LOCAL GAS HOLDUP AND GAS RECIRCULATION RATE IN AN AERATED VESSEL EQUIPPED WITH A RUSHTON TURBINE IMPELLER

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Local gas holdup was measured throughout an aerated vessel equipped with a Rushton turbine impeller by means of an electrical probe. Integration of the data of local gas holdup gave a good correlation for the overall gas holdup. The gas recirculation rate, which influences cavity formation and the related power consumption and mass transfer, was also determined by integrating the data of local gas holdup for regions lower than the height of impeller. By taking into account the gas recirculation rates, a more precise correlation for overall gas holdup could be obtained.

Introduction

In the process industries, gas-liquid contacting in agitated vessels is extensively used in order for mass transfer and chemical reactions. Therefore, characteristics such as gassed power consumption, bubble size, gas holdup and gas-liquid mass transfer in a gas-sparged agitated vessel have been extensively investigated, and many correlations for these characteristics have been proposed by many investigators. However, a distinction still exists in these correlations. It may be due to the fact that the characteristics are dependent upon gas bubble distributions throughout the vessel and gas cavities behind the blades.

In this paper, the local gas holdup throughout the vessel was measured by means of an electrical probe. Complicated gas holdup distributions were obtained, which were almost the same as mentioned by previous investigators (Nienow *et al.*, 1977; Nagase and Yasui, 1983). By integration of local gas holdup throughout the vessel, the correlation of overall gas holdup was derived. The recirculating gas flow rate, which influences cavity formation and the related power consumption, was also determined from the data of local gas holdup for regions lower than the height of impeller.

1. Experiment

1.1 Experimental setup

A six-blade Rushton disc turbine impeller was adopted since its gas-dispersing mechanisms have been investigated and used extensively for gas dispersion in the process industries. An open-topped

0.29-m diameter (T) cylindrical vessel with four baffles having a width of one-tenth of the vessel diameter was used. The liquid height was equal to the vessel diameter and the impeller-to-vessel diameter ratio was 0.4. The clearance of the impeller from the tank base was set at $T/4$. Liquid was the tap water and air was introduced through a point sparger.

Gas flow rates of 3.33×10^{-5} to $2.50 \times 10^{-4} \text{ m}^3 \text{ s}^{-1}$, i.e. 0.104 to 0.783 vvm were used with an impeller speed of $3.33 - 5.00 \text{ s}^{-1}$.

1.2 Measuring points and device

The measurement of gas holdup was conducted at the intersections of the cylindrical coordinates in a quarter of the vessel, as shown in Fig. 1, because the data must be periodical with a period of 90° in circumferential direction.

Local gas holdup was measured by means of a gas-liquid two-phase flow meter system (Kanomax, system 7931) with the electrical conductivity probe. The probe can detect the difference in conductivities between gas and liquid passing through a fine pointed end made of a platinum cylinder of $100 \mu\text{m}$ diameter. Figure 2 shows a schematic diagram of the pointed end of the probe and the signals detected with the relative position of the bubble. From the sum of the time duration of pulses for gas bubbles passed through the pointed end in every direction, the gas holdup at each local position could be determined.

2. Results and Discussion

2.1 Local gas holdup

Figure 3 shows the local gas holdup distributions at cross sections of several heights for different experimental conditions. As can be seen from the figure, the patterns of gas bubble dispersion in regions higher than the height of impeller are almost the same

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Fig. 1 Measuring points of local gas holdup

Fig. 2 Schematic diagram of pointed end of probe and signals detected

Fig. 3 Local gas holdup distributions

in spite of the different experimental conditions covered in this work. Namely, local gas holdup near the vessel wall is high, at $h/H=0.6$, and that between the shaft and vessel wall is high, at $h/H=1.0$, where data corresponding to the air above the liquid free surface were omitted. These results, which approximately correspond to those reported by several investigators

(Nienow *et al.*, 1977; Nagase and Yasui, 1983), may be explained by considering the observed gas dispersion as shown in Fig. 4. The centers of the gross circulation vortices are regions of low velocity and high holdup with their peripheries being regions of high velocity and low holdup. On the other hand, in regions lower than the height of the impeller, local gas

Fig. 4 Gas bubbles flow in vessel

holdup only for $N=5.00 \text{ s}^{-1}$ and $Q_G=2.50 \times 10^{-4} \text{ m}^3 \text{ s}^{-1}$ shows a high value near the vessel wall, because of the onset of small recirculation.

2.2 Correlation of overall gas holdup

Most published correlation for gas holdup are derived from experiments by observing the rise in level of the surface by the naked eye (Chapman *et al.*, 1983) or by measuring using conductivity probes (Greaves and Barigou, 1988).

In this work, the overall gas holdup was determined by integrating the local gas holdup data throughout the vessel for each experimental condition and was correlated by using a multiple non-linear regression. The correlation obtained is given as follows.

$$\varepsilon_{overall} = 0.621 N^{0.21} Q_G^{0.437} \quad (1)$$

The average deviation is 9.93×10^{-3} . Smith and Warmoeskerken (1985) correlated the gas holdup with the equations

before large cavities are formed

$$\varepsilon_{overall} = 0.62 N^{1.6} Q_G^{0.45} \quad (2)$$

Fig. 5 Average gas holdup at lower region (arrow shows calculated value of N_{CD} from Eq. (4))

and after large cavities have been formed

$$\varepsilon_{overall} = 1.67 N^{0.7} Q_G^{0.75} \quad (3)$$

The experimental and calculated values of $\varepsilon_{overall}$ are summarized in Table 1, which shows that the data obtained in this work could not be expressed by Eqs. (2) and (3). This may be due to the difference in the measuring methods. The data obtained by the methods developed previously may include the effect of surface vibration at high impeller speed. On the other hand, it is hard for the method used in this work to measure the gas holdup in impeller and sparger regions.

An interesting information was also derived from the data of the local gas holdup in the lower region than the height of impeller. The average gas holdup at the lower region, which was calculated by integrating the local gas holdup at the regions lower than the height of impeller, is shown in Fig. 5. The solid lines displayed in Fig. 5 were those calculated by using the least-squares method. As can be seen from the figure, the gas holdup at the lower region increases with an increase in impeller speed for each gas flow rate, and the dependency of the gas holdup on impeller speed increases with an increase in gas flow rate.

If the solid lines are extrapolated, the inter-

Table 1 Comparison of gas holdup values $\varepsilon_{overall}$

N [s ⁻¹]	Q_G [m ³ s ⁻¹]	Experimental	Calculated			
			Eq. (1)	Eq. (2)	Eq. (3)	Eq. (9)
3.33	3.33×10^{-5}	5.65×10^{-3}	8.83×10^{-3}	4.12×10^{-2}	1.70×10^{-3}	6.55×10^{-3}
4.17		5.39×10^{-3}	9.26×10^{-3}	5.88×10^{-2}	1.99×10^{-3}	5.84×10^{-3}
5.00		7.17×10^{-3}	9.62×10^{-3}	7.87×10^{-2}	2.26×10^{-3}	6.30×10^{-3}
3.33	1.00×10^{-4}	1.86×10^{-2}	1.43×10^{-2}	6.73×10^{-2}	3.88×10^{-3}	1.86×10^{-2}
4.17		2.01×10^{-2}	1.50×10^{-2}	9.65×10^{-2}	4.54×10^{-3}	1.94×10^{-2}
5.00		1.90×10^{-2}	1.55×10^{-2}	1.29×10^{-1}	5.15×10^{-3}	1.97×10^{-2}
3.33	2.50×10^{-4}	2.02×10^{-2}	2.13×10^{-2}	1.02×10^{-1}	7.71×10^{-3}	5.19×10^{-2}
4.17		1.94×10^{-2}	2.24×10^{-2}	1.46×10^{-1}	9.02×10^{-3}	3.87×10^{-2}
5.00		2.25×10^{-2}	2.32×10^{-2}	1.95×10^{-1}	1.02×10^{-2}	3.71×10^{-2}

section with the abscissa at $\varepsilon_{lower}=0$ may correspond to the minimum speed to just completely disperse the gas throughout the whole vessel, N_{CD} . Nienow *et al.* (1977) have given the following empirical correlation for the complete dispersion condition.

$$Q_G / N_{CD} D^3 = 0.2 (T/D)^{0.5} (N_{CD}^2 D/g)^{0.5} \quad (4)$$

The calculated value of N_{CD} for each Q_G , which fits well with the intersection of the calculated line with the abscissa, is shown in Fig. 5.

2.3 Estimation of recirculated gas flow rate

The gas recirculated comes back into the cavity with freshly sparged gas and affects the gassed power and the mass transfer. The gas recirculation also depends on the bubble size and hence upon the coalescence properties of the dispersion. Therefore, it is useful to quantify the recirculated gas flow rate.

A simple method to estimate the recirculated gas flow rate from power drawn was proposed by van't Riet *et al.* (1976). They assumed that the recirculation was eliminated by using large vessels with very small impellers and determined the recirculated gas flow rate from the curves for the relative power consumption with and without recirculation, that is for an ordinary and a large vessel, under otherwise similar conditions. At a certain gas inflow from the sparger Q_G , power consumption with recirculation corresponds to that without recirculation for a gas inflow Q_T , because of the additional gas flow from recirculation Q_R . This is shown in Fig. 6.

In this work, estimation of the recirculated gas flow rate was tried according to this method first. A vessel of 0.24 m diameter (T_s) and one of 0.98 m diameter (T_l) with four baffles were used as a standard and a large vessel, respectively. The heights of the impeller above the tank base in both vessels were set at $T_s/2$, $T_s/3$ and $T_s/4$. Three typical impellers used were a six-blade Rushton turbine, a flat paddle and a pitched turbine pumping downward. Power was measured by using a digital torque meter. The power curves obtained for the Rushton turbine in large and standard vessels are shown in Fig. 7 as an example. This result indicates that the value of the recirculated gas flow rate cannot be estimated by the method proposed by van't Riet *et al.* (1976). For the other two impellers, almost the same results were obtained. Therefore, it would be concluded that the method proposed by van't Riet *et al.* (1976) was not applicable to assess the recirculated gas flow rate for impellers used in this work.

From the above result, it is obvious that a new method to estimate the recirculated gas flow rate must be established. We consider the method to get the recirculated gas flow rate from the local gas holdup in the aerated stirred vessel.

The bubbles tend to rise upwards through the

Fig. 6 Estimation of recirculating gas flow rate from power data (van't Riet *et al.*, 1976)

Fig. 7 Power curves for Rushton turbine in large and standard vessels

vessel due to the difference in gas and liquid density. Therefore, it is difficult for the gas in the upper circulation region to return to the impeller region. That is, no recirculation, except for very small bubbles. On the other hand, the gas bubbles dispersed into the lower circulated region definitely rise and reach the height of the impeller again, except for large bubbles. Thus, most of the recirculated gas consists of bubbles dispersed to the region lower than the impeller. Therefore, the recirculated gas flow rates Q_R were calculated from the local gas holdup data in the lower region of the vessel when the bubbles dispersed into the lower circulated region are relatively small.

The amount of recirculated gas V_R [m³] was expressed as

$$V_R = \varepsilon_{lower} \times V_{lower} \quad (5)$$

where ε_{lower} and V_{lower} are the gas holdup and the volume in the region lower than the height of impeller, respectively.

The recirculated gas flow rate Q_R is given by

$$R_Q = V_R / t_R \quad (6)$$

where t_R is the time taken by the bubbles to recirculate. Because most bubbles recirculated were considered small ones (Takahashi and Nienow, 1993), we assumed that t_R could be represented by the recirculation time of the liquid. The value of t_R was determined by measuring time needed for the tracer particle to complete one circuit from the impeller region by using the video camera. The tracer used was a single spherical polystyrene particle of density 0.97 kg/m³. The experimental conditions were the same as those in measuring gas holdup.

Bruijn *et al.* (1974) and van't Riet *et al.* (1976) defined an external distribution coefficient α

$$\alpha = Q_R / Q_G \quad (7)$$

and evaluated the recirculated gas flow rate. The results obtained are shown in Fig. 8 with the data obtained by other investigations (van't Riet *et al.*, 1976, Nienow *et al.*, 1977 and Nienow and Chapman, 1979) previously. The external distribution coefficient α was plotted in ordinate and the aeration number in abscissa. The present work agrees well with the previous data. The correlation for Q_R obtained is written as follows:

$$Q_R = 2.24 \times 10^{-6} N^{4.26} Q_G^{0.306} \quad (8)$$

When recirculation occurs, the freshly sparged gas and the recirculated gas must both pass through the impeller cavities. Thus the overall gas flow rate should

Fig. 8 External distribution coefficient

control the characteristics of gas-liquid mixing. As an example, we tried to correlate the overall gas holdup obtained in this work with the overall gas flow rate. The correlation derived is given by

$$\varepsilon_{overall} = 2.87 \times 10^4 N^{-2.12} (Q_G + Q_R)^{1.30} \quad (9)$$

The calculated values are also summarized in Table 1 and the average deviation is 1.55×10^{-3} , which is significantly lower than that obtained for Eq. (1), even though this correlation overestimates at higher gas inflow rates because hardly any large bubbles dispersed into the lower circulated region return to the impeller region.

Conclusion

Local gas holdup throughout a vessel equipped with a Rushton turbine impeller was investigated. A complicated distribution of gas holdup was obtained, which could be explained by considering the observed gas dispersion. By integrating the local gas holdup data, the overall gas holdup was determined and correlated with experimental conditions. The recirculated gas flow rate was also obtained by integration of the local gas holdup in the regions lower than the height of impeller. It is suggested that a more precise correlation for the overall gas holdup could be obtained by taking the recirculated gas flow rate into account.

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estimation of the recirculated gas flow rate according to the method proposed by van't Riet *et al.* (1976) in their laboratory.

Nomenclature

C	=	impeller clearance above vessel base	[m]
D	=	impeller diameter	[m]
N	=	impeller speed	[s ⁻¹]
N_{CD}	=	minimum impeller speed to completely disperse gas throughout vessel	[s ⁻¹]
N_Q	=	gas flow number ($=Q_G/ND^3$)	[—]
P_0	=	ungassed power consumption	[W]
P_g	=	gassed power consumption	[W]
Q_G	=	gas inflow rate	[m ³ s ⁻¹]
Q_R	=	recirculation gas flow rate	[m ³ s ⁻¹]
Q_T	=	overall gas flow rate leaving impeller ($=Q_R+Q_G$)	[m ³ s ⁻¹]
T	=	vessel diameter	[m]
T_l	=	large vessel diameter	[m]
T_s	=	standard vessel diameter	[m]
t_R	=	recirculation time in lower part of the vessel	[s]
V_{lower}	=	volume in lower part of the vessel	[m ³]
V_R	=	volume of recirculated gas	[m ³]
α	=	external distribution coefficient ($=Q_R/Q_G$)	[—]
ϵ_{lower}	=	gas holdup in lower part of the vessel	[—]
$\epsilon_{overall}$	=	overall gas holdup	[—]

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