PERFORMANCE CHARACTERISTICS OF AN AERATED AGITATED VESSEL UNDER MECHANICAL FOAM CONTROL

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For an aerated agitated vessel (AAV) treating various foaming liquids, the foam-breaking characteristics of a rotating-disk mechanical foam-breaker (MFRD) fitted to the AAV were evaluated. Foaming behavior of the AAV and foam-breaking behavior of the MFRD under varying operating conditions were related to the changes in liquid holdup in the foam. The agitation power in required the AAV with MFRD was found to be smaller than that in the AAV using antifoam agents (AFs), due to increased gas holdup. Comparison of the power input between two AAVs when foaming was controlled by the MFRD and AFs also demonstrated the superiority of mechanically controlled foaming.

Introduction

Aerated agitated vessels (AAVs) are reactors widely used for many industrial processes including fermentations. In gas-liquid contacting operations in such a reactor, foaming is a rather common phenomenon. The foaming causes various problems such as decrease in working liquid volume, accumulation of reactants or products in the foam, outflow of reactants or products due to escape of foam and marked limitation in aeration-agitation rate.[7,8] Therefore, it becomes important to control the foam in some way. Antifoam agents (AFs) have been employed in many cases to control the foaming. However, the addition of AFs to a process solution involves the following problems[2,4,6,7,9,18,20-22]: (1) reduction in mass transfer rate; (2) reaction inhibition and toxicity; (3) negative effects on separation and purification of products. In view of these facts, foam-breaking by a mechanical force is desirable. Previously, we examined

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a rotating-disk mechanical foam-breaker (MFRD) fitted to an AAV[13] and a bubble column.[14] It was suggested that when a foaming system was treated in the AAV with MFRD a steady reduction of agitation power consumption could be expected.[15] For development of a new aeration-agitation technique, useful for treating effectively a foaming system without need of AFs, i.e., development of an AAV having a mechanical foam-breaking mechanism, further studies of measures for foaming or of the difference in performance between AAVs with and without the addition of AFs are necessary. In this study, foaming characteristics in an AAV treating various liquids were first examined. Foaming behavior in the AAV and foam-breaking behavior of the MFRD were also investigated in terms of the volume fraction of liquid in the foam, i.e., the liquid holdup in the foam. The differences in power consumption and gas holdup between the two AAVs when the foaming was controlled by the MFRD and AFs were then evaluated. From a comparison of power input between the AAVs with and without the addition of AFs, the advantage of mechanically controlled foaming was further examined.

1. Experimental

The experimental apparatus employed in this study was the same as in the previous work.[15] The vessel, 2.3×10^{-1} m in diameter D_T, was equipped with four baffles (0.1 D_T in width), a six-blade turbine impeller ($D_i = D_T/3$, $b = D_i/5.0$, $l = D_i/2.86$ and $d_i = D_i/1.3$ in dimensions) and ring sparger with twelve holes of 1.0×10^{-3} m diameter. The impeller and liquid depth were held at $D_T/3$ and D_T respectively for all experimental runs. Further details were given in the previous paper.[15] The air sparge rates ranged from 3.79×10^{-3} to 7.58×10^{-3} m/s, corresponding to 1.0 and 2.0 *vvm*. The MFRD was set at a height of 2.0 D_T from the bottom. As the rotating disk, two disks, 1.7×10^{-1} and 1.8×10^{-1} m in diameter D_d, set within the effective D_T/D_d range,[13,14] were employed. The liquid feed rate W onto the rotating disk was varied from 1.0×10^{-5} to 3.0×10^{-5} m^3/s. Additional details of the MFRD have been reported.[13,14] In measurements of the liquid holdup in foam, ϕ_L, foam withdrawn through a glass tube (1.0×10^{-2} m diameter) fitted on the wall between two adjacent baffles was collected in a graduated container of constant volume v_F. The glass tube was kept at a level 2.0×10^{-2} m lower than the disk level, along with a middle axis in an annular section between the disk and the vessel wall, i.e., along with the vertical axis at a distance of $(D_T - D_d)/4$ from the wall. ϕ_L was determined by Eq. (1).[8,16]

$$\phi_L = v_L/v_F \tag{1}$$

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]	Keys
F[1)]-D*	—	998.2	1.00	53.94	○
F[1)]-T4**	—	998.4	1.02	55.20	△
F[1)]-T6***	—	998.4	1.02	45.20	□
F[1)]-E****	—	999.4	1.06	51.60	▽
F[1)]-S*****	—	1000.3	1.13	50.57	◇
NF[2)]-D*	570†	998.2	1.00	39.05	◑
	1140†	998.2	1.01	38.88	◐
	640††	998.2	1.01	29.17	◒
	1280††	998.3	1.02	28.97	◓
NF[2)]-T4**	620†	998.2	1.01	39.35	◮
	1240†	998.4	1.04	38.63	◭
	175††	998.4	1.02	35.73	⧍
	350††	998.5	1.04	35.48	▲
NF[2)]-T6***	125†	998.4	1.02	39.25	◨
	250†	998.5	1.02	37.99	◧
	233††	998.4	1.02	37.45	⬓
	466††	998.4	1.02	32.99	⬒
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^{-2} wt% Tween 40; *** 1.0×10^{-1} wt% Tween 60; **** 5.0×10^{-1} wt% egg albumin; ***** 2.0 wt% soya bean meal (liquid filtered after one hour's boiling).
† KM-70, silicon oil (Shin-Etsu Chemical Co. Ltd.).
†† BF-7, ††† CC-118, †††† BF-75, Nissan Disfoam (Nihon Yushi Corp.).

where v_F is the foam volume and v_L is the net liquid volume in v_F. v_L was measured from spontaneous collapse of foam in the container. Agitation power and gas holdup were measured according to methods identical to those employed in the previous work.[15] As the foaming liquid, five kinds of liquids were used at 293 K. These same solutions to which AFs were added were used as the non-foaming liquids. **Table 1** shows the properties of foaming and non-foaming liquids.

2. Results and Discussion

2.1 Foaming characteristics in the AAV in terms of changes in required disk rotational speed

The change in disk rotational speed of the MFRD with varying operating variables such as V_s and N_i was measured for respective liquids at the critical foam-breaking state.[13,14] The effects of W and V_s on the critical disk speed N_c at which foam-breaking was carried out were almost the same as those observed previously.[13] That is, the smaller is W and the larger is V_s, the higher N_c becomes. Higher values of N_c at smaller W and at larger V_s may be attributed respectively to the decreased number of liquid particles dispersed from the disk and the increased foaming intensity. **Figure 1** shows a typical relationship between N_c and N_i. N_c rapidly increased with the initial increase in N_i in all the systems. This means that there occurs a less foam-breakable tendency due to the increased foaming capacity with increase in N_i. However, when N_i exceeds a certain level, i.e., the first transition impeller speed $(N_i)_{t1}$, N_c decreased and was almost free from the effect of N_i in the high N_i region above the second transition impeller speed $(N_i)_{t2}$. It is well known that when N_i exceeds a certain level, sucking of air from the liquid surface occurs in unaerated and aerated AAVs with baffles.[5] It is conceivable that the mechanism of air entrainment when the head space is filled with foam is somewhat similar to that when the head space is filled only with air. Therefore, we can assume that: (1) when the head space of an AAV is filled with foam produced by foam-breaking, the impeller acts to entrain the foam from the head space to the aerated liquid surface, just as it does with air; (2) foaming is suppressed by the above mechanism which acts on foam, when N_i exceeds a certain level; (3) as a result of this phenomenon, the nature and velocity of the foam ascending through the head space of the AAV changes so as to facilitate the foam-breaking operation of the MFRD; (4) changes in the nature of the foam and of its ascending velocity by the foam entrainment phenomenon become almost constant in the high-N_i region.

These assumptions seem to provide a plausible explanation for the facts, such as the decrease in N_c in the N_i region above $(N_i)_{t1}$ and the near absence of effect of N_i on N_c in the region above $(N_i)_{t2}$.

2.2 Foaming behavior in the AAV and foam-breaking behavior of the MFRD in terms of changes in liquid holdup in foam

The MFRD achieves foam-breaking by means of impact action of liquid particles from the disk against the foam.[13,14] According to this mechanism, the liquid holdup in foam, ϕ_L, may be pointed out as a measure that reflects the foaming intensity of the AAV and is also related to hardness or ease of mechanical foam-breaking. The reason is that foam with larger ϕ_L may be difficult to collapse, due to a high deformation function, i.e., the function that prevents collapsing by deforming the shape.[1] A typical plot of ϕ_L vs. V_s is shown in **Fig. 2**, in which corresponding N_c data are also plotted. It is found that the tendency of increasing ϕ_L is similar to that of increasing N_c. This result shows that ϕ_L is not only a typical measure reflecting the foaming intensity of the AAV but is also a measure related to difficulty or ease of foam-breaking in terms of the changes in the required disk speed. **Figure 3** shows plots of ϕ_L and N_c vs. N_i. The way of changing of ϕ_L with increasing N_i as well was very

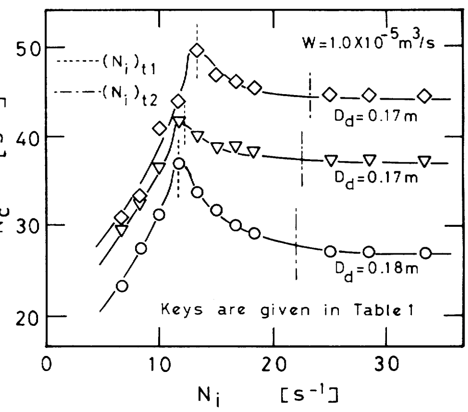


Fig. 1. Relationship between N_c and N_i at $V_s = 5.69 \times 10^{-3}$ m/s

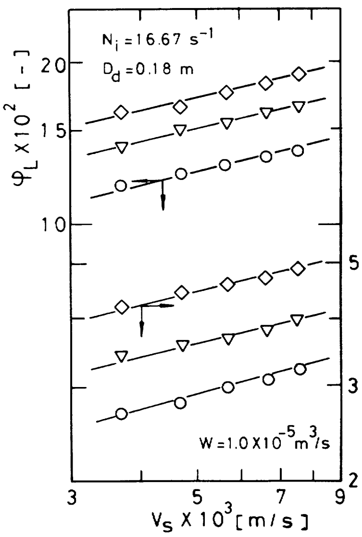


Fig. 2. Effect of V_s on ϕ_L (keys are given in Table 1)

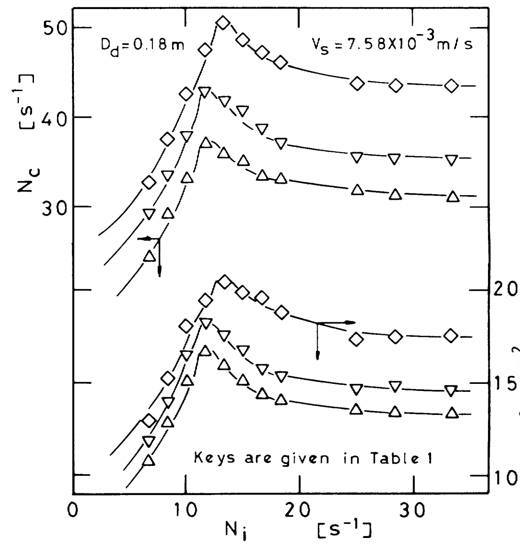


Fig. 3. Effect of N_i on ϕ_L at $W = 1.0 \times 10^{-5}$ m³/s

similar to that of changing of N_c. When the foam entrainment phenomenon mentioned previously occurs at N_i above a certain level, we can anticipate a smaller ϕ_L because the downward flow of the liquid by gravity relatively increases as the ascending velocity of foam decreases, and as a resut the drainage rate of liquid from the foam increases.[8,16] The increase and decrease in ϕ_L in the N_i region below and above $(N_i)_{t1}$ in Fig. 3 seem to support this presumption. Almost constant values of ϕ_L in the region above $(N_i)_{t2}$ may be attributed to the same level of drainage rate of liquid from the foam.

2.3 Relation between liquid holdup in foam and power for foam-breaking

The relation between ϕ_L and the power for foam-breaking (power P_{Kc} required for liquid dispersion by the rotating disk) was investigated. The power P_{Kc} in the critical foam-breaking state was calculated from Eq. (2),[14] by using the measured values of N_c.

$$N_{PK}=4.29(N_W)^{1.0}(N_{Re})^{0.02}(N_{We})^{0.06} \qquad (2)$$

Figure 4 shows the relation between P_{Kc} and ϕ_L. On the whole, good correspondence was seen between the increases of P_{Kc} and ϕ_L. According to this result, it may be pointed out that the value of ϕ_L can be also related to the difficulty or ease of mechanical foam-breaking in terms of the power required for foam-breaking.

2.4 Correlation in critical foam-breaking regions

The correlations for N_c were studied within the range of the effective upper limit of W,[13,14] i.e., the W_t range which could be predicted by Eq. (3),[10] which indicates the transition from ligament formation to film formation.

$$Q_t^+=0.340Re^{2/3}We^{-0.883} \qquad (3)$$

Firstly, the relationship between the peripheral velocity N_cD_d of the disk and the gas-liquid feed ratio Q/W was examined. N_cD_d values for all the systems were found to vary in proportion to Q/W approximately to the 0.22 power. The effect of the Reynolds number Re_i on N_cD_d was then investigated. Their correlations could be expressed by the following form within 10% error.

$$N_cD_d=A(Q/W)^{0.22}(Re_i)^B \qquad (4)$$

The values of empirical constants A and B in Eq. (4), which change according to the range of Re_i and the liquid, are summarized in **Table 2**. Equation (4) is applicable when D_T is 2.3×10^{-1} m; D_T/D_d is 1.28–1.35; Q is 1.58×10^{-4}–3.15×10^{-4} m^3/s; W is 1.0×10^{-5}-W_t m^3/s; and Re_i is 3.5×10^{-4}–2.0×10^5.

2.5 Power requirement for agitation

The agitation power P_0 in ungassed liquids was measured. **Figure 5** shows the relationship between the power number N_{PO} and Re_i. In all the systems used, N_{PO} tended to decrease when Re_i exceeded about 7.4×10^4, due to the effect of air entrainment from the liquid surface.[5,11] The N_{PO} value at Re_i below 7.4×10^4 was 5.10. This value agreed approximately with N_{PO} estimated from the correlation proposed by Bujalski *et al.*[3] For N_{PO} values at Re_i above 7.4×10^4,

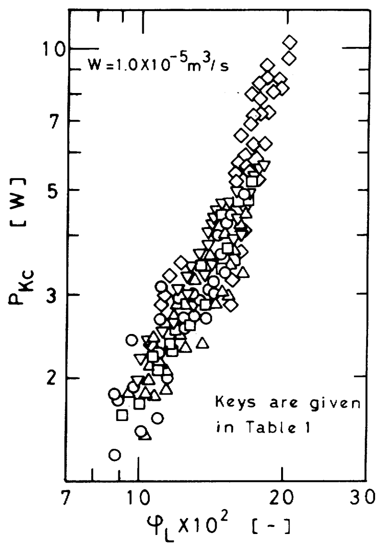


Fig. 4. Relationship between P_{Kc} and ϕ_L

Table 2. Values of A and B in Eq. (3)

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-T4**	3.5×10^4–6.5×10^4	1.98×10^{-3}	0.66
	6.5×10^4–1.3×10^5	21.8	−0.18
	1.3×10^5–2.0×10^5	2.62	0
F-T6***	3.5×10^4–6.5×10^4	4.25×10^{-3}	0.60
	6.5×10^4–1.3×10^5	37.4	−0.22
	1.3×10^5–2.0×10^5	2.81	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

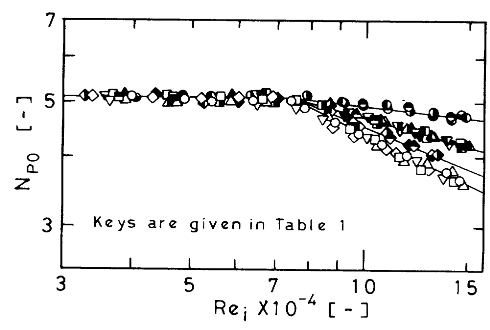


Fig. 5. Relationship between N_{PO} and Re_i

their correlations were expressed by the following equation within 10% error.

$$N_{PO} = a(Re_i)^b \tag{5}$$

where the values of empirical constants a and b are 19.6 and -0.12 for a NF-D solution, 1.17×10^2 and -0.28 for NF-T4, NF-T6 and NF-E solutions, 4.52×10^2 and -0.40 for a NF-S solution, and 1.10×10^3 and -0.48 for all the foaming liquids.

The gassed power P_{gf} in a mechanical foam-control system (MFS) and the gassed power P_g in a non-foaming system (NS) including AFs were then measured. Typical results of P_{gf} and P_g plotted against V_s are shown in **Fig. 6**. The difference between P_{gf} and P_g is obvious and the values of the power ratio P_{gf}/P_g at the same aeration-agitation rate conditions were below 1.0 in all the systems. Moreover, P_{gf} was little affected by W. No significant differences in P_g were observed when the kind and quantity of AF were varied. For the correlation of agitation powers, the following equations in terms of an empirical term,[12,17] $P_O^2 N_i D_i^3 / Q^{0.56}$, were obtained for P_{gf} and P_g respectively, within 10% error.

$$P_{gf} = 7.40 \times 10^{-1} (P_O^2 N_i D_i^3 / Q^{0.56})^{0.43} \tag{6}$$

$$P_g = 9.95 \times 10^{-1} (P_O^2 N_i D_i^3 / Q^{0.56})^{0.45} \tag{7}$$

2.6 Gas holdup

The results of gas holdups, ε_{gf} and ε_g, measured respectively in the MFS and the NS are shown in **Fig. 7**. ε_{gf} values, which were almost free from the effect of W, were quite large compared to ε_g values. That is, the values of the gas holdup ratio $\varepsilon_{gf}/\varepsilon_g$ were found to be larger than 1.0. Moreover, there were few effects of the kind and quantity of AF on ε_g. **Figure 8** shows the changes of ε_{gf} and ε_g with increasing Re_i. The increases of ε_{gf} and ε_g were approximately divided into three and two regions respectively. The values of two transition Re_is on ε_{gf} were close to those of two transition Re_is in Table 2 by which the change of $N_c D_d$ with increasing Re_i was divided into three regions. For the correlations of gas holdup with variables such as V_s and Re_i, plots of $\varepsilon_{gf}/(1-\varepsilon_{gf})^2$ or $\varepsilon_g/(1-\varepsilon_g)^2$ against V_s were first found to show the linear relationships which differ depending on the range of Re_i. The exponents of Re_i were then determined. As a result, Eqs. (8a)–(8c) and Eqs. (9a) and (9b) were obtained respectively for the MFS and the NS, within 10% error.

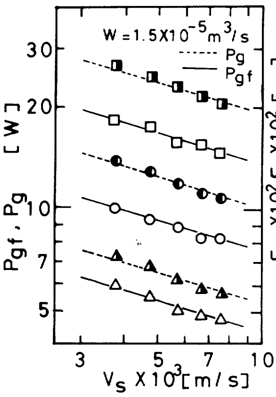
$3.5 \times 10^4 < Re_i \leqq 6.5 \times 10^4$

$$\varepsilon_{gf}/(1-\varepsilon_{gf})^2 = A V_s^{0.75} Re_i^{3.00} \tag{8a}$$

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

$$\varepsilon_{gf}/(1-\varepsilon_{gf})^2 = B V_s^{0.34} Re_i^{1.98} \tag{8b}$$

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



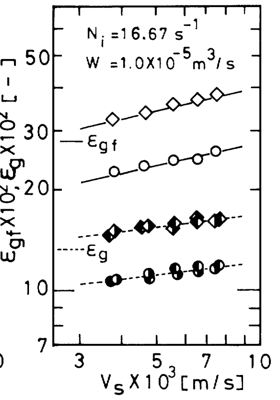


Fig. 6. Comparison of agitation power between MFS and NS (keys are given in Table 1)
N_i [s^{-1}]: (△,▲); 10.00, (○,◐); 11.67, (□,◨); 15.00
Fig. 7. Comparison of gas holdup between MFS and NS (keys are given in Table 1)

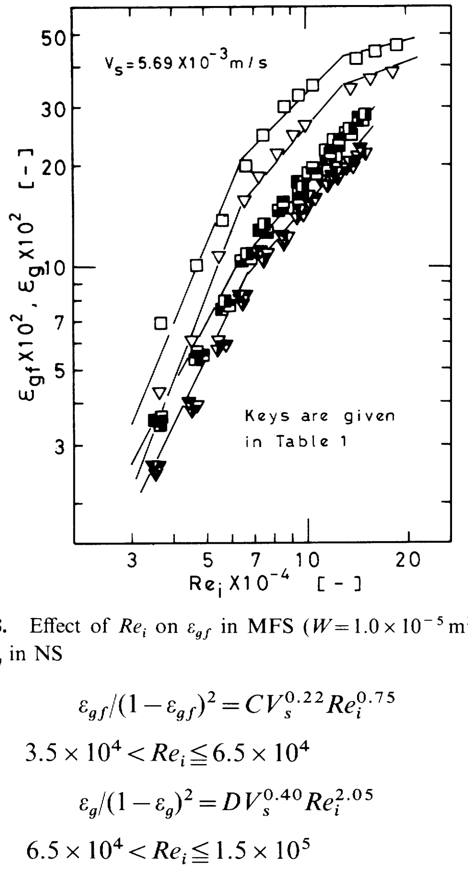


Fig. 8. Effect of Re_i on ε_{gf} in MFS ($W = 1.0 \times 10^{-5}$ m^3/s) and ε_g in NS

$$\varepsilon_{gf}/(1-\varepsilon_{gf})^2 = C V_s^{0.22} Re_i^{0.75} \tag{8c}$$

$3.5 \times 10^4 < Re_i \leqq 6.5 \times 10^4$

$$\varepsilon_g/(1-\varepsilon_g)^2 = D V_s^{0.40} Re_i^{2.05} \tag{9a}$$

$6.5 \times 10^4 < Re_i \leqq 1.5 \times 10^5$

$$\varepsilon_g/(1-\varepsilon_g)^2 = E V_s^{0.15} Re_i^{1.52} \tag{9b}$$

The values of empirical constants A, B, and C for the MFS and D and E for the NS which change according to the liquid are summarized in **Tables 3** and **4** respectively.

2.7 Comparison between the MFS and the NS in terms of power input

Comparison between the power input P_T in the MFS, expressed as the sum of the agitation power P_{gf} and the power P_{Kc} for foam-breaking, and the

Table 3. Values of A, B and C in Eqs. (8a), (8b) and (8c) for MFS

Liquid	$A\times10^{14}$ [$m^{-0.75}s^{0.75}$]	$B\times10^{10}$ [$m^{-0.34}s^{0.34}$]	$C\times10^{4}$ [$m^{-0.22}s^{0.22}$]
F-D*	3.25	3.18	3.33
F-T4**	5.08	4.95	5.19
F-T6***	6.03	5.87	6.16
F-E****	3.80	3.68	3.87
F-S*****	7.97	7.78	8.16

Table 4. Values of D and E in Eqs. (9a) and (9b) for NS

Liquid	$D\times10^{10}$ [$m^{-0.40}s^{0.40}$]	$E\times10^{8}$ [$m^{-0.15}s^{0.15}$]
NF-D*	0.925	0.903
NF-T4**	1.20	1.18
NF-T6***	1.44	1.40
NF-E****	1.18	1.15
NF-S*****	1.64	1.66

agitation power P_g as the power input in the NS was carried out. In comparing the power input at the same V_s, the power input ratio η defined by Eq. (10) was employed.

$$\eta=(P_{gf}+P_{Kc})/P_g \qquad (10)$$

The values of P_{Kc} were calculated in terms of both Eqs. (2) and (4). The values of P_{gf} and P_g were calculated from Eqs. (5) and (6) and Eqs. (5) and (7), respectively. **Figure 9** shows the typical results of η. The values of η decrease with increasing Re_i and then become smaller than 1.0. That is, it is confirmed that when Re_i is above a certain level the power input in the MFS is rather lower than that in the NS. It is generally known that the increase in gas holdup contributes to that in the volumetric mass transfer coefficient.[2,9,22] According to the results of ε_{gf} and ε_g in Fig. 7, the volumetric mass transfer coefficient in the MFS is assumed to be high compared with that in the NS. If the results for mass transfer characteristics are further taken into consideration, the difference in performance between two AAVs may become more notable.

Conclusion

The results obtained in this study are summarized as follows.

1) The liquid holdup in foam, ϕ_L, can be used as a substantial measure of the foaming intensity for the AAV. The effect of operating conditions on ϕ_L is also related to difficulty or ease of mechanical foam-breaking.

2) The agitation power P_{gf} in the MFS is small compared with P_g in the NS, due to the increased gas holdup. Their difference increases with increase of N_i.

3) When a foaming system is treated at Re_i above a certain level, use of an AAV having a mechanical foam-breaking mechanism has an advantage from the viewpoint of power economy.

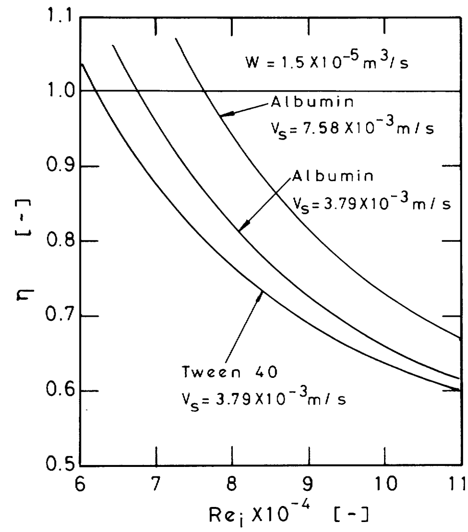


Fig. 9. Relationship between η and Re_i

Nomenclature

b	= impeller blade width	[m]
c_F	= concentration of antifoam agent	[ppm]
D_d	= 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 in the critical foam-breaking state	[1/s]
N_i	= impeller rotational speed	[1/s]
N_W	= flow number ($=W/ND_d^3$)	[—]
N_{PK}	= power number ($=P_K/\rho N^3D_d^5$)	[—]
N_{PO}	= power number ($=P_0/\rho N_i^3D_i^5$)	[—]
N_{Re}	= Reynolds number ($=\rho ND_d^2/\mu$)	[—]
N_{We}	= Weber number ($=\rho N^2D_d^3/\sigma$)	[—]
P_0	= agitation power in ungassed liquid	[W]
P_g	= agitation power in gassed liquid	[W]
P_K	= liquid dispersion power	[W]
P_{Kc}	= liquid dispersion power in the critical foam-breaking state	[W]
P_T	= power input in the MFS ($=P_{gf}+P_{Kc}$)	[W]
Q	= volumetric gas sparge rate	[m³/s]
Q_t^+	= dimensionless transition liquid feed rate from ligament to filmy formation ($=W_t/2\pi R^2\sqrt{\nu\omega}$)	[—]
R	= disk radius	[m]
Re	= Reynolds number ($=R^2\omega/\nu$)	[—]
Re_i	= Reynolds number ($=\rho N_iD_i^2/\mu$)	[—]
v_F	= foam volume	[m³]
v_L	= net liquid volume in v_F	[m³]
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	[m³/s]
We	= Wever number ($=\rho R^3\omega^2/\sigma$)	[—]
Wt	= transition liquid feed rate from ligament to filmy formation,	

		calculated by Eq. (3)	$[m^3/s]$
ε_g	=	gas holdup based on dispersion volume	[—]
η	=	power input ratio defined by Eq. (9)	[—]
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]
ω	=	angular speed of disk	[rad/s]
ϕ_L	=	liquid holdup in foam	[—]

⟨Subscripts⟩

f	=	mechanical foam-controlling system
$t1$	=	transition point on N_i at which N_c begins to reduce
$t2$	=	transition point on N_i from which N_c becomes constant

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