MIXING AND MASS TRANSFER CHARACTERISTICS OF AN UNBAFFLED AERATED AGITATION VESSEL WITH UNSTEADILY FORWARD-REVERSE ROTATING MULTIPLE IMPELLERS

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Abstract— **Mixing and mass transfer characteristics of an unbaffled aerated agitation vessel with a liquid height-to-diameter ratio of 2 having unsteadily forward-reverse rotating multiple impellers, a cross type of impellers with four delta blades (CDs), were experimentally studied for air-water system in comparison with those of a baffled vessel having steadily unidirectionally rotating disk turbine impellers with six flat blades (DTs). For the forward-reverse rotating CD vessel, the contribution of sparged gas to enhancement in liquid phase mixing was observed in the entire range of gas sparging rate including its lower range. Agitating by the forward-reverse rotating CDs functioned effectively to enhance gas-liquid mass transfer not only in the lower range of gas sparging rate but also in its higher range. The features in operating the forward-reverse rotating multiple CD vessel were discussed in terms of the differences in the mixing time and volumetric mass transfer coefficient due to changes in the power input.**

Keywords— **mixing time; volumetric mass transfer coefficient; unbaffled aerated agitation vessel; unsteadily forward-reverse rotating impeller; multiple impeller system**

I. INTRODUCTION

Agitation vessels are widely used to disperse and dissolve gas into liquid for many industrial processes. When the solubility of gas is low as in the case of oxygen in water, deep vessels characterized by a liquid height-to-diameter ratio larger than unity are selected in order to increase the contacting time between dispersed gas and continuous liquid phases (Hudcova *et al.*, 1989; Abrardi *et al.*, 1990; Manikowski *et al.*, 1994). These contactors are usually agitated with more than one impeller attached on a single shaft. The information on the design and operation of the multiple impeller system treating gas-liquid mixtures has an important significance in relation to practical application of the agitation system to the gas-liquid reactors and fermentors, however, the related research is not so abundant. A review of a few literatures (Hudcova *et al.*, 1989; Abrardi *et al.*, 1990; Manikowski *et al.*, 1994; Cronin *et al.*, 1994; Vasconcelos *et al.*, 1995), which dealt with the power consumption and bulk flow pattern of the gas-liquid agitation system using the unidirectionally rotating conventional impellers arranged in multiple fashion in the baffled vessel, rather reveals that there is a need to develop a novel multiple impeller system which may bring about a good liquid phase mixing and mass transfer with a lower power input.

Previously, we proposed an unbaffled vessel having forward-reverse rotating multiple impellers, a cross type of impellers with four delta blades (CDs), whose rotation reverses its direction periodically, and for a system containing water with the liquid height-to-diameter ratio of 2, the effect of clearance on the power consumption of impellers was elucidated (Yoshida *et al.*, 2002). It was also confirmed that a decreased mixing characteristics of liquid phase in the deep vessel were improved by increasing the number of impellers when the forward-reverse rotating CDs were used in multiple fashion (Yoshida *et al.*, 2004). In this work, the unbaffled vessel having the forward-reverse rotating multiple CDs was applied to gas-liquid contacting operation. The liquid phase mixing time and gas-liquid volumetric mass transfer coefficient, which are parameters necessary to design and operate successfully this type of vessel as a gas-liquid contactor, were first measured for air-water system. The relationships between these operational characteristics and the aeration-agitation conditions such as the gas sparging rate, the rotation rate and the number of impellers were then compared between the unbaffled vessel with the forward-reverse rotating CDs and baffled vessel with the unidirectionally rotating disk turbine impellers with six flat blades (DTs). Furthermore, on the basis of the differences in the mixing time and volumetric mass transfer coefficient as viewed from changes in the power input, the features in operating the forward-reverse rotating multiple CD vessel were tried to reveal.

II. METHODS

As the forward-reverse rotating impeller, a cross type

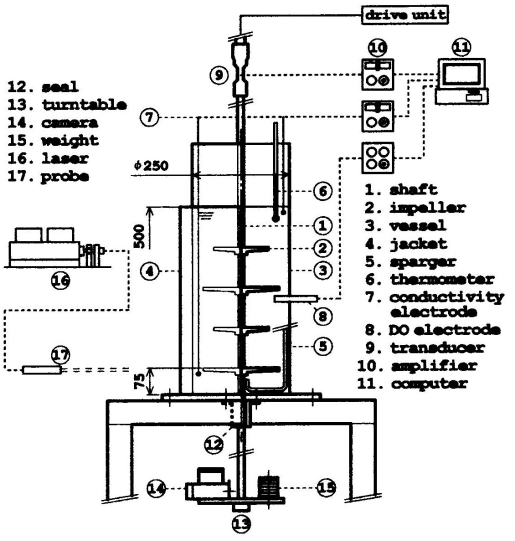

Figure 1. Schematic diagram of experimental apparatus. Dimensions in mm.

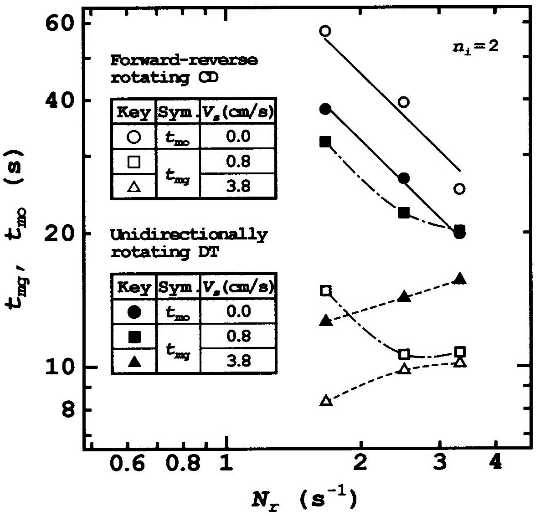

Figure 2. Relationship between mixing time and N_r.

of impeller with four delta blades (CD), 200 mm in diameter (D_i), was employed for the unbaffled vessel. A conventional Rushton turbine impeller, a disk turbine impeller with six flat blades (DT), was adopted as the unidirectionally rotating impeller. DT, 120 mm in D_i, was used under the fully baffled condition (four baffles, 0.1-fold inner diameter of vessel in width). A schematic diagram of the experimental set-up is shown in Fig. 1. The vessel made of transparent acrylic resin, 250 mm in inner diameter (D_t), was used. The depth of liquid, H, was held at twice D_t (500 mm). The geometrical conditions such as D_t and H were common to the forward-reverse and unidirectional agitation modes, except for use of the unbaffled or baffled vessel. The distance from the bottom of the lowest impeller, C_b, was 75 mm. The other impellers were set equidistantly on the shaft in its section (425 mm in distance) between the lowest impeller and the liquid surface. The number of impellers, n_i, was varied from two to eight for the forward-reverse rotating CDs and from two to four for the unidirectionally rotating DTs, respectively. These ranges correspond to the conditions that the impellers on the shaft are almost regarded to act independently of each other without impeller-impeller flow pattern interaction (Yoshida *et al.*, 2002). In the mechanism for transmitting motion used here, when the crank is rotated by one revolution, the impellers first rotate up to one-quarter of a revolution in one direction, stop rotating at that position, and then rotate by one-quarter of a revolution in the reverse direction. That is, the angular amplitude of forward-reverse rotation was π/4. The rotation rate of the forward-reverse rotating impeller changes sinusoidally with time. By adjusting the cyclic frequency of this motion in the range from 3.33 to 6.67 Hz, the average rotation rate, N_r, set was ranged from 100 to 200 rpm. The rotation rate of the unidirectionally rotating impeller was varied in the same range. Single hole nozzle of 7 mm diameter was used for air sparging. The superficial gas velocity, V_s, ranged from 0.4 to 5.9 cm/s. A reflex or a video camera was set on the turntable, which rotated together with the impeller, underneath the vessel. The horizontal plane including the impeller, namely, impeller region, illuminated with a 0.5 W laser light source was photographed, and the pictures giving a display of the flow behavior of gas phase were recorded on films or video tapes. For all experiments, deionized water was employed at 298 K.

The power consumption of the impellers, P_m, was determined by measuring the torque with the strain gauges fitted on the shaft (Yoshida *et al.*, 2002). Batch mixing time of liquid phase was evaluated by the pulse method. A passive tracer was introduced at a fixed point near the liquid surface and fluctuation of the tracer concentration as a function of time was measured at the upper and lower points of vessel. Details of the technique are described in the previous report (Yoshida *et al.*, 2004).

For mass transfer runs, the physical absorption of oxygen in air was used. The volumetric oxygen transfer coefficient, $k_L a_L$, based on the liquid volume was determined by the gassing-out method with purging nitrogen. Errors in the volumetric coefficient values due to the response lag of the DO electrode were corrected based on the first-order model (Dang *et al.*, 1977) using the time constant of the electrode obtained by response experiments.

III. RESULTS AND DISCUSSION

A. Liquid Phase Mixing

Figure 2 shows the effect of impeller rotation rate, N_r,

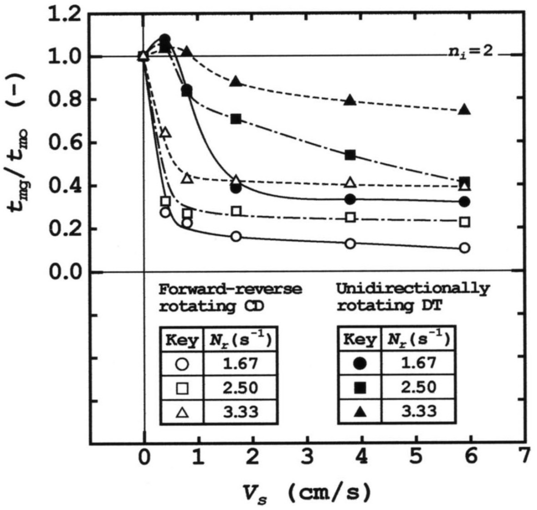

Figure 3. Relationship between t_{mg}/t_{mo} and V_s with N_r as a parameter.

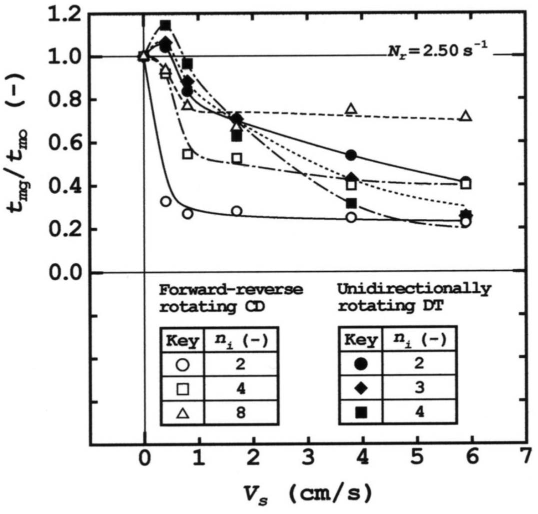

Figure 5. Relationship between t_{mg}/t_{mo} and V_s with n_i as a parameter.

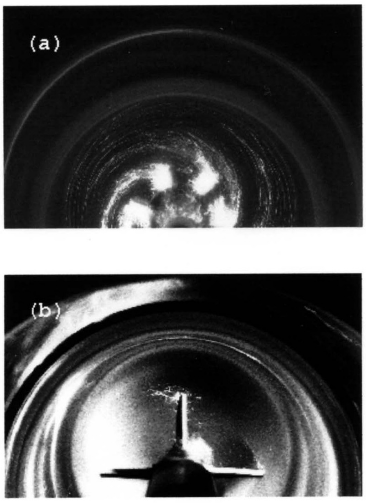

Figure 4. Gassed flow in impeller region. (a) unidirectionally rotating DT, (b) forward-reverse rotating CD.

on the gassed mixing time, t_{mg}, for the double impeller system using the forward-reverse rotating CDs in the unbaffled vessel and that using the unidirectionally rotating DTs in the baffled vessel, respectively. In the figure, the values of ungassed mixing time, t_{mo}, were also plotted for comparison. For both the modes of operation, t_{mo} decreased with increase of N_r, and there was an inverse relation between t_{mo} and N_r. As for the results under aeration, it was found that the dependence of t_{mg} on N_r differed depending on the agitation mode and superficial gas velocity, V_s. That is, gas sparging has an irregular effect on liquid phase mixing at different N_r. Such tendency was observed also when the number of impellers was varied.

The effect of gas sparging on liquid phase mixing was then examined using the ratio of gassed mixing time to ungassed mixing time, t_{mg}/t_{mo}. Figure 3 shows the relationship between t_{mg}/t_{mo} and V_s for each double impeller system with N_r as a parameter. The way of change in t_{mg}/t_{mo} with V_s differed between two different modes of operation. For the unidirectionally rotating DT vessel, t_{mg}/t_{mo} tended to increase slightly with initial increase of V_s, exhibiting the values beyond 1, but then decreased with further increase of V_s. The tendency for t_{mg}/t_{mo} to increase in the lower V_s range may be mainly attributed to a decreased rate of discharge flow from the impeller due to formation of the large cavities [see Fig. 4 (a)] behind the blades, as seen also in the studies by other workers (Van't Riet and Smith, 1973; Bruijn *et al.*, 1974). Also, the result that t_{mg}/t_{mo} decreased in the higher V_s range may be mainly caused by the contribution of the axial liquid flow produced by sparged gas to enhancement in mixing between the adjacent impellers (Pandit and Joshi, 1983; Abrardi *et al.*, 1990; Cronin *et al.*, 1994; Vasconcelos *et al.*, 1995). On the other hand, for the forward-reverse rotating CD vessel, there was no tendency for t_{mg}/t_{mo} to increase with initial increase of V_s, exhibiting the values below 1 under all V_s conditions, and sparged gas tended to contribute on the whole to enhancement in liquid phase mixing. For the impeller region of the forward-reverse rotating CD, as illustrated in Fig. 4 (b), unsteady behavior with the cavities behind the blades dispersed each time the rotation of impeller was reversed was observed throughout the entire range of V_s. Absence of the large cavities as formed behind the blade of the unidirectionally rotating DT causes an inconsiderable fall in the gassed power consumption of the impeller, namely, the capacity of energy transmission through the impeller to fluid, leading to an unmarked decrease in the rate of discharge flow from the impeller. Also, as reported previously (Yoshida *et al.*, 2002), bulk liquid

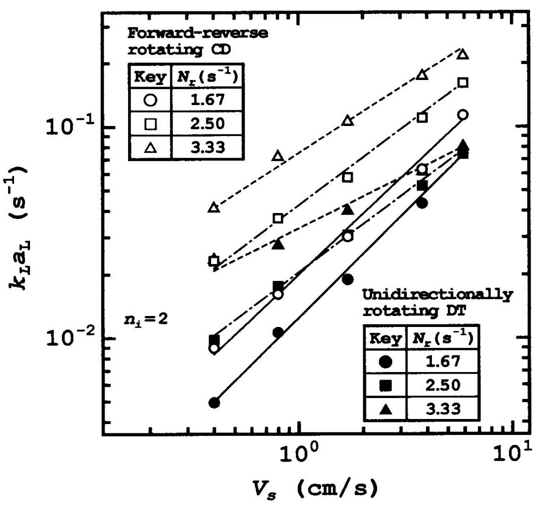

Figure 6. Relationship between k_La_L and V_s with N_r as a parameter.

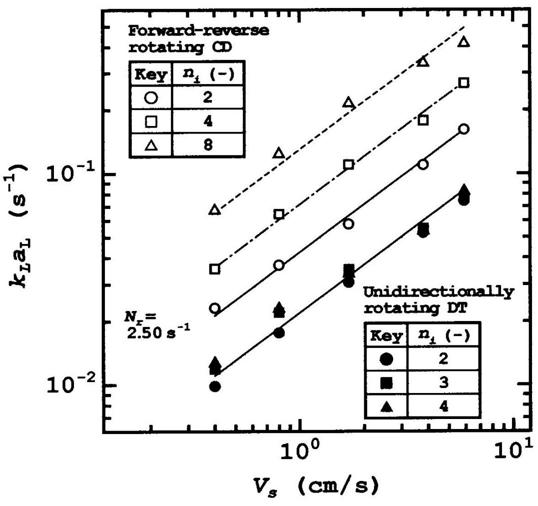

Figure 7. Relationship between k_La_L and V_s with n_i as a parameter.

presents a favorable flow pattern as a result that the discharge flow from the forward-reverse rotating CD has the larger axial component and that use of the impellers in multiple fashion brings about a series of discharge flows between the adjacent impellers. The axial liquid flow produced due to discharge from the multiple impellers superposed on that produced due to rise of gas bubbles is perceived to be effective for whole mixing throughout the vessel. The main cause for the sufficient mixing characteristics of gassed liquid phase of the forward-reverse rotating CD vessel exhibiting the relatively low values of t_{mg}/t_{mo} may be a reflection of combined contribution of liquid flow produced by sparged gas and the impellers to enhancement in mixing. As for the effect of N_r, the tendency for t_{mg}/t_{mo} to increase with N_r was found to be common to two agitation modes. Figure 5 shows the relationship between t_{mg}/t_{mo} and V_s for multiple impeller systems with the number of impellers, n_i, as a parameter. When n_i was increased in the forward-reverse rotating multiple CD vessel, t_{mg}/t_{mo} tended to increase. That is, the contribution of sparged gas to enhancement in liquid phase mixing became smaller. Taking into consideration the negative dependence of t_{mg}/t_{mo} on N_r as shown in Fig. 3, the difference in the gassed mixing characteristics when the agitation conditions was increased may be mainly attributed to a decreased rising velocity of gas bubble swarm due to an increased gas hold-up with increase of the agitation intensity.

B. Gas-Liquid Mass Transfer

Figure 6 shows the relationship between the volumetric oxygen transfer coefficient, k_La_L, and the superficial gas velocity, V_s, for the double impeller system using the forward-reverse rotating CDs in the unbaffled vessel and that using the unidirectionally rotating DTs in the baffled vessel, respectively, with the impeller rotation rate, N_r, as a parameter. For all systems, k_La_L increased with increase of V_s, and the larger was N_r the smaller the rate of its increase became. The difference in the dependence of k_La_L on V_s was more conspicuous in the system with the unidirectionally rotating DTs, resulting in almost unchanged k_La_L when N_r was varied under the higher V_s condition. This means flooding of the unidirectionally rotating DT by gas bubbles. It is generally known that under flooding condition the increase in volumetric mass transfer coefficient can not be expected even if the impeller rotation rate is increased (Warmoeskerken and Smith, 1985). In the system with the forward-reverse rotating CDs, such tendency was not observed throughout the entire range of V_s. Figure 7 shows the relationship between k_La_L and V_s for both the multiple impeller systems with the number of impellers, n_i, as a parameter. There was a significant difference in the effect of n_i on k_La_L between two agitation modes. That is, while k_La_L in the unidirectional agitation mode was almost independent of n_i, k_La_L in the forward-reverse agitation mode increased with increase of n_i regardless of V_s. This difference indicates that for the forward-reverse rotating multiple CD vessel the contribution of increasing the number of impellers to enhancement in gas-liquid mass transfer is relatively large.

C. Characterization of forward-reverse rotating multiple CD vessel in terms of relationships between operational characteristics and power input

For the gas-liquid contactors agitated by multiple impellers, changes in the aeration-agitation conditions such as the gas sparging rate, the rotation rate and the number of impellers and changes in the gas sparging rate result in differences in the agitation power input and those in the aeration power input, respectively. That is, the power inputs are the parameter reflecting the changes in the aeration-agitation conditions. The

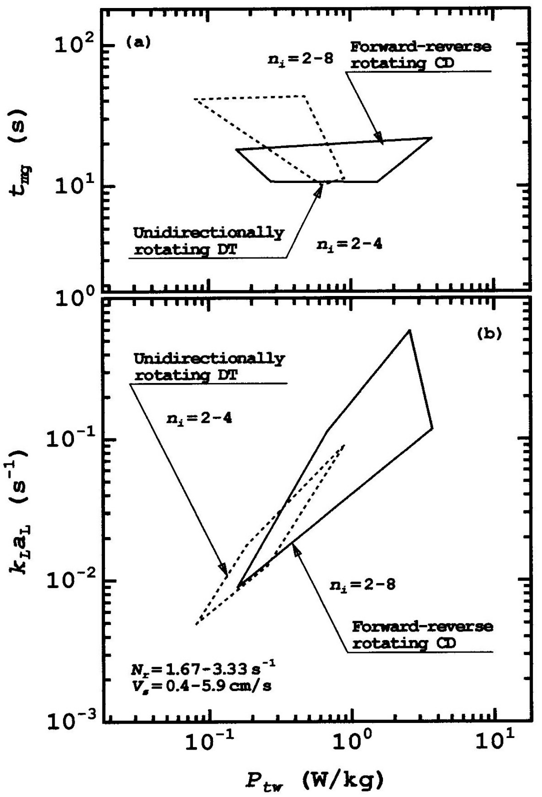

Figure 8. Relationships between operational characteristics and P_{tw}.

operational characteristics such as the mixing time and the volumetric mass transfer coefficient are frequently related to the power inputs. On the basis of these relationships, the liquid phase mixing and gas-liquid mass transfer characteristics are discussed, and a characterization of the contactors is made to obtain their operational features. The relationships between the operational characteristics and power input in the forward-reverse rotating multiple CD vessel were first examined in comparison with those in the unidirectionally rotating DT vessel. The features in operating the forward-reverse rotating multiple CD vessel were then sought, based on the differences in the operational characteristics as viewed from changes in the power input.

Figure 8 shows the results of the operational characteristics plotted as a function of the total power input, which is the sum of the agitation and aeration power inputs, per unit mass of liquid, P_{tw}. The upper figure (a) is for the gassed mixing time, t_{mg}, and the lower figure (b) is for the volumetric mass transfer coefficient, k_La_L. In the operating region of low P_{tw} below about 1.0 W/kg corresponding to the aeration-agitation conditions that the gas sparging rate, the rotation rate and the number of impellers are lower, although there is no significant difference in k_La_L between the forward-reverse rotating CD vessel and unidirectionally rotating DT vessel, the t_{mg} values for the former vessel were small compared with those for the latter vessel. A considerable difference in the P_{tw} values attainable when aeration-agitation conditions were increased was also observed between two vessels operated in different modes. That is, the P_{tw} values attainable for the forward-reverse rotating CD vessel were about three-fold higher than those attainable for the unidirectionally rotating DT vessel. This demonstrates that the efficiency of the energy transmission through the impeller to fluid under aeration is sufficiently high without formation of the cavities leading to the reduced performance of impeller, contrary to the unidirectionally rotating DT vessel. For the forward-reverse rotating CD vessel operated in such region of high P_{tw} above about 1.0 W/kg, while the t_{mg} values, as can be seen from Fig. 8 (a), remained smaller, the larger k_La_L values with maximum being about 0.6 s^{-1}, as shown in Fig. 8 (b), were obtained. According to these results, the operational features can be pointed out for the unbaffled aerated agitation vessel with the forward-reverse rotating multiple CDs operable over a wide range of P_{tw}, as follows. In the operating region of low P_{tw}, this type of vessel, which has the same level of gas-liquid mass transfer characteristics as the existing type of vessel, is superior in the liquid phase mixing characteristics. For this type of vessel operated in the region of high P_{tw}, not only the sufficient mixing characteristics but also the mass transfer characteristics exceeding those for the existing type of vessel are expected.

IV. CONCLUSIONS

Liquid phase mixing and gas-liquid mass transfer in an unbaffled aerated agitation vessel with a liquid height-to-diameter ratio of 2 having the unsteadily forward-reverse rotating multiple cross type of impellers with four delta blades (CDs) was experimentally investigated for air-water system in comparison with those in a baffled vessel having the steadily unidirectionally rotating disk turbine impellers with six flat blades (DTs). For the forward-reverse rotating CD vessel, the values of gassed mixing time was small compared with those of ungassed mixing time throughout the entire range of gas sparging rate. Also, the volumetric oxygen transfer coefficient increased with increase of the agitation intensity such as the rotation rate and the number of impellers over a wide range of gas sparging rate. Evaluation of these operational characteristics as viewed from changes in the total power input per unit mass of liquid revealed the following features of this type of vessel with the forward-reverse rotating CDs exhibiting the superiority in the range of power input over the existing type of vessel with the unidirectionally rotating DTs: this type of vessel has the mixing and mass transfer characteristics that are not at all inferior to those in the existing type of vessel, and especially in the operating region of high power input unattainable in operation of the existing type of vessel, this type of vessel provides the larger values of volumetric mass transfer coefficient.

NOMENCLATURE

C_b	= off-bottom clearance of the lowest impeller, mm
D_i	= impeller diameter, mm
D_t	= vessel diameter, mm
k_La_L	= volumetric oxygen transfer coefficient based on liquid volume, s^{-1}
n_i	= number of impellers, -
N_r	= rotation rate of impeller, s^{-1}
P_{tw}	= total power input per unit mass of liquid, W/kg
t_m	= mixing time of liquid phase, s
t_{mo}	= ungassed mixing time of liquid phase, s
t_{mg}	= gassed mixing time of liquid phase, s
V_s	= superficial gas velocity, cm/s

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