OPERATIONAL CHARACTERISTICS OF AERATED AGITATED VESSELS UNDER MECHANICAL FOAM CONTROL

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The mechanical foam-control method is free of problems when foaming is controlled by antifoam agents (AFs).^{2,3,6)} In addition, its application to the aerated agitated vessel (AAV) allows substantial reduction of agitation power compared to the AAV including an AF, due to the increased gas holdup.⁴⁾ The performance characteristics of the AAV with a rotating disk foam-breaker (MFRD) were demonstrated in a previous paper.⁵⁾ The main objective of the present note is to investigate the operational characteristics of AAVs with MFRDs of different sizes.

1. Experimental

Two AAVs with vessels diameter D_T of 0.19 and

0.27 m were used. They were geometrically similar to the AAV of $D_T=0.23$ m.^{4,5)} A six-blade turbine ($D_i=D_T/3$, $b=D_i/5$, $l=D_i/2.86$ and $d_i=D_i/1.3$ in dimensions) was used for each AAV. For air sparging, two ring spargers ($D_T/3$ in diameter) with seven and seventeen holes respectively of 1.0×10^{-3} m diameter were used for AAVs of $D_T=0.19$ and 0.27 m. The impeller and liquid depth were held at $D_T/3$ and D_T . For additional details of this type of AAV, refer to the previous papers.^{4,5)} The gas superficial velocity V_g ranged from 3.79×10^{-3} to 7.58×10^{-3} m/s. The MFRD was set at a height of $2.0 D_T$ from the bottom. As the rotating disk, two disks, 0.1487 and 0.2114 m in diameter D_d , were employed for AAVs of $D_T=0.19$ and 0.27 m respectively. The ratio of D_T to D_d in the two AAVs was approximately equal to 1.28^{4,5)} in the AAV of $D_T=0.23$ m. The liquid feed rate W onto the

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rotating disk was varied from 1.0×10^{-5} to 3.0×10^{-5} m³/s. Critical disk rotational speed required for foam-breaking, liquid holdup in foam, agitation power and gas holdup were measured according to the respective methods employed in the previous work.⁵⁾ **Table 1** shows the properties of foaming and non-foaming liquids used at 293 K.

2. Results and Discussion

2.1 Foam-breaking characteristics of the MFRD in terms of changes in the required disk rotational speed

The change in critical disk rotational speed N_c was measured for each AAV at a transient state, which is in the regime of foam-breaking to non-foam-breaking as a critical foam-breaking state.⁴⁾ The effects of W and V_s on N_c were similar to those observed previously.⁵⁾ That is, the smaller is W and the larger is V_s , the higher N_c becomes. The typical relationship between N_c and Re_i is shown in **Fig. 1(a)**, together with the results in the AAV of $D_T=0.23$ m and $D_d=0.1800$ m.⁵⁾ N_c values tended to be high in the AAV of small D_T . As to the Reynolds numbers $(Re_i)_1$, at which N_c begins to decrease, and $(Re_i)_2$, above which N_c is almost free from the effect of Re_i , there was little difference in value due to those of D_T .

For the data observed when W was varied within the range below W_t values which could be predicted by Eq. (1),⁵⁾ the correlations of N_c with the operating variables were then carried out.

$$N_w^+ = 0.441(N_{Re})^{2/3}(N_{We})^{-0.883} \quad (1)$$

Equation (1) indicates the transition boundary at which the pattern of liquid disintegration by a rotating disk changes from the region of ligament formation effective for foam-breaking to the region of liquid film formation which is ineffective for foam-breaking. In the same manner as in the previous work,⁵⁾ the N_c values expressed in the form of the peripheral velocity $N_c D_d$ of the disk were found to be correlated by the following form within 10% error.

$$N_c D_d = A(Q/W)^{0.22}(Re_i)^B \quad (2)$$

Equation (2) is applicable when D_T is 0.19–0.27 m, D_T/D_d ratio is 1.28, Q is 1.07×10^{-4} – 4.34×10^{-4} m³/s, W is 1.0×10^{-5} – W_t m³/s and Re_i is 3.0×10^4 – 2.0×10^5 . The values of empirical constants A and B in Eq. (2) which change according to the range of Re_i and the liquid are summarized in **Table 2**.

2.2 Foaming behaviour in AAVs and foam-breaking behaviour of the MFRD in terms of changes in liquid holdup in foam

The relationship between the liquid holdup in foam, ϕ_L , measured at the same operating conditions as in **Fig. 1(a)**, and Re_i is shown in **Fig. 1(b)**. It is found from a comparison between **Figs. 1(a)** and **1(b)** that the change in ϕ_L with Re_i is very similar to that in

Table 1. Properties of liquids

Liquid	C_F [ppm]	ρ [kg/m ³]	$\mu \times 10^3$ [Pa·s]	$\sigma \times 10^3$ [N/m]
F ¹⁾ -D*	—	998.2	1.00	53.94
F ¹⁾ -E**	—	999.4	1.06	51.06
F ²⁾ -S***	—	1000.3	1.13	50.57
NF ²⁾ -D*	570 [†]	998.2	1.00	39.05
	11140 [†]	998.2	1.01	38.88
	640 ^{††}	998.2	1.01	29.17
	1280 ^{††}	998.3	1.02	28.97
NF ²⁾ -E**	741 [†]	999.6	1.04	39.31
	1482 [†]	999.8	1.05	35.78
	159 ^{†††}	999.6	1.04	36.20
	318 ^{†††}	999.7	1.05	35.66
NF ²⁾ -S***	60 [†]	1000.3	1.13	41.71
	120 [†]	1000.4	1.13	40.60
	127 ^{†††}	1000.4	1.13	32.79
	254 ^{††††}	1000.4	1.14	30.03

¹⁾ F; foaming, ²⁾ NF; non-foaming.

* 10^{-2} vol% detergent (Lipon F, Lion Corp.), ** 5.0×10^{-1} wt% egg albumin, *** 2.0 wt% soybean meal (liquid filtered after one hours' boiling), [†] KM-70, silicon oil (Shin-Etsu Chemical Co. Ltd.), ^{††} BF-7, ^{†††} CC-118, ^{††††} BF-75, Nissan Disfoam (Nihon Yushi Corp.).

Fig. 1. (a), Relationship between N_c and Re_i ; (b), Relationship between ϕ_L and Re_i

N_c . Good correspondence between the change in N_c and ϕ_L with V_s was also observed. These results show that ϕ_L is not only a typical measure reflecting foaming behavior in AAVs but also a measure related to hardness or ease of mechanical foam-breaking in terms of required disk speed.

2.3 Relationship between power consumption for foam-breaking and ϕ_L

The power consumption for foam-breaking, i.e., the power P_{Kc} required for liquid dispersion by the rotating disk, was calculated from Eq. (3)⁵⁾ by using the measured values of N_c .

Table 2. Values of A and B in Eq. (2)

Liquid	Re_i [—]	A [m/s]	B [—]
F-D*	3.5×10^4 – 6.5×10^4	2.57×10^{-3}	0.64
	6.5×10^4 – 1.3×10^5	1.69×10^2	–0.36
	1.3×10^5 – 2.0×10^5	2.41	0
F-E**	3.5×10^4 – 6.5×10^4	1.72×10^{-3}	0.69
	6.5×10^4 – 1.3×10^5	42.2	–0.22
	1.3×10^5 – 2.0×10^5	3.09	0
F-S***	3.5×10^4 – 6.5×10^4	1.66×10^{-3}	0.71
	6.5×10^4 – 1.3×10^5	28.6	–0.17
	1.3×10^5 – 2.0×10^5	3.86	0

$$N_{PK} = 4.29(N_W)^{1.0}(N_{Re})^{0.02}(N_{We})^{0.06} \quad (3)$$

Equation (3) is applicable when N_W is 5.6×10^{-6} – 1.2×10^{-3} , N_{Re} is 5.9×10^4 – 3.4×10^6 and N_{We} is 1.5×10^3 – 1.2×10^6 . The typical relationship between P_{Kc} and ϕ_L for each AAV is shown in Fig. 2, in which the data⁵⁾ in the AAV of $D_T = 0.23$ m are also plotted. On the whole, good correspondence is seen between the increases in P_{Kc} and ϕ_L , indicating that a foam of larger ϕ_L requires more power for foam-breaking. This result suggests that the value of ϕ_L can also be related to hardness or ease of mechanical foam-breaking in terms of power for foam-breaking. Moreover, regarding the fact that P_{Kc} values tend to be high in the large AAV, the main cause seems to be related to the increased dispersion distance of the liquid particles from the disk due to the increase of D_T and the increased frequency of impact between the dispersed liquid particles and the ascending foam.

2.4 Agitation power

For ungassed foaming liquids, the power number N_{P0} was measured for each AAV. All the systems had the tendency that N_{P0} decreased when Re_i exceeded about 7.4×10^4 , due to the effect of air entrainment from the free liquid surface.⁵⁾ The N_{P0} values at Re_i below 7.4×10^4 were 4.9, 5.1 and 5.8 for AAVs of $D_T = 0.19$, 0.23 and 0.27 m respectively, which agreed with those estimated from the correlation proposed by Bujalski *et al.*,¹⁾ within 5% error. The N_{P0} values at Re_i above 7.4×10^4 were expressed by the following form within 10% error.

$$N_{P0} = Re_i^{-3.95 \times 10^{-5} D_T^{-6.40}} e^{f(D_T)} \quad (5)$$

$$f(D_T) = 10^{4.03 - 14.69 D_T} + 2.532 \quad (6)$$

The agitation power P_{gf} in a mechanical foam-control system (MFS) and the agitation power P_g in a non-foaming system (NS) including AFs were then measured. P_{gf} was little affected by W . There were no significant differences in P_g when the kind and quantity of AF were varied. Figure 3 shows typical results of P_{gf}/P_g at W ranging from 1.0×10^{-5} to 3.0×10^{-5}

Fig. 2. Relationship between ϕ_L and P_{Kc}

Fig. 3. Change of P_{gf}/P_g with Re_i

m^3/s plotted against Re_i . In all the systems, P_{gf}/P_g values at the same aeration-agitation rate conditions were below 1.0. The P_{gf} values were correlated by the following equation, obtained in the previous work,⁵⁾ within 10% error regardless of D_T .

$$P_{gf} = 7.40 \times 10^{-1} (P_0^2 N_i D_i^3 / Q^{0.56})^{0.43} \quad (7)$$

2.5 Gas holdup

The gas holdups based on dispersion volume, ϵ_{gf} and ϵ_g , in the MFS and the NS were measured. ϵ_{gf} values, which were almost free from the effect of W in the range between 1.0×10^{-5} and $3.0 \times 10^{-5} m^3/s$, were large compared to ϵ_g values. That is, as shown in an example of Fig. 4, the values of the gas holdup ratio ϵ_{gf}/ϵ_g were larger than 1.0. Moreover, there were few effects of the kind and quantity of AF on ϵ_g in each AAV. For the correlations of gas holdup ϵ_{gf} , the effect of V_s on $\epsilon_{gf}/(1 - \epsilon_{gf})^2$ was almost the same as that⁵⁾ observed in the AAV of $D_T = 0.23$ m. In the same manner as in the change of $N_c D_d$ in Fig. 1(a), the increases of $\epsilon_{gf}/(1 - \epsilon_{gf})^2$ with Re_i were also found to be divided into three regions by two transition Re_i s, as shown in Table 2. The effect of power input per unit volume P_{gf}/V_L on $\epsilon_{gf}/(1 - \epsilon_{gf})^2$ was then examined. As a result, Eqs. (8a)–(8c) were obtained within 15% error regardless of D_T .

Fig. 4. Change of ϵ_{gf}/ϵ_g with V_s

$$3.0 \times 10^4 < Re_i \leq 6.5 \times 10^4$$

$$\epsilon_{gf}/(1 - \epsilon_g)^2 = a V_s^{0.75} (P_{gf}/V_L)^{1.00} \quad (8a)$$

$$6.5 \times 10^4 < Re_i \leq 1.3 \times 10^5$$

$$\epsilon_{gf}/(1 - \epsilon_g)^2 = b V_s^{0.34} (P_{gf}/V_L)^{0.66} \quad (8b)$$

$$1.3 \times 10^5 < Re_i \leq 2.0 \times 10^5$$

$$\epsilon_{gf}/(1 - \epsilon_g)^2 = c V_s^{0.22} (P_{gf}/V_L)^{0.25} \quad (8c)$$

where a , b and c are empirical constants. The values of a were 1.14×10^{-2} , 1.24×10^{-2} and 1.90×10^{-2} , respectively; those of b 1.28×10^{-2} , 1.37×10^{-2} and 2.89×10^{-2} , respectively; and those of c 2.32×10^{-1} , 2.41×10^{-1} and 6.15×10^{-1} , respectively for F-D, F-E and F-S solutions.

2.6 Application of the MFRD to a large AAV

Estimation of characteristics values such as N_c and P_{Kc} in a MFRD fitted in a larger AAV than those used in this work was attempted. The dimensions of a large AAV having the same geometrical design as that of the AAV used in the present work (the vessel, the rotating disk, the impeller, etc.) were first determined. For the large AAV with the MFRD having the dimensions determined, N_c and P_{Kc} values were then calculated with Eqs. (2) and (3), respectively, assuming that correlation equations can be also used for the large AAV.

The results of N_c and P_{Kc} for the large AAV when D_T is scaled up to 5.0×10^{-1} m and a disk of $D_T/D_a = 1.28$ is employed for F-D solution at V_s ranging from 8.32×10^{-3} to 1.66×10^{-2} m/s, corresponding to 1.0 to 2.0 vvm, and at Re_i above 1.3×10^5 corresponding to 4.7 rps, which is the region where N_c is almost free from the effect of Re_i , are shown in Fig. 5. The dotted line in Fig. 5(a) represents Eq. (1) for a disk of $D_a = 0.39$ m, that is, the boundary above which the reduction of N_c caused by the increase of W begins to level off. In Fig. 5(a), the oblique-lined areas enclosed with the curve drawn by Eq. (1) and the $N_c - W$ curves drawn by Eq. (2) are the operational range under which foaming can be controlled effectively and economically with the MFRD. For a more accurate scaleup of the MFRD fitted to the

Fig. 5. (a), Characteristic curve of N_c in large MFRD; (b), Characteristic curve of P_{Kc}

AAV, although further information concerning the oxygen transfer rate will be necessary, the estimation method demonstrated here may be used to predict the performance and effective operational range of a MFRD fitted into the larger AAV.

Nomenclature

b	= impeller blade width	[m]
C_F	= concentration of antifoam agent	[ppm]
D_a	= rotating disk diameter	[m]
D_i	= impeller diameter	[m]
D_T	= vessel diameter	[m]
d_i	= impeller disk diameter	[m]
l	= impeller blade length	[m]
N	= rotating disk speed	[1/s]
N_c	= rotating disk speed required at the critical foam-breaking state	[1/s]
N_i	= impeller rotational speed	[1/s]
N_W	= flow number ($= W/ND_a^3$)	[—]
N_W^*	= dimensionless transition liquid feed rate from ligament to filmy formation ($= W_i/D_a^2 \sqrt{vN}$)	[—]
N_{PK}	= power number ($= P_K/\rho N^3 D_a^5$)	[—]
N_{P0}	= power number ($= P_0/\rho N^3 D_a^5$)	[—]
N_{Re}	= Reynolds number ($= \rho N D_a^2/\mu$)	[—]
N_{We}	= Weber number ($= \rho N^2 D_a^3/\sigma$)	[—]
P_0	= agitation power in ungassed liquid	[W]
P_g	= agitation power in gassed liquid	[W]
P_K	= power consumption for foam-breaking (= power for liquid dispersion by rotating disk)	[W]
P_{Kc}	= power consumption for foam-breaking at the critical state	[W]
Q	= volumetric gas sparge rate	[m ³ /s]
Re_i	= Reynolds number ($= \rho N_i D_i^2/\mu$)	[—]
V_L	= working volume	[m ³]
V_s	= gas superficial velocity	[m/s]
vvm	= volumetric air flow per minute per working volume	[1/min]
W	= liquid feed rate onto the disk	[m ³ /s]
W_i	= transition liquid feed rate from ligament to filmy formation, calculated by Eq. (1)	[m ³ /s]
ϵ_g	= gas holdup based on dispersion volume	[—]
μ	= viscosity of liquid	[Pa·s]
ν	= kinematic viscosity of liquid	[m ² /s]
ρ	= density of liquid	[kg/m ³]
σ	= surface tension of liquid	[N/m]
ϕ_L	= liquid holdup in foam	[—]

<Subscripts>

- f = mechanical foam-controlling system
- 1 = transition point on Re_i at which N_c begins to decrease
- 2 = transition point on Re_i from which N_c becomes constant

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