Performance Characteristics of a Stirred-Tank Reactor with a Mechanical Foam-Breaker Utilizing Shear Force

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A new mechanical foam-breaker was developed. It uses the shear force between a fixed orifice plate and a rotating disk (MFUS). Foam-breaking performance of the MFUS fitted to a stirred-tank reactor (STR) was evaluated from changes in foam density and shearing power. The maximum value of the ratio of foam density (after foam breaking) to liquid density was 0.90. Change in foam densities before and after foam breaking in the MFUS was considerably larger than that in existing mechanical foam-breakers with rotating parts at the same level of power for foam breaking. The volumetric liquid-phase oxygen transfer coefficient was measured in the bubble-dispersing and foam-ascending sections of the STR with the MFUS. Comparison of the volumetric liquid-phase oxygen transfer coefficient between the STR with the MFUS and the STR or the foam column in terms of the specific power input demonstrated higher oxygen transfer performance and saving power requirements for the STR with the MFUS.

Introduction

Undesirable foaming frequently occurs in gas–liquid contacting operations using a reactor with gas sparging transport. It decreases the working liquid volume. Additionally, reactants and products accumulate in the foam and may be lost from the reactor along with the escape of foam. Consequently, the aeration-agitation rate may be limited unless foaming is controlled by some means (Hall *et al.*, 1973; Viesturs *et al.*, 1982; Ghildyal *et al.*, 1988; Boon *et al.*, 2002; Hoeks *et al.*, 2003). Both chemical and mechanical methods are available for foam control. Mechanical foam-control is preferable to chemical foam-control because it avoids problems such as the lowering of the mass transfer rate, reaction inhibition, and toxicity; moreover, adverse effects on separation and purification of products occur when foaming is controlled by adding antifoam agents (Yagi and Yoshida, 1974; Andrew, 1982; Koide *et al.*, 1985; Hoeks *et al.*, 1997). Numerous mechanical foam-breakers have been proposed. Viesturs *et al.* (1982) and Ghildyal *et al.* (1988) have classified mechanical foam-breakers, including

many patented devices. However, most of those foam-breakers are ineffective against large-scale foam masses or foam produced by high aeration and agitation, unless used in combination with antifoam agents. In other words, none of the proposed mechanical foam-breakers are entirely satisfactory or universally applicable. Therefore, demand exists for development of a new type of mechanical foam-breaker that is effective for foam-control under high aeration-agitation rate conditions.

Mechanical foam-breakers cannot completely separate foams into gas and liquid phases (Gutwald and Mersmann, 1997). Primary foams ascending from the aerated liquid surface are collapsed by mechanical foam-breakers, creating very stable secondary foams with small bubbles and a high liquid holdup. In most of the proposed mechanical foam-breakers, the resultant secondary foams are returned to the area of primary foam generation and are thus accumulated in the reactor over its long lifetime. Examples include mechanical foam-breakers with rotating installations such as turbines, vaned disks, and paddles (Ng and Gutierrez, 1977; Deshpande and Barigou, 1999; Takesono *et al.*, 2001, 2002). In such devices, persistent secondary foams recirculate into the foam-breaker, but cannot be broken twice by the foam-breaker. Considering that recirculation of the secondary foams into

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Fig. 1 Schematic diagram of experimental apparatus

the foam-breaker must be avoided, we constructed a new mechanical foam-breaker (MFUS) that utilizes a shear force between a fixed orifice plate and a rotating disk. It does not return the secondary foams to the ascending area of the primary foams. This study evaluates the foam-breaking performance of the MFUS fitted to a stirred-tank reactor (STR), represented by the changes in foam density and shearing power. The gas holdup and volumetric liquid-phase oxygen transfer coefficient in the STR with the MFUS were then examined for two flow sections: bubble-dispersing and foam-ascending sections.

1. Experimental

1.1 Apparatus

Figure 1 shows a schematic diagram of the experimental apparatus. The STR, 0.19 m in diameter D_T , was equipped with four baffles ($D_T/10$ in width). A six-bladed turbine impeller ($D_T/3$ in diameter) was set at a height of $D_T/3$ above the vessel bottom. The liquid depth was held at $1.5D_T$. A ring sparger with twelve holes of 0.001-m diameter was used for air sparging. The MFUS was set at a height of $2.5D_T$ from the bot-

Fig. 2 Foam-breaking mechanism of the MFUS

tom. The rotating steel disk was 0.20 m in diameter and 0.001 m thick. Orifice diameters of the 0.01-m-thick fixed plate made of transparent acrylic resin were 0.06 and 0.09 m to change the foam-breaking area over which the shear force acts. The gap between the fixed orifice plate and the rotating disk was maintained at 0.001 m, which was perceived to be the practical minimum gap with easy adjustment. A collapsed foam liquid–gas separation column ($1.35D_T$ in diameter) was mounted outside the upper part of the vessel. Primary foams passing through the orifice are forced to flow through the gap between the fixed orifice plate and the rotating disk and are collapsed by a shear force that acts on the foam, as illustrated in Figure 2. The pressure drop, which was measured by the manometer (14 in Figure 1), was less than 90 Pa. For that reason, foam breaking by the MFUS was inferred to occur mainly through a shear force. The collapsed foam, i.e. the secondary foam, is dispersed horizontally from the edge of the gap by centrifugal force created by the rotating disk. It is collected in the separation column. Refoaming by colliding with the separation column wall was not observed within the range of this experiment. The secondary foam collected in the separation column was returned continuously to the bottom using a roller pump. The gas superficial velocity U_g ranged from 6.52×10^{-3} to $3.10 \times 10^{-2} \text{ m}\cdot\text{s}^{-1}$. The impeller rotational speed N_i was varied from 10.0 to 20.0 s^{-1} . For foam-breaking experiments, the foaming liquid (density, $998.2 \text{ kg}\cdot\text{m}^{-3}$; viscosity, $1.00 \times 10^{-3} \text{ Pa}\cdot\text{s}$; surface tension, $47.8 \times 10^{-3} \text{ N}\cdot\text{m}^{-1}$) was a diluted solution ($0.04 \text{ g}\cdot\text{L}^{-1}$) of a surfactant agent Triton X-100. For mass transfer experiments, the foaming liquid (density, $1022.6 \text{ kg}\cdot\text{m}^{-3}$; viscosity, $1.25 \times 10^{-3} \text{ Pa}\cdot\text{s}$; surface tension, $30.6 \times 10^{-3} \text{ N}\cdot\text{m}^{-1}$) was a 500 $\text{mol}\cdot\text{m}^{-3}$ sulfite solution to which Triton X-100 was added at a concentration of $0.1 \text{ g}\cdot\text{L}^{-1}$. Both liquids were maintained at $293 \pm 1 \text{ K}$.

1.2 Foam density

Foam density before foam breaking ρ_a was calculated as

$$\rho_a = \rho_L \phi_L + \rho_g(1 - \phi_L) \quad (1)$$

where ρ_g is the air density, ρ_L is the liquid density, and ϕ_L is the liquid holdup in ascending foam. To measure ϕ_L , foam was withdrawn through a glass tube (0.01 m in diameter) fitted on the wall 0.09 m below the fixed orifice plate and collected in a graduated container. ϕ_L was determined from Eq. (2).

$$\phi_L = \frac{v_l}{v_f} \quad (2)$$

Therein, v_f is the volume of foam collected and v_l is the volume of liquid remaining after the collapse of foam in the container.

The foam density after the foam breaking ρ_f was calculated from the following equation, obtained from the mass balance when the weight of the gas entrained in the collapsed foam liquid flow was neglected.

$$\rho_f = \frac{Q_c \rho_L}{Q_f} \quad (3)$$

Therein, Q_f is the volumetric rate of collapsed foam liquid flow; Q_c is the volumetric rate of the liquid contained in the collapsed foam liquid. Firstly a certain amount of the collapsed foam liquid was sampled carefully in a graduated cylinder at position A shown in Figure 1. Q_f was then determined by dividing the measured volume of the collapsed foam liquid with the sampled time. Q_c was determined by dividing the net liquid volume, measured by the spontaneous collapse of foam in the cylinder, with the sampled time.

1.3 Power consumption for foam breaking, agitation, and aeration

The shearing power P_s , based on the shear force between the fixed orifice plate and the rotating disk, and the agitation power P_g in the gassed liquid, were determined with a spring-type torque meter. Aeration power P_a was calculated from the following equation (Sato *et al.*, 1989).

$$P_a = \rho_L g U_g V_L \quad (4)$$

1.4 Gas holdup

The mean gas holdup $(\varepsilon_g)_B$ in the bubble-dispersing section was determined by the manometric technique. The manometer reading was corrected for dynamic pressure changes (Sridhar and Potter, 1980). The mean gas holdup $(\varepsilon_g)_F$ in the foam-ascending section

was estimated from Eq. (5) using the value of the liquid holdup in ascending foam, ϕ_L . No significant difference was observed in ϕ_L values at different positions along the vessel height.

$$(\varepsilon_g)_F = 1 - \phi_L \quad (5)$$

1.5 Volumetric liquid-phase oxygen transfer coefficient

Catalytic oxidation of a sodium sulfite solution with air was applied to measure the volumetric liquid-phase oxygen transfer coefficient $k_L a$. In this work, oxygen from air was absorbed into a 500 mol·m⁻³ sodium sulfite solution, pH 7.7, and containing 1 × 10⁻⁴ mol·m⁻³ cobalt sulfate. Two assumptions are made in deriving the absorption rate: 1) gas-side resistance to mass transfer is negligible; 2) Henry's law is applicable. In this catalytic oxidation of sodium sulfite solution, the oxygen absorption rate N_A is expressed as (Linek and Vacek, 1981)

$$N_A = k_L a \left(\frac{Py}{He} \right) \quad (6)$$

where P is the mean total pressure and y is the oxygen mole fraction. The flow regime in the STR with the MFUS is divided into different two sections: the bubble-dispersing section, in which bubbles are dispersed uniformly in the bulk liquid; and the foam-ascending section, in which foams ascend continuously from the aerated liquid surface, as shown in **Figure 3**. Completely mixed flow and piston flow were assumed for the gas phase in the bubble-dispersing section and that in the foam-ascending section, respectively. The $k_L a$ values were estimated from the oxygen mass balance in the vessel and Eq. (6).

The volumetric liquid-phase oxygen transfer coefficient $(k_L a)_B$ in the bubble-dispersing section was calculated as

$$(k_L a)_B = \frac{G_M^+ \cdot He \cdot S}{P \cdot V_b} \cdot \frac{1}{y_S} \cdot \left(\frac{y_I}{1 - y_I} - \frac{y_S}{1 - y_S} \right) \quad (7)$$

where G_M^+ and V_b are the molar flow rate of inert gas and the vessel volume in the bubble-dispersing section, respectively. The Henry's law constant He is based on the data of Rice and Benoit (1986).

The volumetric liquid-phase oxygen transfer coefficient $(k_L a)_F$ in the foam-ascending section was calculated as

$$(k_L a)_F = \frac{G_M^+ \cdot He}{P \cdot h_f} \cdot [f(y_S) - f(y_O)] \quad (8)$$

Fig. 3 A flow model of the gas phase

where

$$f(y) = \ln \frac{y}{1-y} + \frac{1}{1-y}$$

and h_f is the foam-ascending distance.

The oxygen mole fractions at the inlet of the vessel, the border of the two flow sections, and the outlet of the vessel, i.e., y_I , y_S , and y_O , were measured with a magnetic oxygen analyzer (LF-700, Toray Engineering Co., Ltd.). In measurement of y_S , the gas-liquid mixture was withdrawn through the glass tube packed with polyurethane foam from the sampling tap nearest the border of the two flow sections. It was separated completely into gas and liquid phases. The gas phase was only introduced into the oxygen analyzer and the liquid phase was returned to the vessel. The $(k_L a)_B$ values determined from the gas-phase balance equation, Eq. (7), concurred well with those measured according to the common sulfite oxidation method based on the concentration change of Na_2SO_3 in the liquid.

2. Results and Discussion

2.1 Foam density before foam breaking

Liquid holdup in foam, ϕ_L , which is necessary for the evaluation of foam density before foam breaking, ρ_a , was measured first. Figure 4 shows a typical relationship between ϕ_L and the disk rotational speed N . ϕ_L decreased with increasing N and then became almost independent of N . Using the measured values of ϕ_L , ρ_a was calculated from Eq. (1). The relationship between

Fig. 4 The effect of disk rotation speed on liquid holdup in ascending foam

ρ_a and the gas superficial velocity U_g is shown in Figure 5, where ρ_a is based on the ϕ_L value independent of N . ρ_a tended to decrease with increasing U_g . Visual observation indicated that the size of foam in the ascending-foam section became larger as U_g increased in the same agitation rate condition. An increase in foam size decreases the liquid holdup (Hass and Johnson, 1965; Rubin *et al.*, 1967). Therefore, smaller values of ρ_a at larger U_g are attributable to the decreased liquid holdup caused by an increase in the foam size. Regarding the effect of the impeller rotational speed N_i on ρ_a , the value of ρ_a tended to increase with increasing N_i . The increased foaming capacity with increasing N_i causes an increase of the ascending velocity of the foam. We can anticipate a larger liquid holdup because the downward liquid velocity with respect to the foam decreases as the ascending velocity of the foam increases, as a result the drainage rate of liquid from the foam decreases. Higher values of ρ_a at larger N_i may be attributable to the increased liquid holdup. ρ_a was also unaffected by orifice diameter, D_o .

2.2 Foam density after foam breaking

Figure 6 shows a typical relationship between the ratio of the foam density (after foam breaking) to the liquid density ρ_f/ρ_L and N . The value of ρ_f/ρ_L tends to become higher as U_g increases and N_i decreases. In view of the change in ρ_a shown in Figure 5, the higher the ρ_a , the smaller ρ_f/ρ_L became. In addition, ρ_f/ρ_L increased with the initial increase in N . Nevertheless, when N became larger than a certain rotational speed, ρ_f/ρ_L values were almost independent of N . This disk rotational speed at which ρ_f/ρ_L began to level off was defined as the transitional disk rotational speed N_t . To determine

Fig. 5 Relationship between foam density before foam-breaking and gas superficial velocity

Fig. 6 Relationship between foam density after foam breaking and disk rotation speed

N_t , $1/(\rho_f/\rho_L)$ replotted against $1/N$ (Figure 7). N_t values were obtained from intersections of the straight lines with different slopes. The maximum value of ρ_f/ρ_L in the N range above N_t at all operating conditions was 0.90. This value may be dependent on the foam density before foam braking, ρ_a , and the velocity of the foam passing through the orifice. Figure 8 shows the typical relationship between N_t and U_g . N_t decreases with increasing U_g and slightly increases as N_i increases. Regarding the effect of D_o on N_t , a slight in-

Fig. 7 Plot of $1/(\rho_f/\rho_L)$ against $1/N$

Fig. 8 Relationship between transition disk rotational speed and gas superficial velocity

crease in N_t was observed as D_o increased. This increase may be attributable to a reduction of the area over which the shear force acts because of increased orifice diameter.

Within the range examined, correlation of N_t was then carried out. By using operational parameters such as U_g , N_i and D_o/D_T , the following equation was obtained within $\pm 10\%$ error.

$$N_t = 6.59 U_g^{-0.33} N_i^{0.08} (D_o/D_T)^{0.06} \quad (9)$$

2.3 Shearing power

We investigated the change of the shearing power P_s required for the collapse of the foam flowing through the gap between the fixed orifice plate and the rotating

Fig. 9 Relationship between foam-breaking power and disk rotational speed

disk. **Figure 9** shows the results of P_s plotted against N . P_s tended to be large with increasing U_g and N_i . Because the volumetric rate of collapsed foam liquid flow Q_f after foam breaking increased with increasing U_g and N_i , this tendency is inferred to result from the increased amount of foam liquid flow through the gap. Changing P_s also differed at N below and above N_t , as shown in the figure. When a disk made of transparent acrylic resin was used as a rotating disk, observations of the upper part of the rotating disk indicated the different behavior for the collapsing foam flow through the gap between the fixed orifice plate and the rotating disk at N below and above N_t . The collapsing foam path line at N below N_t was curved gently toward the edge of the gap from the orifice, while at N above N_t it was arched greatly. The difference of the change in P_s at N below and above N_t may be mainly attributed to the difference of the collapsing foam path line, i.e., the difference of the distance in which a shear force acts on the foam. Moreover, from both the results in this figure and those in Figure 6, it is clear that the disk most effectively operated at the transition disk rotational speed N_t .

2.4 Comparing foam-breaking performance of the MFUS and existing mechanical foam-breakers: power for foam breaking

We compared the ratio of foam density after foam breaking to that before foam breaking, ρ_f/ρ_a , for the

Fig. 10 Comparison of foam-breaking performance between MFUS and existing mechanical foam-breakers

MFUS and existing mechanical foam-breakers with rotating parts. Thereby, we determined their respective power for foam breaking. The shearing power P_{st} at N_t in the MFUS and the foam-breaking power P_{kc} at the required critical rotational speed N_c (the minimum foam-breaking rotational speed sufficient to prevent the foam from rising above the foam-breaker level) in the existing mechanical foam-breakers were the criteria to measure foam-breaking power. Experimental conditions of the existing foam-breakers were $D_T = 0.23$ m, $H_L = D_T$, $D_{FB} = 1/2 D_T$, $U_g = 3.79 \times 10^{-3} - 7.58 \times 10^{-3}$ m·s⁻¹, $N_i = 6.67 - 30.0$ s⁻¹ and 0.01 vol% anionic soft detergent solution (Takesono *et al.*, 2002). The foaming characteristic term of this detergent solution was almost identical to that of Triton X-100 solution used in the present work (Takesono *et al.*, 1993a, 1993b). This similarity means that foaming characteristics of both solutions are very similar. **Figure 10** shows the results of ρ_f/ρ_a plotted against P_{st} or P_{kc} . The ρ_f/ρ_a values in the MFUS were considerably larger than those in the existing mechanical foam-breakers at the same level of power for foam breaking. This result suggests that the MFUS provides a higher level of foam-breaking performance while requiring less power.

2.5 Gas holdup

The gas holdup was examined in two sections: the bubble-dispersing and foam-ascending sections. **Figure 11** shows typical results of the gas holdup, $(\epsilon_g)_B$ and $(\epsilon_g)_F$, in the bubble-dispersing and foam-ascending sections. In all the systems, $(\epsilon_g)_B$ increased with increasing N_i and U_g . In contrast, $(\epsilon_g)_F$ in the foam-ascending section tended to become smaller as N_i increased and slightly larger as U_g increased. This

Fig. 11 Gas holdup in the bubble-dispersing and foam-ascending sections

tendency may result from the increase in ϕ_L with increasing N_i , which corresponds to the change of ρ_a shown in Figure 5. $(\varepsilon_g)_B$ and $(\varepsilon_g)_F$ were also independent of D_o .

2.6 Volumetric liquid-phase oxygen transfer coefficient

Volumetric liquid-phase oxygen transfer coefficients $(k_L a)_B$ and $(k_L a)_F$ in the bubble-dispersing and foam-ascending sections were measured as U_g , N_i , and D_o were varied. **Figure 12** shows the typical results of $(k_L a)_B$ and $(k_L a)_F$ plotted against U_g . In both sections, the tendency of changing $k_L a$ was found to correspond well to that of changing ε_g shown in Figure 11. The relationship between $k_L a$ and the specific power input P_T/V_L was then investigated. For comparison of $(k_L a)_B$, we referred to the results of Van't Riet (1979) for STR containing ionic solutions. Because $k_L a$ data of the foam-ascending section in the STR have not been published, the result of $(k_L a)_F$ that Onda *et al.* (1969) measured in the foam column containing surfactant solutions was used for reference. Power input, P_T , in the STR with the MFUS was evaluated as the sum of the power, P_{st} , for foam breaking, the pneumatic power, P_a , for gas input and the agitation power, P_g . P_T values in the STR and the foam column were evaluated as the sum of P_a and P_g , and only P_a , respectively. **Figure 13** shows the results of $(k_L a)_B$ and $(k_L a)_F$ plotted

Fig. 12 Volumetric liquid-phase oxygen transfer coefficient in bubble-dispersing and foam-ascending section

against P_T/V_L , together with the results described above. That figure shows that $(k_L a)_B$ and $(k_L a)_F$ in the STR with the MFUS are large compared with those in other reactors at the same level of specific power input. That result supports the superiority of STR with the MFUS with respect to both mass transfer rate and power requirements. The STR with the MFUS demonstrated here, for which high oxygen transfer rate can be expected with reliable foam control, is considered to be useful as a reactor for those reactions with intense foaming.

Conclusions

We constructed a mechanical foam-breaker utilizing shear force (MFUS) between a fixed orifice plate and a rotating disk. It can prevent recirculation of persistent secondary foams. The foam-breaking performance of the MFUS was examined for a stirred-tank reactor (STR) containing a Triton X-100 solution. The ratio of the foam density after foam breaking to the liquid density ρ_f/ρ_L increased as the disk rotation speed N increased; however, when N exceeded the transition disk rotational speed N_t , ρ_f/ρ_L was almost independent of N . The maximum value of ρ_f/ρ_L was 0.90 within the present experimental condition. The ratio of foam density after foam breaking to that before foam breaking ρ_f/ρ_a in the MFUS was considerably larger than that in the existing mechanical foam-breakers with rotating

Fig. 13 Relationship between the volumetric liquid-phase oxygen transfer coefficient and a specific power input

parts at the same level of the power for foam breaking.

The gas holdup ε_g and volumetric liquid-phase oxygen transfer coefficient $k_L a$ in the STR with the MFUS was evaluated separately in bubble-dispersing and foam-ascending sections. Comparison of $k_L a$ for the STR with the MFUS and other reactors in terms of specific power input demonstrated higher oxygen transfer performance and lower power requirements for the STR with the MFUS.

Nomenclature

D_{FB}	=	foam-breaker diameter	[m]
D_o	=	orifice diameter	[m]
D_T	=	column diameter	[m]
G_M^+	=	superficial molar velocity of inert gas	[mol·m ⁻² ·s ⁻¹]
g	=	gravitational acceleration	[m·s ⁻²]
He	=	Henry's law constant	[Pa·m ³ ·mol ⁻¹]
H_L	=	static liquid height in a vessel	[m]
h_f	=	foam-ascending distance	[m]
$k_L a$	=	volumetric liquid-phase oxygen transfer coefficient	[s ⁻¹]
N	=	disk rotational speed	[s ⁻¹]
N_A	=	oxygen absorption rate per unit volume	[mol·m ⁻³ ·s ⁻¹]
N_c	=	critical foam-breaker rotational speed required for foam breaking	[s ⁻¹]
N_i	=	impeller rotational speed	[s ⁻¹]
N_t	=	transition disk rotational speed	[s ⁻¹]
P	=	mean total pressure	[Pa]
P_a	=	pneumatic power of gas input	[W]
P_g	=	agitation power of gassed liquid	[W]

P_{kc}	=	power consumed for foam breaking at a critical state	[W]
P_k	=	power for foam breaking	[W]
P_{st}	=	power for foam breaking at a transition disk rotational speed	[W]
P_T	=	power input	[W]
Q_e	=	volumetric rate of the liquid contained in the collapsed foam liquid	[m ³ ·s ⁻¹]
Q_f	=	volumetric rate of the collapsed foam liquid flow	[m ³ ·s ⁻¹]
S	=	cross-sectional area of a vessel	[m ²]
U_g	=	gas superficial velocity	[m·s ⁻¹]
V_b	=	vessel volume in the bubble-dispersing section	[m ³]
V_L	=	working liquid volume	[m ³]
v_f	=	foam volume	[m ³]
v_l	=	net liquid volume in v_f	[m ³]
y	=	oxygen mole fraction	[—]
ε_g	=	gas holdup in the bubble-dispersing section	[—]
ρ_a	=	density of foam before foam breaking	[kg·m ⁻³]
ρ_f	=	density of collapsed foam liquid after passing through the orifice	[kg·m ⁻³]
ρ_g	=	density of air	[kg·m ⁻³]
ρ_L	=	density of liquid	[kg·m ⁻³]
ϕ_L	=	liquid holdup in ascending foam	[—]

<Subscript>

B	=	bubble-dispersing section
F	=	foam-ascending section
I	=	inlet
S	=	surface
O	=	outlet

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