

EFFECT OF PHYSICAL PROPERTIES ON THE SUSPENSION OF SOLID PARTICLES IN THREE-PHASE SPARGED REACTORS

A. B. PANDIT and J. B. JOSHI†

Department of Chemical Technology, University of Bombay, Matunga, Bombay 400 019, India

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Abstract—Experiments were performed in a 200 mm i.d. column with liquids other than water. Quartz particles with average sizes of 110, 340, 500, 850 and 2000 μm were employed and the solid loading was varied up to 20 wt%. The surface tension and liquid viscosity were in the range of 61–72 mN/m and 1–30 mPa s, respectively. Aqueous solutions of guar gum and carboxy methyl cellulose were used to study the effect of pseudo-plastic behaviour. The effects of drag-reducing agents and electrolytes were also investigated. The suspension of solid particles was studied over a wide range of physical properties. An attempt has been made to rationalize the variation in the superficial gas velocity for suspension in three-phase sparged reactors on the basis of variation in the liquid-phase physical properties. Quantitative correlations and predictive methods are proposed to predict critical superficial gas velocity for the suspension. Qualitative trends in the variation of the performance are discussed and a unified approach is presented.

INTRODUCTION

The problem of suspension of solid particles in three-phase sparged reactors has attracted attention for the last 10 years. Many correlations and predictive procedures are available in the literature. A critical review of this work has been presented by Pandit & Joshi (1984).

Most of the work on this topic has been restricted to three-phase systems where water forms the liquid phase. The effect of liquid-phase physical properties on the suspension has not been studied in detail. Koide *et al.* (1983) studied the effect of liquid-phase viscosity by using various concentrations of glycerol solutions on the critical superficial gas velocity for the suspension of solid particles. Koide *et al.* restricted their understanding of the suspension phenomena by attributing the liquid viscosity effect to the decrease in the settling velocity of the solid particles. Their correlation does not take into account the behaviour of fractional gas hold-up and bubble rise velocity and their effect on the suspension as a function of liquid-phase viscosity.

In order to understand the performance of three-phase sparged reactors, it is necessary to study the effect of liquid-phase physical properties, e.g. the electrolytic nature of solutions, the effect of adding alcohols to vary the surface tension, the effect of liquid-phase viscosity, the non-Newtonian behaviour of the liquid phase and the effect of adding drag-reducing agents.

In this paper the suspension of solids has been studied for a wide range of the physical properties of the liquid. An attempt has been made to correlate the results rationally and some suggestions have been made for future work.

EXPERIMENTAL

Experiments were carried out in a 0.2 m dia Perspex column with a sieve plate as a gas distributor. The distributor had 180 equally-spaced holes of 2 mm dia. Figure 1 shows the experimental setup. Further details of the equipment have been described by Pandit & Joshi (1984).

The physical properties of the liquid were varied by using aqueous solutions of electrolytes, alcohols and glycerol. The liquid was made non-Newtonian by adding carboxy methyl cellulose (CMC) and guar gum to water (municipal tapwater). Drag-reducing agents, like polyethylene oxide and polyacrylamide, were used at different concentration levels. Table 1 shows the range of the physical properties of the various aqueous solutions used and the particle sizes used.

†To whom all correspondence should be addressed.

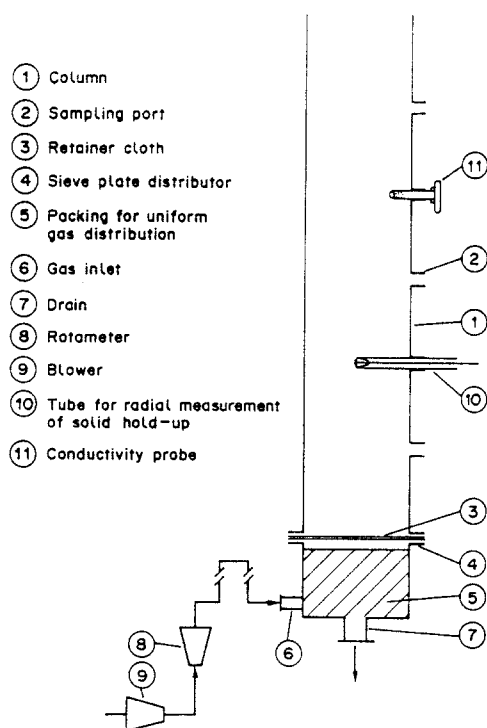


Figure 1. Experimental setup.

Experiments were performed in a semibatch manner. Predetermined amounts of solid particles and liquid were added to the column and the gas was passed continuously. Fractional gas hold-up was measured by noting the liquid height in the presence and absence of gas. The particles were said to be suspended when no particle remained on the bottom for more than 1–2 s. The minimum gas velocity at which this occurs was termed the critical gas velocity for suspension of solid particles.

RESULTS AND DISCUSSION

Theory

In the case of sparged reactors two distinct regimes are observed. These are called homogeneous (which prevail at relatively low superficial gas velocities) and heterogeneous regimes (which prevail at higher superficial gas velocities). Joshi & Lali (1984) have discussed the details of these regimes and the transition characteristics.

The average downward liquid velocity in the case of a homogeneous regime is given by (Joshi 1981)

Table 1a,b. Range of variables covered in this work

(a) Solid particles

No.	Size range (μm)	Average particle size (μm)	Density (kg/m^3)	Shape factor	Terminal settling velocity in water (mm/s)
1	83–150	110	2260	0.727	12.5
2	250–420	340	2500	0.718	76.0
3	400–600	500	2500	0.687	104.0
4	750–950	850	2500	0.623	134.0
5	1680–2200	2000	2500	0.752	164.0

(b) Liquid-phase physical properties

Column diameter (m)	μ (mPa s)	n	k (Pa s^n)	γ (N/m)
0.2	1.0–30.3	0.466–1.0	0.08–1.28	0.061–0.072

$$V_{CL} = \frac{\delta \epsilon_G \cdot V_B}{(1 - \epsilon_G - \delta \epsilon_G - \epsilon_S)}, \quad [1]$$

where V_B is the hindered rise velocity of a bubble, ϵ_G and ϵ_S are the fractional gas and solid hold-ups, δ is the ratio of wake volume to bubble volume and V_{CL} is the downward liquid velocity in the homogeneous regime (Joshi & Lali 1984):

$$\frac{V_B}{V_{B\infty}} = \frac{1}{\sqrt{\frac{(1.5 \epsilon_G)^2}{C_{Dx}} + 1}}, \quad [2]$$

$$C_{Dx} = \frac{g d_B}{3 V_{B\infty}^2}, \quad [3]$$

where $V_{B\infty}$ is the terminal rise velocity of a bubble and C_{Dx} is the drag coefficient for a single bubble, rising in an infinite medium, d_B is the bubble diameter and g is the gravitational acceleration.

In the homogeneous regime the liquid turbulence is relatively low. For solid particles having low settling velocities, Pandit & Joshi (1984) have shown that the particles become suspended when the liquid circulation velocity, calculated from [1] is equal to the settling velocity of the particle.

It is evident from [1] that V_{CL} depends strongly on the fractional gas hold-up and the terminal rise velocity of the bubble. Hence, the changes in the fractional gas hold-up and bubble rise velocity with the changes in the physical properties of the liquid will affect the critical gas velocity for the suspension.

In the heterogeneous regime, large-scale liquid turbulence is present. Joshi (1983) has given the following equation for liquid-phase turbulence intensity:

$$u'_z = u'_y = 0.25 \left\{ \frac{gT}{(\rho_C - \rho_G)} [(V_G + V_L)(\rho_C - \rho_G)(1 - \epsilon_G) - (\rho_C - \rho_G)\epsilon_G V_{B\infty} - \epsilon_S V_{SN}(\rho_S - \rho_C) - V_L \rho_L] \right\}^{1/3}, \quad [4]$$

where

$$\rho_C = \epsilon_S \rho_S + \epsilon_L \rho_L. \quad [5]$$

For semibatch operation ($V_L = 0$), [4] reduces to

$$u'_z = 0.25 \left\{ gT \left[\frac{V_G - \epsilon_G V_{B\infty} - \epsilon_S V_{SN}(\rho_S - \rho_C)}{\rho_C} \right] \right\}^{1/3}, \quad [6]$$

where

- g = acceleration due to gravity (m/s^2),
- T = column diameter (m),
- u'_y = transverse component of turbulence intensity (m/s),
- u'_z = axial component of turbulence intensity (m/s),
- $V_{B\infty}$ = terminal rise velocity of a single bubble (m/s),
- V_G = superficial gas velocity (m/s),
- V_L = superficial liquid velocity (m/s),
- $V_{S\infty}$ = terminal settling velocity of a spherical particle (m/s),
- V_{SN} = hindered settling velocity of a non-spherical particle (m/s),
- ϵ_G = fractional gas hold-up,
- ϵ_L = fractional liquid hold-up,
- ϵ_S = fractional solid hold-up,
- $\bar{\epsilon}_S$ = average fractional solid hold-up,
- ϵ_{Sb} = fractional solid hold-up at the bottom of the column,
- ρ_C = continuous-phase density (kg/m^3),
- ρ_G = gas-phase density (kg/m^3),
- ρ_L = liquid-phase density (kg/m^3),

and

$$\rho_S = \text{density of solid (kg/m}^3\text{)}.$$

It is known that the sparger influences the hydrodynamic behaviour in the bottom (sparger) region. Above a certain distance from the bottom the sparger influence is negligible and the flow pattern is said to be developed in the rest of the column (bulk region), which occupies most of the column volume. Equations [2] and [4] have been developed for the bulk region. Pandit & Joshi (1984) have shown that the fractional solid hold-up, solid-phase axial dispersion coefficient and solid-liquid mass-transfer coefficient are higher near the bottom than in the rest of the column. This has two implications:

- (i) In [4], ϵ_s needs to be replaced by ϵ_{sb} , the value of fractional solid hold-up near the bottom.
- (ii) Joshi (1983) and Pandit & Joshi (1986) have shown that the bed-wall mass-transfer coefficient is proportional to the normal component of turbulence intensity. Further, the values of the bed-wall mass-transfer coefficient in the bottom region were found to be about 30% greater than in the rest of the column (bulk region). Therefore, the constant in [6] needs to be modified when using it for the bottom region:

$$u'_z = 0.325 \left\{ gT \left[\frac{V_G - \epsilon_G V_{B\infty} - \epsilon_s V_{SN} (\rho_s - \rho_c)}{\rho_c} \right] \right\}^{1/3} \quad [7]$$

Pandit & Joshi (1984) have shown that particles are suspended when the vertical component of turbulence intensity (u'_z) equals the settling velocity of a particle.

Equations [1] and [7] can be used for the prediction of the critical superficial gas velocity for a suspension of solid particles for homogeneous and heterogeneous regimes, respectively. To use [1], we need to know fractional gas hold-up (ϵ_G) and the rise velocity of a bubble (V_B).

To apply [7], values of ϵ_{sb} and the settling velocity of a particle are needed. The settling velocity of a particle in three-phase reactors is different from the terminal settling velocity. This is because: (a) In three-phase sparged reactors, in the heterogeneous regime, intense liquid circulation develops, upward at the centre and downward near the column wall. This flow pattern is superimposed on the particle velocity. As a result, the particle settling velocity is very high near the wall compared to that in the central region. Since the solid concentration profile is not uniform throughout, the liquid circulation affects the particle settling velocity. (b) In sparged reactors, liquid-phase turbulence enhances the particle-liquid drag and decreases the settling velocity. (c) In sparged reactors, part of the solid travel occurs in the gas phase if the particle size is smaller than the bubble size. The settling velocity in the gas phase is very high compared to that in the liquid phase.

There have been some attempts in the literature to measure V_{SN} in three-phase sparged reactors. Recently, Smith & Ruether (1985) proposed the correlation

$$V_{SN} = 1.1 V_G^{0.026} V_{SN\infty}^{0.8} \left[\frac{\epsilon_L}{(1 - \epsilon_G)} \right]^{3.5} \quad [8]$$

where $V_{SN\infty}$ is the terminal settling velocity of a non-spherical particle. This equation was developed for systems where water is the liquid phase. Further work is required to find V_{SN} when the liquid phase is other than water.

While predicting the effect of physical properties on the critical gas velocity for a suspension of solid particles, we need to know their effect on ϵ_G , V_G and V_{SN} . In the absence of any data, it will be assumed that the settling velocity of a particle in a three-phase sparged reactor equals the terminal settling velocity ($V_{SN\infty}$).

Pandit & Joshi (1984) have discussed in detail the effects of particle size and density, height-to-diameter ratio of the column, fractional solid hold-up and column diameter on the critical gas velocity for a suspension of solid particles (V_{GC}). In the following discussion, an attempt will be made to explain the effect of physical properties on V_{GC} .

Effect of surface tension

Aqueous solutions of methanol, ethanol and butanol were employed (0.5, 1 and 2 vol% see table

Table 2. Surface tensions of the alcohol solutions

No.	Alcohol	Concentration (vol%)	Surface tension, σ (N/m)
1	Methanol	0.5	0.069
2	Methanol	1.0	0.068
3	Methanol	2.0	0.064
4	Ethanol	0.5	0.066
5	Butanol	0.5	0.061

2) with particles having settling velocities of 14, 76 and 134 mm/s. The solid-phase concentration was varied in the range of 1–10 vol%.

For the smallest particles, about a 60% increase in V_{GC} was observed at $\bar{\epsilon}_s = 0.10$ with methanol concentrations as low 0.5 vol%. This increase in V_{GC} is expected from [2]. Addition of methanol increases ϵ_G and also decreases $V_{B\infty}$. This will reduce V_{CL} at the same superficial gas velocity. Hence higher superficial gas velocities are needed to increase V_{CL} , which can be equal to $V_{SN\infty}$. The extent of the increase in V_{GC} decreases with an increase in the particle size or terminal settling velocity of the particle. In the heterogeneous regime, the particle becomes suspended when u'_z is equal to $V_{SN\infty}$. According to [7], an increase in the fractional gas hold-up will decrease u'_z at the same superficial gas velocity but, at the same time, $V_{B\infty}$ values were also found to decrease in the presence of alcohols. The increase in ϵ_G is compensated by a decrease in $V_{B\infty}$ and hence the product $\epsilon_G V_{B\infty}$ is marginally affected.

Figure 2 summarizes the results for the air–aqueous methanol–solid systems. Table 3a shows good agreement between the V_{CL} values, calculated from [2], and $V_{SN\infty}$ in the homogeneous regime. Similarly, in the heterogeneous regime, good agreement can be seen between u'_z , estimated by [7], and the terminal settling velocity of a particle:

Effect of adding electrolytes

The critical superficial gas velocities were measured for particles having $V_{SN\infty}$ values of 76 and 134 mm/s at solid loading levels up to 5 vol% ($\bar{\epsilon}_s$). Aqueous solutions of NaCl (0.1–1 kg ion/m³) and KCl (0.1 kg ion/m³) were used for this purpose.

It was observed that the value of V_{GC} increases by about 13% (as compared to that in the absence of electrolyte) for particles having $V_{SN\infty} = 76$ mm/s and by about 4.5% for larger particles ($V_{SN\infty} = 134$ mm/s) at $\bar{\epsilon}_s = 0.01$. The percentage increase in V_{GC} decreases on increasing the $\bar{\epsilon}_s$ value when compared to otherwise identical conditions in the absence of electrolytes.

Figure 3 summarizes the results and Table 3b shows the comparison. Adding electrolytes increases the fractional gas hold-up, which in turn will decrease u'_z [7], and hence an increase in V_{GC} is observed. With increasing $\bar{\epsilon}_s$, the contribution of $\epsilon_s V_{SN}$ becomes so large that small changes in $\epsilon_G V_{B\infty}$ only marginally affect u'_z . Hence little increase in V_{GC} was observed over that of the air–water system at high values of $\bar{\epsilon}_s$.

The above discussion indicates that the change in physical properties affects V_{GC} to a greater extent in the homogeneous regime, whereas the effect is marginal in the heterogeneous regime.

Effect of liquid viscosity

Aqueous glycerine solutions were used having viscosities of 30.3, 17.5 and 7 mPa s, respectively. Quartz particles of 500, 850 and 2000 μm average size were used. The terminal settling velocities of these particles were measured in different glycerine solutions and the results are given in table 3c.

The main effect of liquid viscosity is to reduce the terminal settling velocity of a particle. Another important effect is the extension of the homogeneous regime upto higher values of V_G with an increase in liquid viscosity. Table 3c and figure 4 show the comparison between $V_{SN\infty}$ and V_{CL} in the homogeneous regime and $V_{SN\infty}$ and u'_z in the heterogeneous regime. A favourable comparison can be seen in the homogeneous regime. However, in the heterogeneous regime the predicted u'_z are about 20% higher than $V_{SN\infty}$. To explain this discrepancy, experimental measurements of $V_{SN\infty}$ are needed. A systematic investigation is in progress in our laboratory.

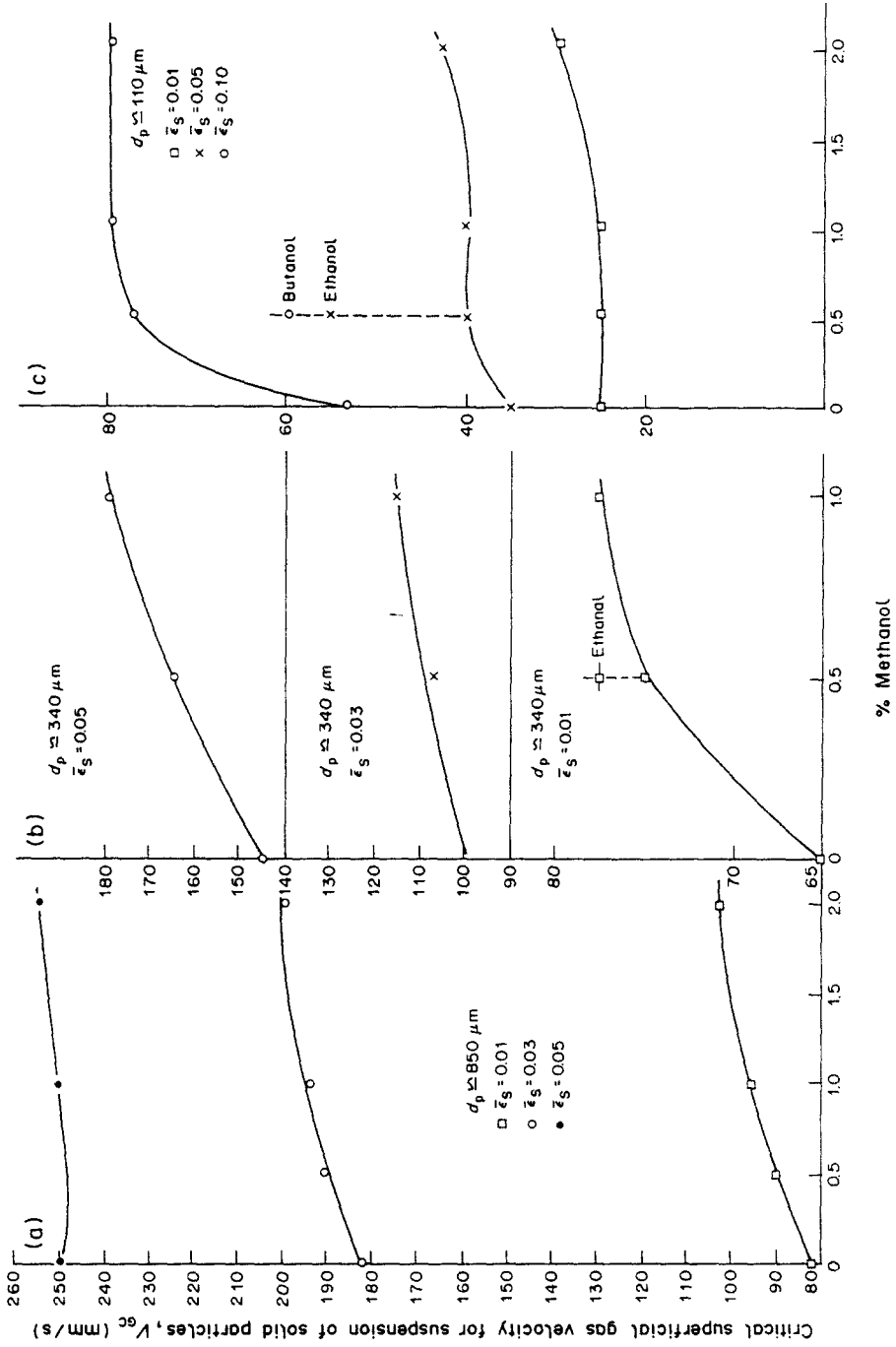


Figure 2. Effect of surface tension on the critical superficial gas velocity for a suspension of solid particles.

Table 3a-d. Comparison between V_{CL} and u'_z with $V_{SN\infty}$ under various experimental conditions: experimental u'_z have been obtained from mixing-time data

(a) Effect of surface tension

Vol% of alcohol	d_p (μm)	$\bar{\epsilon}_s$	$V_{SN\infty}$ (mm/s)	V_{GC} (mm/s)	Predicted u'_z (mm/s)	Experimental u'_z (mm/s)
0.5% Methanol	850	0.01	134	90	130	132
0.5% Methanol	850	0.03	134	191	148	136
0.5% Methanol	850	0.05	134	248	152	148
2% Methanol	850	0.01	134	102.5	123	134
2% Methanol	850	0.03	134	200	159	132
2% Methanol	850	0.05	134	255	167	134
0.5% Methanol	340	0.01	76.6	75	90	78.7
0.5% Methanol	340	0.03	76.6	107.5	92.8	80
0.5% Methanol	340	0.05	76.6	165	89	79
					V_{CL} (mm/s)	V_{CL} (mm/s)
0.5-2% Methanol	110	0.01	14	25	16.5	15.2
0.5-2% Methanol	110	0.05	14	40	15.45	14.8
0.5-2% Methanol	110	0.10	14	77.5	15.2	15.4

(b) Effect of the presence of an electrolyte

Electrolyte (kg ion/m ³)	d_p (μm)	$\bar{\epsilon}_s$	$V_{SN\infty}$ (mm/s)	Predicted u'_z (mm/s)	Experimental u'_z (mm/s)
0.5, NaCl	850	0.01-0.05	134	131.5	136.3
0.1, NaCl	340	0.01-0.05	76.6	77.2	83.6
0.1, KCl	340	0.01-0.05	76.6	92.0	87.2

(c) Effect of liquid viscosity

Viscosity (mPa s)	d_p (μm)	$\bar{\epsilon}_s$	$V_{SN\infty}$ (mm/s)	Predicted V_{CL} (mm/s)	Experimental V_{CL} (mm/s)
30.3	850	0.01-0.1	38.6	34.5	36.8
30.3	2000	0.01-0.05	96.6	99	98
17.5	2000	0.01-0.02	125.6	124	125.8
17.5	850	0.01-0.055	46.2	48.4	57.4
17.5	500	0.01-0.08	38.9	42.1	40.5
7.0	2000	0.01-0.02	157.0	161.5 ^a	147.0 ^a
7.0	850	0.01-0.033	63.0	89.0 ^a	78.2 ^a
7.0	500	0.01-0.08	49.2	60.4 ^a	58.2 ^a

^aValues of u'_z in the heterogeneous regime.

(d) Effect of adding a drag-reducing agent

Amount of polyacrylamide (ppm)	d_p (μm)	$\bar{\epsilon}_s$	$V_{SN\infty}$ ^a (mm/s)	Predicted u'_z (mm/s)	Experimental u'_z (mm/s)
1500	850	0.01-0.04	134	158	135
1500	340	0.01-0.05	76.6	116	82.6
500	850	0.01-0.04	134	178	126.2
500	340	0.01-0.05	76.6	116	89.6

^aIn water.

Figure 5 shows the effect of solid loading on V_{GC} . For the particles used in this study, at low $\bar{\epsilon}_s$ values V_{GC} was found to be proportional to $\bar{\epsilon}_s^{0.5-0.6}$, while for $\bar{\epsilon}_s > 0.1$, V_{GC} was proportional to $\bar{\epsilon}_s^{0.2}$. These observations are consistent with those reported by Pandit & Joshi (1984) and Koide *et al.* (1983).

Effect of non-Newtonian behaviour of the liquid

Aqueous solutions of guar gum (0.5, 0.25 and 0.125 wt%) and CMC (1, 0.5 and 0.25 wt%) were used to study the non-Newtonian behaviour of fluids. Details of the rheological properties are reported in table 4. Solids having average sizes of 2000, 850 and 500 μm were used at various concentration levels.

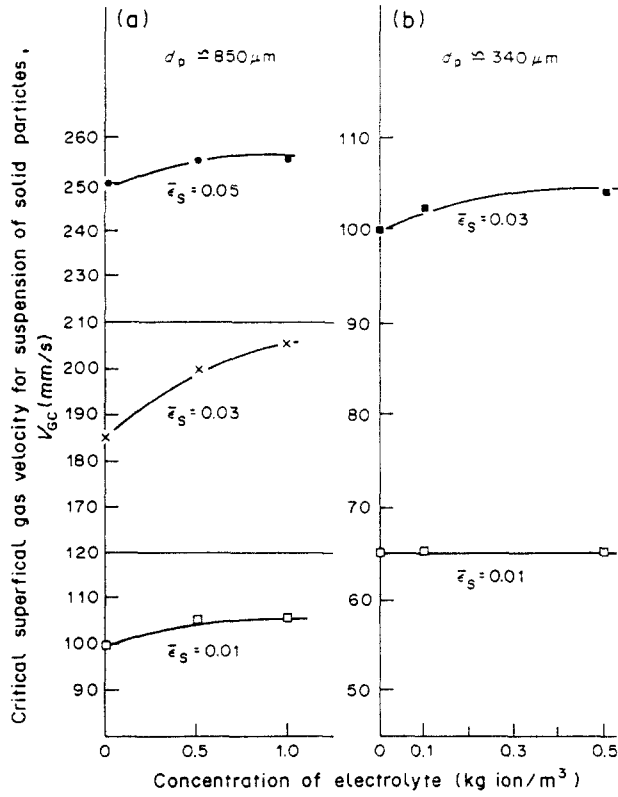


Figure 3. Effect of the presence of an electrolyte on the critical superficial gas velocity for a suspension of solid particles.

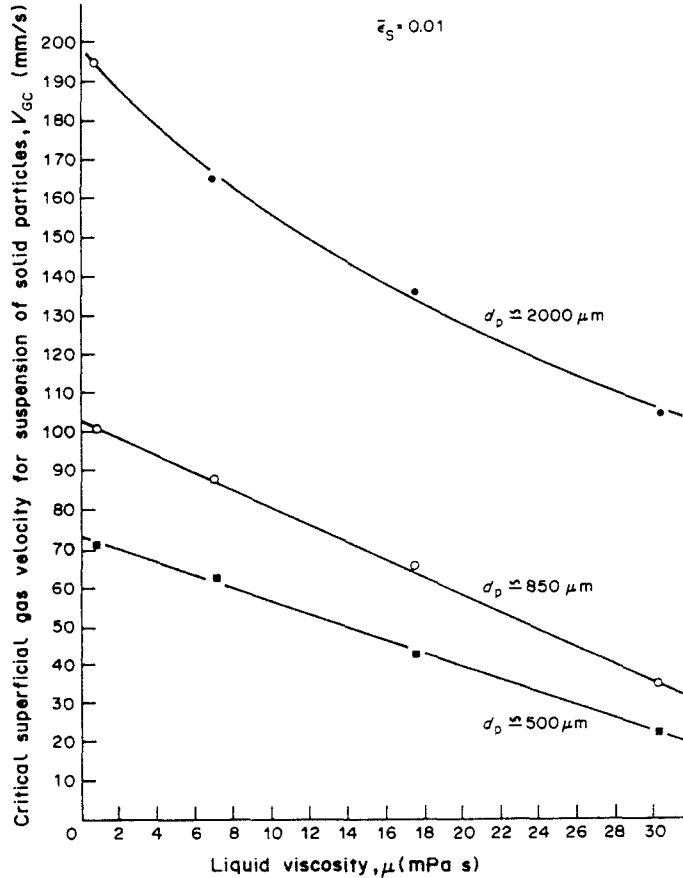


Figure 4. Effect of liquid viscosity on the critical superficial gas velocity for a suspension of solid particles.

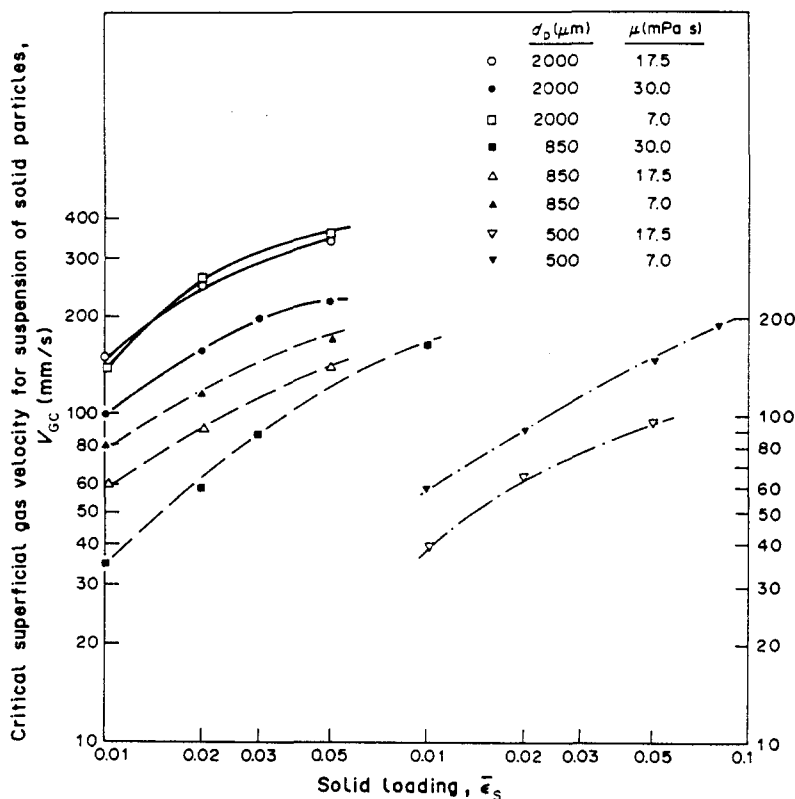


Figure 5. Effect of solid loading and liquid viscosity on the critical superficial gas velocity for a suspension of solid particles.

Figure 6 shows a peculiar behaviour of V_{GC} for larger particles. At 0.125% guar gum concentration, V_{GC} increases by about 15% compared to that with water. This phenomena can mainly be attributed to the substantial increase in the fractional gas hold-up reducing liquid circulation velocity and also the turbulent intensity. As the suspension of larger particles mainly depends upon u'_z and the non-Newtonian behaviour of the guar gum solution can substantially decrease u'_z , an increase in V_{GC} occurs. A further increase in guar gum concentration reduces fractional gas hold-up, mainly due to the increase in bubble size. The reduction in ϵ_G reduces V_{GC} because of the increase in liquid circulation velocity and hence u'_z . As discussed later, the effect of the increased concentration of drag-reducing agent (the main effect of which is to reduce u'_z) is marginal. With a further increase in guar gum concentration (0.5 vol%), V_{GC} was found to increase again. This can be explained on the basis of a substantial increase in the bubble size (which may approach even the column diameter). These large bubbles do not generate sufficient liquid circulation or turbulence to lift the particles.

Table 4. Rheological properties of the aqueous solutions of guar gum and CMC

Material	wt%	n	k (Pa s ^{n})
Guar gum	0.5	0.466	1.28
Guar gum	0.25	0.80	0.316
Guar gum	0.125	1.00	0.148
CMC	1.0	0.5	0.331
CMC	0.5	0.86	0.17
CMC	0.25	1.00	0.08

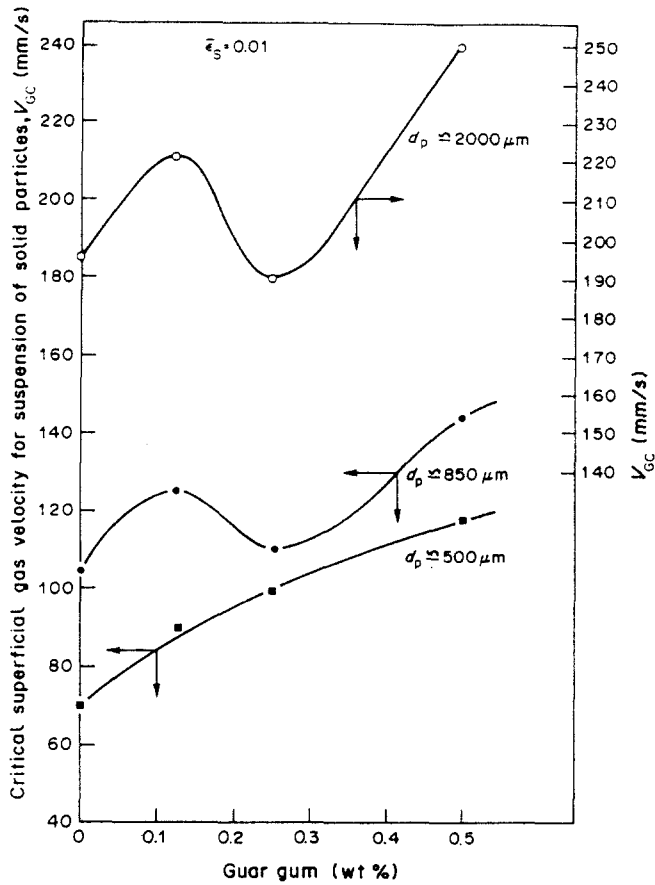


Figure 6. Effect of non-Newtonian behaviour of the liquid on the critical superficial gas velocity for a suspension of solid particles for guar gum solutions.

For smaller particles, a gradual increase in V_{GC} was observed with an increase in guar gum concentration. This behaviour is consistent with the observed fractional gas hold-up behaviour. The apparent anomaly of an increase in V_{GC} , even with a decrease in ϵ_G , can be explained if the substantial increase in the bubble diameter is considered. The product $\epsilon_G V_{B\infty}$ may still decrease if the decrease in ϵ_G is compensated by an increase in $V_{B\infty}$ (due to the increase in bubble size). It was shown by Pandit & Joshi (1983) that the procedure adopted to obtain the liquid circulation velocity, and hence u'_L , may not be valid in the case of very large bubbles.

One more important factor should be considered at this point. For larger particles (having large $V_{SN\infty}$ values), V_{GC} is also large. It was reported by Nishikawa *et al.* (1977) that the shear rate in a bubble column is given by $50 V_G/s$ (where V_G is in cm/s). This indicates that at larger superficial gas velocities the apparent viscosity will be much less, which will result in an increase in $V_{SN\infty}$ (with an increase in V_G) and hence an increase in V_{GC} . If we calculate the typical apparent viscosity values at V_{GC} for the $2000 \mu m$ particles at three levels of guar gum concentration, the argument will be much clearer. The observed behaviour of V_{GC} seems consistent with the variation in the apparent viscosity, when coupled with the variation in the bubble size and fractional gas hold-up. For smaller particles, the variation in the apparent viscosity is small and hence little variation in V_{GC} was observed.

Figure 7 shows similar behaviour in the case of CMC solutions. Figure 8 shows the effect of fractional solid hold-up on V_{GC} . It can be seen that V_{GC} is proportional to $(\bar{\epsilon}_s)^{0.55}$ for guar gum and to $(\bar{\epsilon}_s)^{0.45}$ for CMC. These exponents are slightly lower than those reported by Pandit & Joshi (1984) for an aqueous system. The lower exponent for CMC solutions is due to the higher apparent viscosity values than guar gum solutions at the same shear rate. It has been shown earlier that an increase in viscosity lowers the exponent on $\bar{\epsilon}_s$.

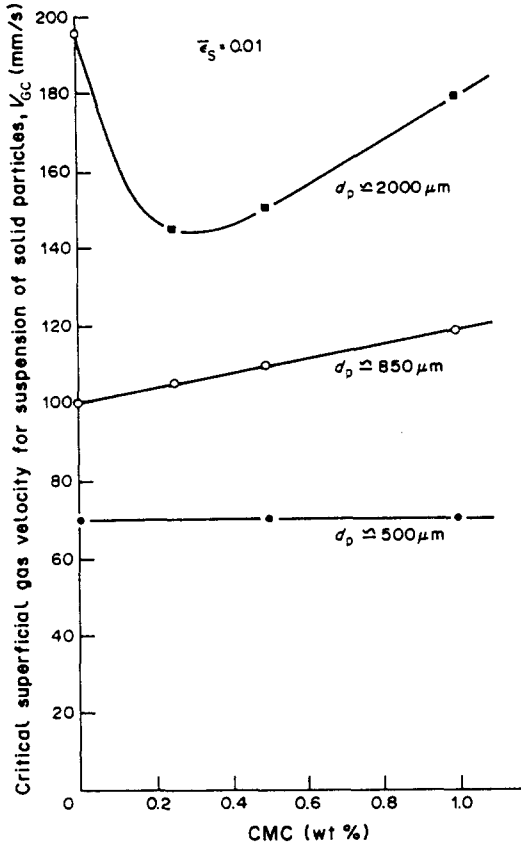


Figure 7. Effect of non-Newtonian behaviour of the liquid on the critical superficial gas velocity for a suspension of solid particles for CMC solutions.

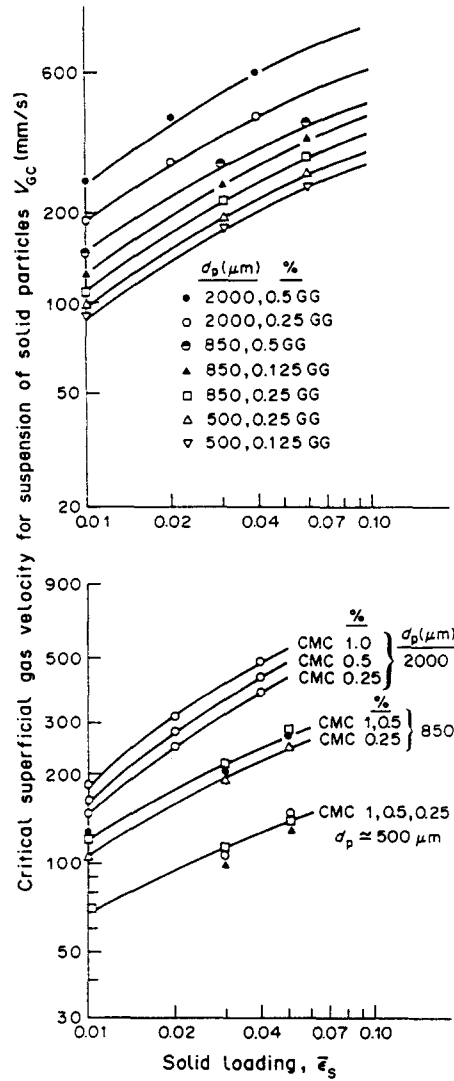


Figure 8. Effect of solid loading and non-Newtonian behaviour of the liquid on the critical superficial gas velocity for a suspension of solid particles.

Quantitative comparison between predicted u'_z and $V_{SN\infty}$ values has not been attempted because:

- (i) For given values of n and k (table 4), the shear stress depends upon the shear rate. The shear rate depends upon the superficial gas velocity, particle settling velocity, gas hold-up and solid hold-up. As a result, $V_{SN\infty}$ cannot be estimated with the present knowledge.
- (ii) The terminal rise velocity of a bubble also depends on the shear rate and indirectly on V_G , $V_{SN\infty}$, ϵ_G and ϵ_S .

Effect of drag-reducing agents

Aqueous solutions of polyacrylamide (500 and 1500 ppm) were used. Solids having $V_{SN\infty}$ values of 134 and 76 mm/s were used at different concentration levels.

Addition of 500 ppm polyacrylamide, increased V_{GC} by about 35% for smaller particles and by about 20% for larger particles. Further increases in polyacrylamide concentration to 1500 ppm increased V_{GC} only by about 5–8%.

Pandit & Joshi (1983) have shown that the addition of drag-reducing agents increases mixing time. This was mainly due to the increase in fractional gas hold-up and the decrease in turbulence

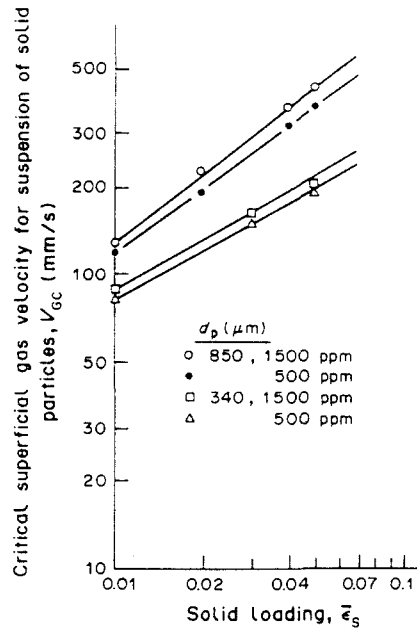


Figure 9. Effect of a drag-reducing agent on the critical superficial gas velocity for a suspension of solid particles.

intensity due to the elastic nature of the fluid. An increase in mixing time indicates a decrease in the liquid circulation velocity (due to the increase in ϵ_G) and/or a decrease in the contribution of turbulent mixing. The decrease in u'_z will result in a higher value of V_{GC} . Table 3d shows the values of u'_z calculated using [7]. It can be seen from table 3d that the predicted u'_z values are about 20–55% larger than $V_{SN\infty}$. The reported values of $V_{SN\infty}$ are for water. It is likely that $V_{SN\infty}$ also increases in the presence of drag-reducing agents, which perhaps explains the difference. The differing extent of the increase in V_{GC} for different particles is due to the difference in the fractional gas hold-up on addition of a drag-reducing agent.

Figure 9 shows the effect of $\bar{\epsilon}_s$ on V_{GC} . The exponent on ($\bar{\epsilon}_s$) for larger particles ($Re_p > 150$) is increased from 0.6 (for air–water) to 0.8. However, the exponent on ($\bar{\epsilon}_s$) for smaller particles is unchanged. Joshi (1983) has shown that larger particles act as turbulence promoters and an increase in ϵ_s increases turbulence. The addition of drag-reducing agents dampens the turbulence and hence more energy (larger V_{GC}) is required to attain u'_z equal to $V_{SN\infty}$. The smaller particles may not be affected significantly, as the turbulence intensity may not be playing a major role in their suspension.

CONCLUSION

Bubble size, bubble rise velocity, particle size and particle settling velocity are shown to be the most important parameters which decide the suspension performance of particles in three-phase sparged reactors. The effect of physical properties on bubble rise velocity, particle settling velocity and fractional gas hold-up explains the variation of critical superficial gas velocity for suspensions.

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