipation rate ε_a as follows:

$$\varepsilon_a = \varepsilon_g + \varepsilon_s$$

$$= \left[\left(N_p - N_{qd}\pi^2\right) \cdot n_r \right]$$

$$\times \left\{ D^3 \left[\left(\frac{D^3 b}{\delta(D+\delta)} \right) + \frac{\pi^2 n_s^{\ 2} d(d+4\ell)}{4N_{qd}} \cdot \left(\frac{d^2}{n_s \cdot d^2 + 4\delta(D+\delta)} \right) \right] \right\} \left(\frac{N^4 \cdot t_m}{V} \right)$$

(A-20)

Here

$$K_g = \left(\frac{D^3 b}{\delta(D+\delta)} \right) \quad \text{(A-21)}$$

$$K_s = \frac{\pi^2 n_s^{\ 2} d(d+4\ell)}{4N_{qd}} \cdot \left(\frac{d^2}{n_s \cdot d^2 + 4\delta(D+\delta)} \right) \quad \text{(A-22)}$$

$$K_h = \left(N_p - N_{qd}\pi^2\right)\cdot n_r \cdot D^3 \cdot \left(K_g + K_s\right) \qquad \text{(A-23)}$$

$$\varepsilon_a = K_c \cdot \left(\frac{N^4 \cdot t_m}{V}\right) \qquad \text{(A-24)}$$

Here, K_g [m^2] is the influence factor of the gap, K_s [m^2] is the influence factor of the stator openings, and K_c [m^5] is the configuration evaluation coefficient.

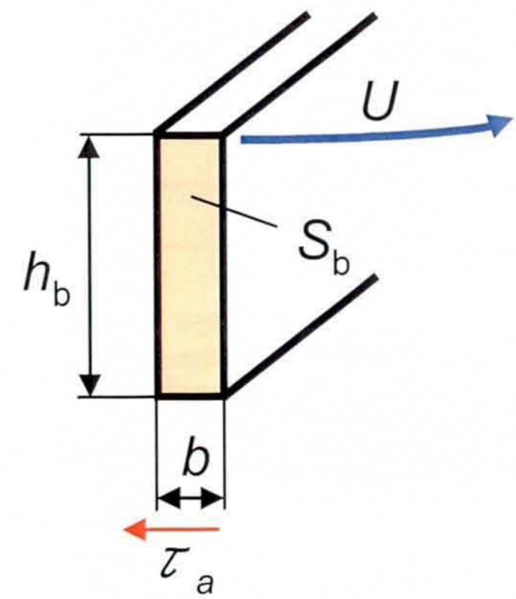

Fig. A-1 Schematic diagram of the rotor tip

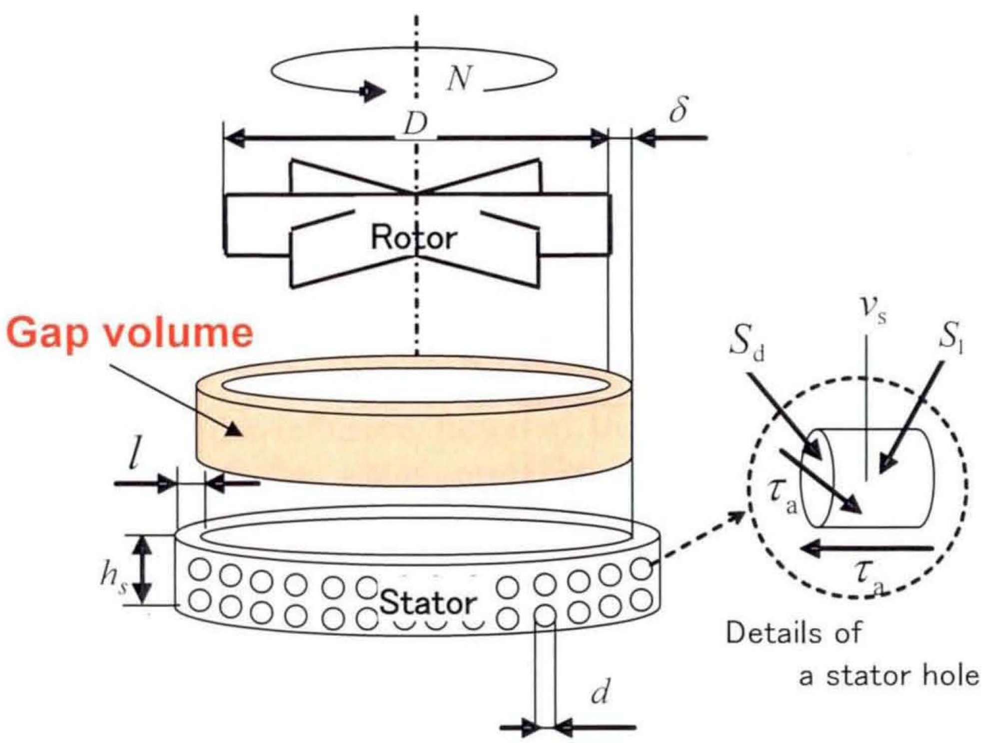

Fig. A-2 Schematic diagram of the mixing unit

Nomenclature

A	=	opening ratio of stator	[-]
b	=	rotor blade thickness	[m]
C'	=	constant	[-]
C_h	=	homogenization coefficient	[m^5]
D	=	rotor diameter	[m]
D_t	=	stator diameter	[m]
D_0	=	vessel diameter	[m]
d	=	stator hole diameter	[m]
d_{32}	=	Sauter mean diameter	[m]
d_{32}^*	=	steady state Sauter mean diameter	[m]
d_{50}	=	mean drop diameter	[m]
F_a	=	average force	[N]
F_b	=	average force at rotor tip	[N]
F_s	=	average force at a stator hole	[N]
f_g	=	shear frequency at gap volume	[1/s]
f_s	=	shear frequency at stator openings	[1/s]
$f_{s,h}$	=	shear frequency for unit hole	[1/s]
H_t	=	total energy loss	[kg/m/s^2]
H_k	=	kinetic energy loss	[kg/m/s^2]
H_{pr}	=	pressure	[Pa]
H_{pt}	=	potential energy loss	[kg/m/s^2]
$H_{k.ave}$	=	average velocity loss	[kg/m/s^2]
$H_{k,fluc}$	=	fluctuation velocity loss	[kg/m/s^2]
$H.I$	=	homogenization index	[m^2/s^3]
h	=	height of stator	[m]

h_b	=	height of rotor blade	[m]
K_g	=	influence factor of gap	[m^2]
K_s	=	influence factor of stator openings	[m^2]
k	=	constant	[m]
l	=	stator thickness	[m]
N	=	rotational speed	[1/s]
N_c	=	circulation number	[-]
N_{max}	=	maximum rotational speed	[1/s]
N_p	=	power number	[-]
N_{qc}	=	circulation flow number	[-]
N_{qd}	=	flow number	[-]
n_r	=	number of rotor blades	[-]
n_s	=	number of stator slots	[-]
n_v	=	number of holes in the total volume	[-]
P_a	=	power loss by running mixer in air	[W]
P_g	=	gross electrical power	[W]
$P_{g,max}$	=	maximum gross electrical power	[W]
P_h	=	power consumption for homogenization	[W]
P_n	=	net power consumption	[W]
P_{max}	=	maximum power consumption	[W]
P_p	=	pump power consumption	[W]
Q	=	flow rate	[m^3/s]
Q_c	=	circulation flow rate	[m^3/s]
S_d	=	area of a stator hole cross section	[m^2]
S_g	=	total area of gap cross section	[m^2]
S_h	=	total area of a stator hole cross section	[m^2]

S_l	= area of a stator hole side wall	[m^2]
S_s	= area subjected to shear stress	[m^2]
T_M	= time for complete mixing	[s]
t_e	= equivalent mixing time	[s]
t_m	= mixing time	[s]
U	= rotor tip velocity	[m/s]
V	= total product volume	[m^3]
v_g	= gap volume	[m^3]
v_h	= volume contributed to homogenization	[m^3]
v_s	= total slot volume	[m^3]
W_b	= homogenization intensity at rotor tip	[W]
We	= Weber number	[-]
W_s	= homogenization intensity at stator openings	[W]

α	= constant	[-]
α_L	= leakage ratio	[-]
δ	= gap width between rotor and stator	[m]
ε	= energy dissipation rate	[m^2/s^3]
ε_a	= overall energy dissipation rate	[m^2/s^3]
ε_g	= energy dissipation rate at gap	[m^2/s^3]
ε_l	= local energy dissipation rate of turbulence	[m^2/s^3]
ε_s	= energy dissipation rate at stator openings	[m^2/s^3]
ε_t	= total energy dissipation rate of turbulence	[m^2/s^3]
η	= motor efficiency	[%]
μ	= viscosity	[Pa・s]

ρ	=	density of model product	[kg/m^3]
σ	=	surface tension	[N/m]
τ_a	=	average shear stress	[N/m^2]
ω	=	angular velocity	[rad/s]

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