Interfacial Area and Coalescence Frequency in Gas-Slurry Stirred Reactors

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Three-phase contacting is often carried out in gas-slurry stirred vessels. The influence of the solids concentration on the gas-liquid interfacial area has to date always been determined by chemical methods. This method has many drawbacks, including the fact that the mass transfer coefficient k_L itself is dependent on the bubble diameter and interfacial area. Therefore a mass-transfer-independent means was used to evaluate the gas-liquid interfacial area. Also the solids concentration and sizes were varied and a coalescence frequency determined to evaluate the influence of the size of the solids on bubble coalescence.

Experimental Procedure

The experimental apparatus, shown in Figure 1, consisted of a 0.44 m dia. by 0.46 m high fully baffled stirred tank agitated with a single six-blade, flat-disk impeller. Two impellers having diameters of 0.23 and 0.15 m, respectively, and an impeller width-to-diameter ratio of 1/5 were used at an impeller location of one impeller diameter off of the bank bottom.

Dispersions of air in water slurries of glass beads, having average sizes of 25, 70, and 200 μm, were studied at various concentrations. The method of light scattering (Calderbank, 1958) was used to determine the gas-liquid interfacial area. Details of the equipment can be found elsewhere (Nagaraj, 1984). In each case the gas rate was maintained at a constant rate of 0.0283 m^3/min and the light intensity readings were taken at an optical path length of 0.0508 m. Measurements in liquid, gas-liquid, solid-liquid and gas-liquid-solid systems were made for calibration purposes.

The concentrations of solids were kept low to limit the effect of multiple scattering. McLaughlin and Rushton (1973) and Weinstein and Treybal (1973) have discussed conditions under which multiple scattering is negligible, and McLaughlin and Rushton have considered that when less than 10% of the incident intensity is received by the photocell, multiple scattering becomes important. This was further confirmed by two methods.

1. Since the solids are much smaller than the gas bubbles, it could be expected that any multiple scattering, if present, would largely be due to the solids. Absence of multiple scattering in a solid-liquid system was confirmed by the method of Van de Hulst (1957), whereby a linear relationship was obtained between light attenuation and solids concentration.
2. The effect of multiple scattering on the data obtained was found to be negligible by comparing the results obtained for the cases where the photocell received less than 10% of the incident light, using the linear correlation of Mclaughlin and Rushton (1973), and also using the multiple scattering calculations of Langlois et al. (1954). The work of Langlois et al. does not cover a gas-liquid-solid system, but does cover a liquid-solid system (glass beads in liquid) and a gas-liquid (air-glucose) system. By extrapolating these results, a value of $\beta = 1.4$ was used for the present system. This value also gave good agreement for the case when the light intensity received by the photocell was approximately 10% of the incident light intensity, in comparison to calculations involving no multiple scattering. At higher attenuation, both methods of calculation yielded comparable values, confirming that the effects of multiple scattering were negligible for the conditions considered.

Also, in each case values of the overall gas holdup were taken under gassed conditions. These were compared to the values of Dickey (1979) obtained under scale-up conditions, and reasonable agreement was obtained. The point gas holdups were measured using a small suction probe connected to a vacuum pump. The volume of gas and liquid removed gave an *approximate* local gas holdup since the sampling was not isokinetic. These gas holdup measurements varied by ±35%. The gas holdup values at the vertical level of the impeller in the region considered were found to be one-half of the overall holdup value, in agreement with the work of Nagase and Yasui (1983) and Nienow et al. (1977). For the low concentrations of solids used, the effect of

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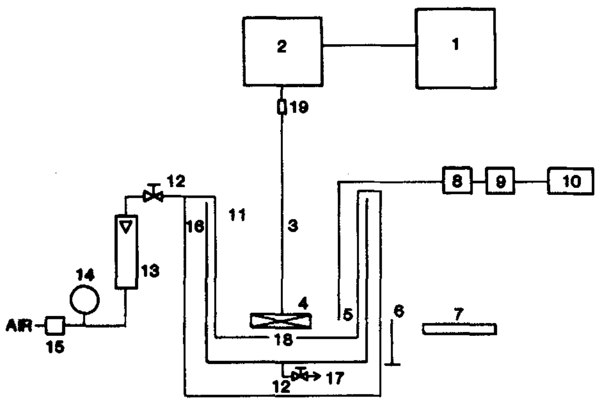

1. MOTOR
2. VARIAC
3. SHAFT
4. IMPELLER
5. PHOTODIODE AT END OF PROBE
6. NEUTRAL DENSITY FILTER
7. LIGHT SOURCE
8. OPERATIONAL AMPLIFIER CIRCUITRY
9. 18-RANGE MICROTESTER
10. CHART RECORDER
11. GAS-SLURRY SUSPENSION
12. VALVE
13. ROTAMETER
14. PRESSURE GAUGE WITH SET POINT
15. AIR FILTER
16. GLASS TANK WITH FOUR (T/10 WIDTH) BAFFLES
17. DRAIN
18. SPARGERS
19. COUPLING

Figure 1. Experimental apparatus.

solids on the overall and local gas holdups was found to be negligible, which is in agreement with the work of Chapman et al. (1983).

Results

The gas-liquid interfacial area, as a function of the solids weight fraction, is shown in Figure 2 for the two impellers and the three solid sizes investigated. A plot of the local interfacial area vs. the overall energy dissipation revealed apparent inconsistencies between the two impeller sizes investigated, since an average overall energy dissipation value does not represent the local energy dissipation within the impeller region where interfacial areas were measured. For the same overall energy dissipation, the local interfacial area for the 0.23 m dia. impeller was significantly higher than for the 0.15 m dia. impeller. This was due to the difference in the local energy dissipation, which was calculated using the work of Okamoto et al. (1981), who have obtained the energy dissipation rate distribution in a mixing tank by means of a two-region model. The two regions considered are the impeller flow region with volume V_i, and the circulation flow region with volume V_c. In Figure 2, $\epsilon = 2.078$ is for the 0.23 m dia. impeller and $\epsilon = 0.46$ is for the 0.15 m dia. impeller.

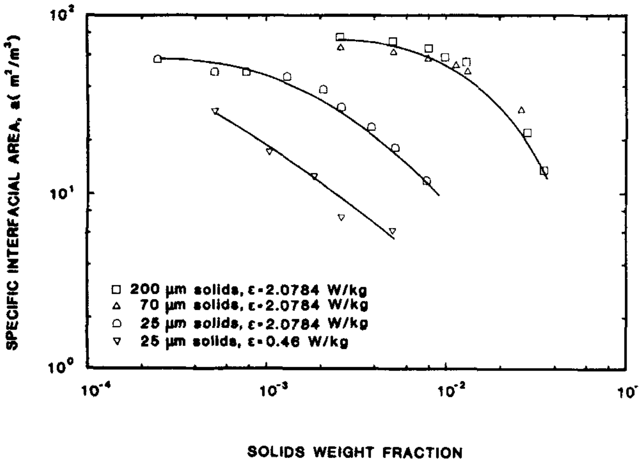

Figure 2. Interfacial area v. solids weight fraction, 20°C.

Taking the width for the impeller stream to be 1.2 times the impeller width (Rao and Brodkey, 1972), and assuming a cylindrical volume for the impeller flow region, the present authors' data using the 0.23 m impeller was found to be within the impeller flow region defined by Okamoto et al. The data obtained with the 0.15 m impeller were found, by a similar analysis, to be in the intermediate region between the impeller flow region and the circulation flow region. Calculations were made based on the work of Okamoto et al. for the energy dissipation rates for the 0.15 m impeller in the impeller flow region and the circulation flow region. For the region of interest (0.0508 m from wall at the vertical level of the impeller), the energy dissipation rate was then approximated by taking the geometric mean of the energy dissipation rates of the impeller flow region and the circulation flow region. The geometric mean, rather than the arithmetic mean, was taken because of the differences in volumes of the two regions described by Okamoto et al. A plot of interfacial area vs. local energy dissipation rate is shown in Figure 3.

Bubble diameters were calculated by using the equation for the Sauter mean diameter

$$D_B = 6\phi_G/a \qquad (1)$$

where a and ϕ_G are the local interfacial area and gas holdup,

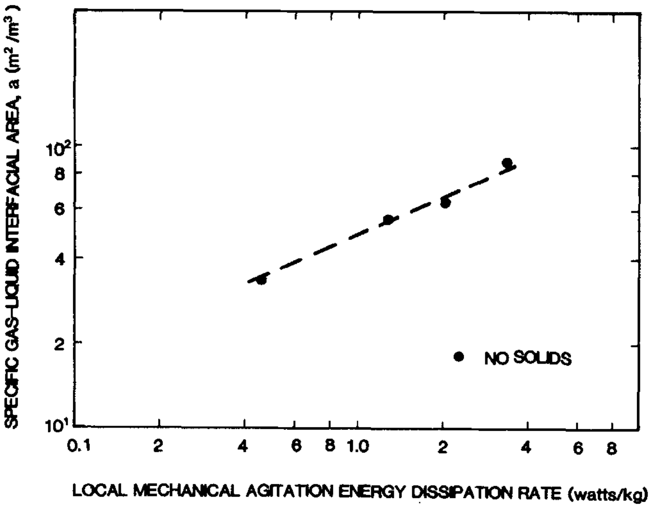

Figure 3. Interfacial area v. local mechanical energy dissipation rate.

respectively. The coalescence frequency was defined as the volume fraction of bubbles coalescing per unit time. Different approximations have been used to correlate the coalescence frequency (Talvarides and Stamatondis, 1981). Lee and Ssali (1972), for example, have defined bubble coalescence frequencies for bubble transport in vertical pipes. This definition is based on the number density of bubbles at a given location. Such an evaluation would be difficult in a stirred tank, however, due to the recirculation of bubbles to the impeller region. In this work, therefore, a relative bubble coalescence frequency has been defined based on the individual bubble volumes under breakage-controlled conditions only. Solids are not present; therefore the bubble sizes measured under these conditions are sizes controlled by bubble breakage only. The solids studied in this work tend to promote coalescence, hence the bubble diameters are controlled by both breakage and coalescence. Letting D_{Bc} and D_{Bb} denote, respectively, bubble diameters with breakage and coalescence and with breakage alone, the volume change ratio of the average bubble with coalescence to the bubble volume with only breakage is given by $(D_{BC} - D_{Bb})/D_{Bb}$.

The volume fraction of dispersed phase coalescing per unit volume of dispersion (liquid and gas) is given by

$$\omega' = \frac{D_{BC}^3 - D_{Bb}^3}{D_{Bb}^3} (\phi_g)_{\text{local}} \tag{2}$$

and the volume fraction of dispersed phase coalescing per unit time is given by

$$\omega = \frac{D_{BC}^3 - D_{Bb}^3}{D_{Bb}^3} (\phi_g)_{\text{local}} \, (\text{V.V.M}/60) \tag{3}$$

A plot of the coalescence frequency thus evaluated is plotted vs. the solids weight fraction in Figure 4. It can be seen that $\omega \propto$ (solids fraction)$^{3.7}$, but that the exact dependence varies with the local energy dissipation rate and the size of the solids employed.

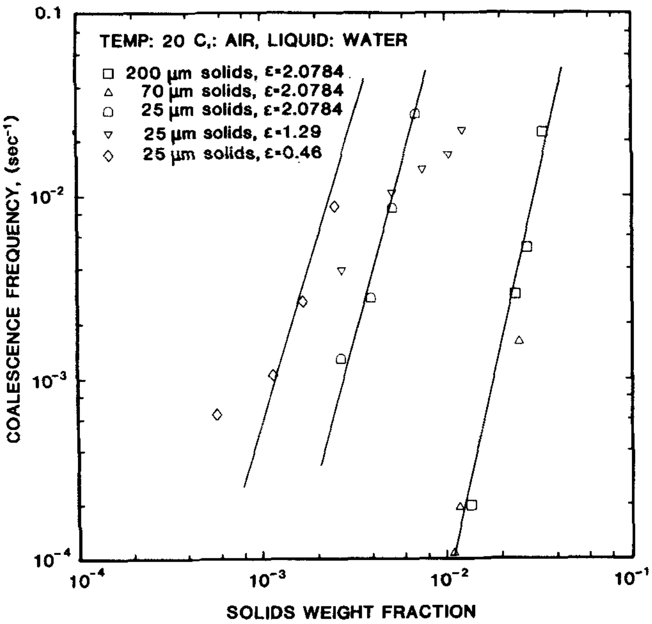

Figure 4. Coalescence frequency v. solids weight fraction.

Discussion

For all solid sizes, the coalescence frequency increased with increased solid loading. The presence of suspended solids tends to dampen the turbulent intensity. According to Kirkpatrick and Lockett (1974), bubbles will not coalesce if the approach velocity is greater than a certain velocity V^*. The reduced turbulent intensity results in a lower approach velocity for two bubbles attempting to coalesce. In addition, solids would tend to increase the drag on bubbles, also decreasing their approach velocities. Both effects may lead to increased coalescence frequencies.

The 25 µm size particles produced a higher coalescence frequency than the 70 and 250 µm size particles at the same solid loading. Particles that follow the fluid motion tend to follow in the bubble wakes, adding to the inertia force at impact and/or acting as a barrier to resist the rebounding effect of the bubbles, thus leading to an increased coalescence efficiency. Abrahamson (1975) has used the particle relaxation time

$$\tau_p = \rho_p d_p^2/(18\mu) \tag{4}$$

to derive the minimum particle size d_p that will have a velocity independent of the surrounding fluid

$$d_p^2 > \left(\frac{15\,\mu\,\overline{U^2}}{\rho_p \epsilon}\right) \tag{5}$$

For a stirred tank, using the parameters in the work of Rao and Brodkey (1972) to determine $\overline{U^2}$, it is found for the range of data studied that particle sizes of approximately 60 µm would move independently of the fluid motion. The results indicate that for particles of 70 and 200 µm size the coalescence frequency and interfacial area can be correlated as one group, while the 25 µm size particles exhibit a higher coalescence frequency at the same solid loading.

Conclusion

The presence of solids in gas-liquid dispersions was found to increase the coalescence frequency of bubbles, thereby reducing the gas-liquid interfacial area in a stirred tank. The coalescence frequency was found to depend on the local energy dissipation rate, as well as on the solid loading and particle size. Smaller particles, which tend to follow in the bubble wakes, produce a higher bubble coalescence efficiency than larger particles, resulting in a lower gas-liquid interfacial area for these systems. Increased solid loading dampens the turbulent intensity, resulting also in an increase in coalescence efficiency.

Acknowledgment

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Notation

a = interfacial area, m^2/m^3
c = impeller height off tank bottom, m
d = particle diameter, m
D = bubble diameter, m
D_I = impeller diameter, m

D_{Bc} = bubble diameter with coalescence due to addition of solids, m
D_{Bb} = bubble diameter without addition of solids, m
k_L = mass transfer coefficient, mol · m^{-2} · s^{-1} · (mol frac)$^{-1}$
U^2 = mean squared velocity fluctuation in fluid, $m^2 \cdot s^{-2}$
V = volume, m^3

Greek Symbols

β = slope in the equation $I_o/I = (1 + a)$, Langlois et al. (1954)
ϵ = energy dissipation rate per unit mass, w · kg^{-1}
μ = viscosity of fluid, kg · s^{-1} · m^{-1}
ρ = density, kg · m^{-3}
ϕ = holdup
τ = relaxation time, s^{-1}
ω = coalescence frequency, s^{-1}
ω' = coalescence frequency, m^{-3}

Subscripts

c = circulation flow region
g = gas
I = impeller region
P = particle
T = total

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