Critical Impeller Speed for Suspending Solids in Aerated Agitation Tanks

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Systematic measurements have been carried out in agitated gas–liquid–solids systems to determine the just off-bottom suspension speed. A variety of solids sizes, solids concentrations, impeller sizes and tank sizes are used. The difference between the just off-bottom suspension speeds with and without gas sparging does not show a linear relationship with the gassing rate and the relation is system-dependent. The relative just off-bottom suspension speed RJSS = N_{jsg}/N_{js} is found to be dependent only on the just suspension aeration number $Na_{js} = Q_g/N_{js}D^3$ and, for DT6 impellers, the relation is RJSS = $1 + mNa_{js}^n$ with the values of 2.6 and 0.7 for m and n, respectively. The relation is independent of the impeller size, solids size, solids loading and tank size, and can be used to scale up laboratory data to full-scale mixing vessels. Data from different studies support the present findings.

Des mesures systématiques ont été effectuées dans des systèmes gaz-liquide-solides agités afin de déterminer la vitesse de suspension minimale au-dessus du fond du réservoir. Diverses tailles de solides, concentrations de solides, dimensions de turbines et dimensions du réservoir sont utilisées. La différence entre les vitesses de suspension minimale avec et sans aspersion de gaz ne suit pas une relation linéaire avec la vitesse de gazage et la relation est dépendante du système. On a trouvé que la vitesse relative de suspension minimale au-dessus du fond $RJSS = N_{jsg}/N_{js}$ est dépendante uniquement du nombre d'aération en suspension $Na_{js} = Q_g/N_{js}D^3$ et que, pour les turbines DT6, la relation est $RJSS = 1 + mNa_{js}^n$, avec des valeurs pour m et n de 2,6 et 0,7, respectivement. La relation est dépendante de la dimension de la turbine, de la taille des solides, du chargement en solides et de la dimension du réservoir, et elle peut être utilisée pour mettre à l'échelle des données de laboratoire pour les mélangeurs en pleine grandeur. Des données provenant de diverses études appuient les présentes conclusions.

Keywords: solids suspension, just suspension speed, three-phase systems.

Three-phase reactors with mechanical agitation are commonly used in industry. The solids phase may act as a catalyst or undergo a chemical reaction. In order to achieve optimum process efficiency, the solid particles must be kept in suspension to increase the contacting area with the liquid. Agitators are usually used in the tanks to stir up the liquid for the purpose of both suspending the solids and enhancing mixing. One of the most important parameters one needs to know for the design of reactors is the minimum agitator speed at which all particles are in motion and no particles remain on the tank base for more than a short period, say 1~2 seconds. This speed is usually called the just off-bottom suspension speed or N_{js}.

Over recent decades, solid suspension in agitated tanks has been extensively researched (e.g., Zwietering, 1958; Chapman et al., 1983; Frijlink et al., 1990; Buurman et al., 1986; Wong et al., 1987; Bujalski et al., 1988; Raghava Rao et al., 1988; Rewatkar et al., 1991; Drewer et al., 1994, Dutta and Pangarkar, 1995; Ibrahim and Nienow, 1996; Pantula and Ahmed, 1997, 1998; Myers and Bakker, 1998; Lehn et al., 1999; Wu et al., 2000, 2001. See also, for example, Nienow et al. (1985) and Nienow (1992) for reviews on the subject. Most of the studies were focused on liquid–solids systems. Little information has been obtained for gas–liquid–solids systems. When gas is sparged into the system, the interaction of gas bubbles with the impeller and the liquid/solids phases affects both the power draw, and, in turn, the solids suspension behaviour. Current knowledge of such behaviour remains limited. For example, the dependence of just off-bottom suspension speed on operating conditions and tank/agitator geometry is not yet fully understood. Several studies have proposed a linear relationship between ΔN_{js} and the gas sparging rate Q_g, i.e.:

$$\Delta N_{js} = N_{jsg} - N_{js} = aQ_g \tag{1}$$

where a is a constant, N_{js} is the just off-bottom suspension speed in liquid–solids systems, while N_{jsg} is the just off-bottom suspension speed under gas sparging conditions. However, the value of a varied significantly from one study to another. For the commonly used Rushton impellers (DT6), the value was found to be 0.94, 0.65, 2.03 and 3.75 from the studies by Chapman et al., 1983 (see also Nienow et al., 1985); Bujalski et al., 1988; Wong et al., 1987; and Dutta and Pangarkar, 1995, respectively. The large

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variation in values throws doubt on the validity of Equation (1) to describe the complicated three-phase systems. A direct examination of Equation (1) also reveals that a cannot be a constant, since both N_{jsg} and N_{js} are dependent on operating conditions such as impeller type, impeller size, solids concentration, solids size, tank geometry, and so on. Furthermore, the relation is in the dimensional form and thus is system-dependent, thereby limiting its use for scale-up. The present study aims to investigate the effect of the gas sparging rate on N_{js} and to provide more reliable relationships for predicting N_{js} under gassing conditions. Although the investigations have been carried out for different impellers and tank shapes, only the results obtained in the flat-bottomed tank with the Rushton turbine impellers are presented here.

Experimental

The experiments were carried out at the CSIRO Thermal and Fluids Engineering laboratory, in Melbourne, Australia. Two geometrically similar cylindrical vessels with flat bottoms were used (Figure 1). The diameters of the vessels or T were 0.39 and 1.07 m, respectively. Both vessels were fitted with four vertical baffles with a width of $T/12$. The clearance of baffles from the tank wall was $T/64$.

Tap-water was used for the liquid phase and closely graded glass ballotini (Burwell Pty Ltd, density 2520 kg·m^{-3}) were used for the solids phase. Four grades of particles were used, i.e., grade AI (10–50 μm, median diameter d_{50} = 23 μm), grade AE (90–150 μm, d_{50} = 116 μm), grade AB (180–300 μm, d_{50} = 232 μm) and grade AA (212–425 μm, d_{50} = 300 μm). The solids concentration C_v (volume/volume) varied from 2 to 20%, which corresponds to X = 5 to 63 wt%. The diameter of the DT6 impellers varied from D/T = 0.33–0.41 for the small tank, while for the big tank only one impeller size (D/T = 0.33) was used. The impeller off-bottom clearance, C, was $T/3$ for all measurements. Details of the present experimental conditions and those quoted in this paper are listed in Table 1.

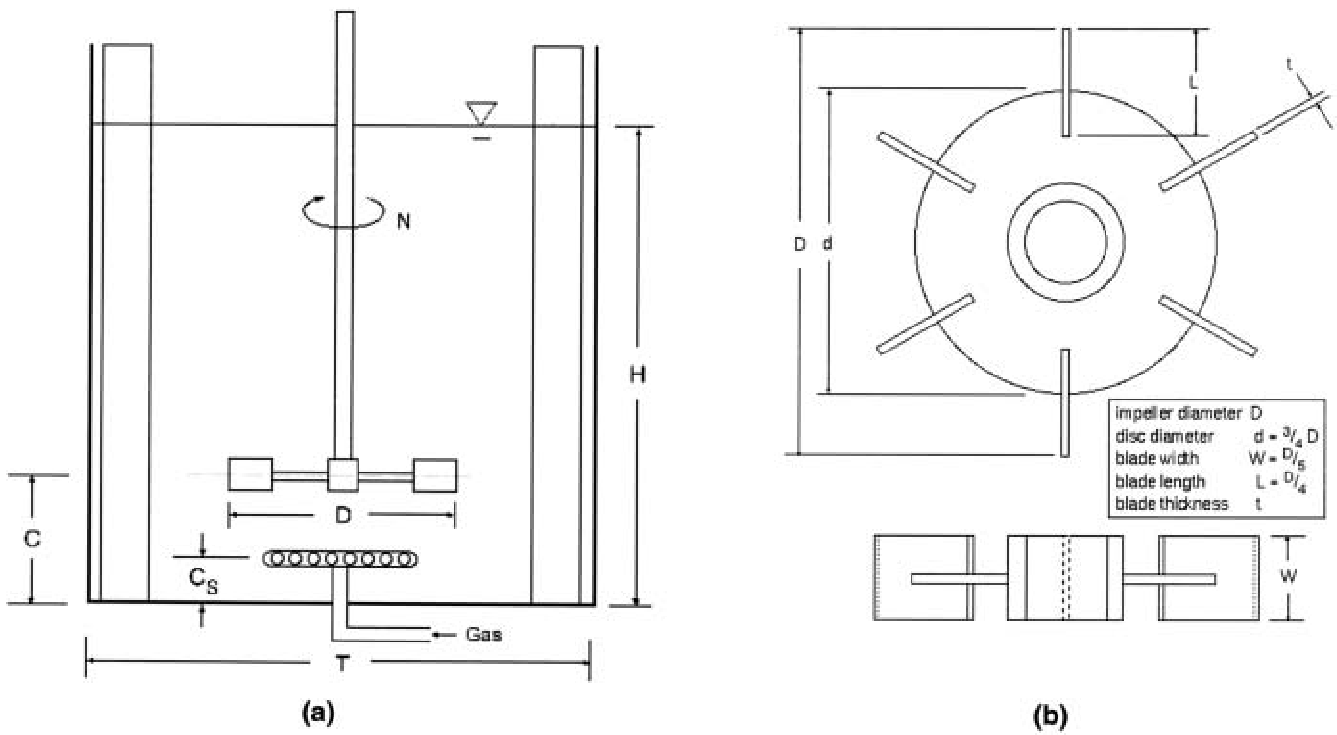

Figure 1. Schematic drawing of: (a) the flat-bottom mixing tank; and (b) the Rushton turbine impeller.

Table 1. Experimental conditions for various studies.

Reference	T (m)	D/T	C/T	Solids (size in μm)	X (wt%)	Sparger
Present study	0.39–1.07	0.33–0.41	1/3	Glass beads (10–425)	5.0–63.0	Pipe, ring
Chapman et al. (1983)	0.56	1/3	1/4	Glass beads (180–250)	3	Pipe
Dutta and Pangarkar (1995)	0.15	1/3	1/3	Sand particles (125–150)	10	Ring
Frijlink et al. (1990)	1.2	2/5	2/5	Glass beads (~120)	1	Ring
Nienow et al. (1985)	0.45	1/2	1/4	Glass beads (440–530)	0.1	Ring
Pantula and Ahmed (1997)	0.4	1/3–1/2	1/4	Glass beads (125–250)	30	Ring
Rewatkar et al. (1991)	0.57	1/3	1/3	Quartz particles (~180)	6.7	Ring
Wong et al. (1987)	0.29	1/3	1/4	Sand, glass beads (~200)	0.2~10	Ring

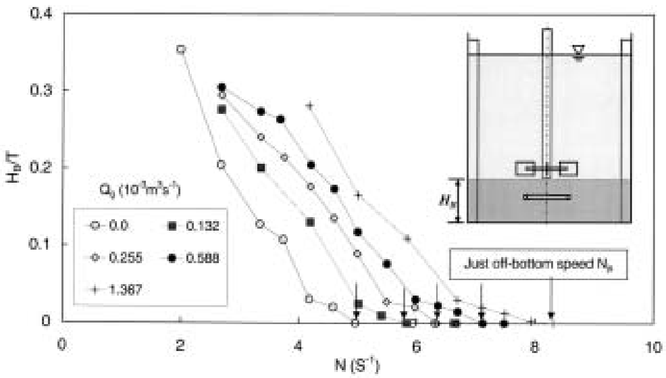

Figure 2. Solids bed height as a function of impeller speed for different gas sparging rates. ○ $Q_g = 0.0$ $m^3{\cdot}s^{-1}$, ■ 0.132×10^{-3}, ◇ 0.255×10^{-3}, ● 0.588×10^{-3}, + 1.367×10^{-3}. C_v = 20% for all the data. Point sparger used. T = 0.39m, D/T = 1/3. Arrows indicates just off-bottom suspension speed.

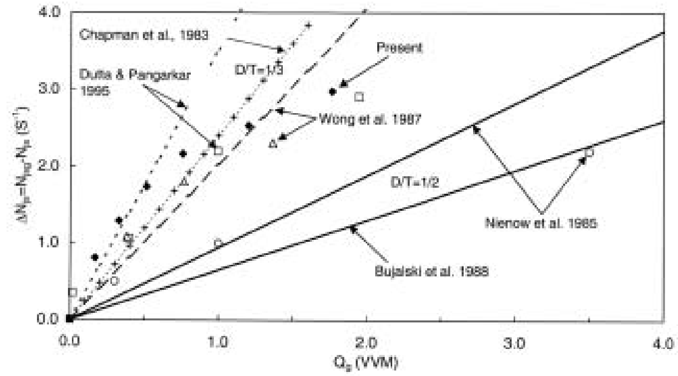

Figure 3. ΔN_{js} as a function of gas sparging rate Q_g (vvm). Lines represent correlations. Solid lines: Nienow et al. (1985) and Bujalski et al. (1988), D/T = 1/2; dashed and crossed line: Chapman et al. (1983), D/T = 1/3; dashed line: Wong et al. (1987), D/T = 1/3; dotted line: Dutta and Pangarkar (1995), D/T=1/3. Symbols are measured data. ◆ present (T = 0.39 m, D/T = 1/3, X = 63); ○ Nienow et al. (1985); △ Wong et al. (1987); □ Dutta and Pangarkar (1995).

The gas was sparged from a nozzle located centrally with the exit 20 mm from the tank bottom. The gassing rate varied from 0 to 0.00137 $m^3{\cdot}s^{-1}$ in the small tank and 0 to 0.00667 $m^3{\cdot}s^{-1}$ in the large tank. In some of the experiments, a ring sparger with a diameter of 0.8D and C_s/T = 1/6 was used (Figure 1). The measurement instruments included an in-line torque transducer (ONO SOKKI), an ultrasonic level meter and a speed meter, which allowed the liquid level, torque and shaft speed to be recorded during the experiments. A bank of rotameter tubes was used to monitor the flow rate of the sparged gas.

Results

Determination of Just Off-Bottom Suspension Speed

The flow in the tank was visually observed through the transparent tank wall and tank bottom with the aid of a mirror. Zwietering's "no particles stay at the bottom for more than 1-2 seconds" criterion is often used in the literature for determining the just off-bottom suspension speed. This is a very subjective measure and the uncertainty for a single study can be about ±5% (Hicks et al., 1997). From a practical point of view, it is insignificant that a small proportion of particles may settle in relatively stagnant regions (e.g., around the baffles, tank corners or centre of the tank) to form fillets. This condition may be more cost-effective because of the large energy savings in terms of power consumption compared with complete suspension conditions. Sometimes it is necessary to increase the impeller speed substantially (up to 20~50%) to lift statistically insignificant particles, often easily doubling energy consumption. The loss of a small amount of active solids thus may be insignificant compared with the energy savings.

In this study, a similar approach to that used by Hicks et al. (1997) was used. The settled bed height was measured at different impeller speeds. The just off-bottom suspension speed is defined as the speed at which the height of the settled bed is zero and a further reduction in the impeller speed will cause the solids to settle. Due to the complicated flow pattern in the tank, the bed surface is usually uneven. In the present study, the bed height near the wall and halfway between the baffles was used to represent the average height.

The bed height H_B, normalized by the tank diameter T, is shown in Figure 2 as a function of impeller speed for different gas sparging rates. All the curves show that when the impeller speed was reduced to below a certain value, the solids started to accumulate on the tank bottom (i.e., $H_B > 0$). This value is interpreted as N_{js}. For example, for the DT6 impeller at zero gassing rate, when the impeller speed is below 5 rev/s, the solids settled on the bottom. Therefore, the N_{js} for this condition is 5 rev/s. Although the determination of N_{js} in this way is still subjective, the uncertainty of the N_{js} measurements was found to be typically within about ±5%.

Effect of the Gas Sparging Rate on ΔN_{js}

The effect of gas sparging rate on ΔN_{js} is shown in Figure 3. Equation (1) is shown in the figure for the studies of Chapman et al. (1983), Dutta and Pangarkar (1995), Nienow (1992), Bujalski et al. (1988) and Wong et al. (1987). For clarity, only one set of the measured data is shown for each study. It is clear from the figure that none of the measured data follow a linear relationship. ΔN_{js} increases with Q_g. However, the rate of increase is larger at small gassing rates, whereas at large gassing rates the rate of increase is smaller. Further, there is a significant difference in ΔN_{js} between different studies. The data of Nienow (1992) and Bujalski et al. (1988) show the smallest dependence on Q_g (D/T = 1/2), while the present data and those by Dutta and Pangarkar (1995) (D/T = 1/3) and Chapman et al. (1983) (D/T = 1/3) show the largest dependence. The large difference is unlikely to be due to measurement errors (such as errors in the interpretation of solids bed height). Rather, this range mainly reflects differences in experimental conditions, such as solids size and loading, tank size, impeller size and so on. Such diversity it clearly demonstrates that Equation (1) is inappropriate for correlating ΔN_{js} with Q_g and that it is system-dependent. Therefore, it is impossible to use the correlation to scale up small-scale laboratory data for the design of large-scale mixing vessels. Rewatkar et al. (1991) also proposed a slightly different linear correlation for ΔN_{js}. However, correlation is also in dimensional form and contains this particle terminal velocity. Therefore, it is also system-dependent.

Effect of the Gas Sparging Rate on Relative Just Suspension Speed (RJSS)

To obtain a general form for N_{jsg}, non-dimensional quantities must be used in the correlation. In the present study, two non-dimensional variables are introduced: RJSS ($\equiv N_{jsg}/N_{js}$); and a just suspension aeration number (or flow number) Na_{js}, defined as:

$$Na_{js} \equiv \frac{Q_g}{N_{js}D^3} \tag{2}$$

When the just off-bottom suspension speed is plotted in the form of RJSS as a function of Na_{js} (Figure 4), data from different experiments almost collapse onto one curve. The measured data were obtained with a large range of solids loading (C_v = 5 to 20%, or X = 13~63 wt%) and three impeller sizes (D/T = 0.33, 0.37 and 0.41). This demonstrates that RJSS depends only on Na_{js} and is independent of the impeller size and solids concentration. A least-squares fit to the data revealed that the correlation between RJSS and Na_{js} can be represented by the following equation:

$$RJSS = 1 + mNa_{js}^{n} \tag{3}$$

where m and n are constants. For the DT6 impeller, the values for m and n are 2.6 and 0.7, respectively.

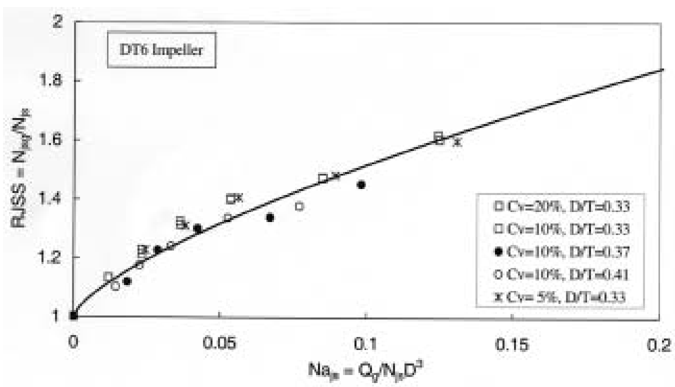

Figure 4. RJSS as a function of Na_{js} for DT6 impellers: effect of impeller size and solids concentration. T = 0.39 m, D = 0.13~0.16 m and $\nu = 1 \times 10^{-6}$ $m^2 \cdot s^{-1}$. Pipe sparger. Glass beads (Burwell grade AE, d_{50} = 116 µm) as solids. Solid line represents the best fit. All data from present measurements.

Effect of Particle Size

To examine the possible dependence of Equation (3) on the particle size, experiments were also carried out for three different particle sizes: Burwell glass beads grade AI (d_{50} = 23 µm), AE (d_{50} = 116.2 µm) and AA (d_{50} = 300.2 µm). The effect of particle size on RJSS is shown in Figure 5. The solids concentration C_v is 10% for the three measurements. The data of Rewatkar et al. (1991) are also shown in the Figure. In spite of the large range of particle sizes, both the present data and those from Rewatkar et al. (1991) are in good agreement and are well represented by Equation (3). This reveals that RJSS is independent of the particle size. It should be mentioned that the particle size used in the present measurements was very large (d_{50} = 23~300 µm) and the amount of very fine particles was small. Therefore, the solids particles had little effect on the rheology of the slurry. For very fine particles, the solids suspension behaviour may be affected by changes to the slurry rheology. The latter case requires further study.

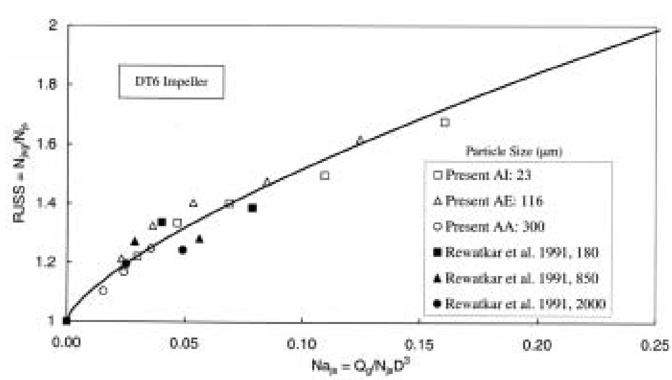

Figure 5. RJSS as a function of Na_{js} for DT6 impellers: effect of particle size. Open symbols: present data, T = 0.39 m, $D/T = C/T$ = 1/3, C_v = 10%, X = 28%. Pipe sparger. Glass beads as solids. Solid symbols: Rewatkar et al. (1991), T = 0.57 m, $D/T = C/T$ = 1/3, C_v = 0.28%, X = 0.7%, ρ_s = 2520 $kg \cdot m^{-3}$. Ring sparger. Quartz particles as solids. The solid line represents Equation (3). All data from present measurements.

Effect of Tank Size

Equation (3) was also tested in the large tank to examine the possible effect of tank size. This test is also important since it can provide information for scaling up results. Figure 6 shows the comparison between the RJSS data obtained in the large tank and that obtained in the small tank, represented by Equation (3). The large tank data are in very good agreement with Equation (3), indicating that Equation (3) is independent of the tank size, at least for the range of tank sizes used in this study.

Comparison with Data Published in the Literature

From the above discussion, it is clear that Equation (3), with m = 2.6 and n = 0.7, represents the present data very well, in spite of the wide ranges in impeller size, tank size, particle size and concentration. To further support its validity, Equation (3) is also

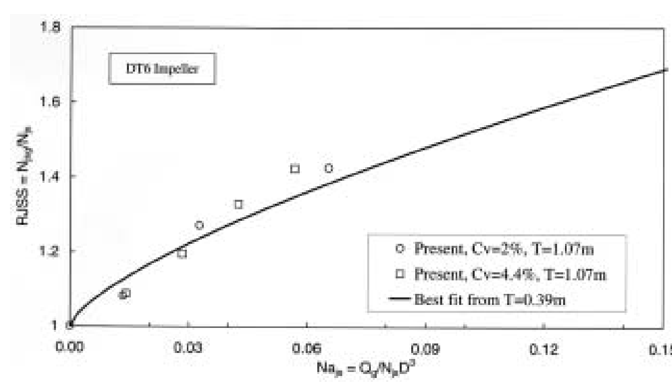

Figure 6. RJSS as a function of Na_{js}: effect of tank size. The solid line represents Equation (3) based on the small tank data. Burwell glass beads with a size range of 180~300 µm (grade AB) were used in the large tank. All data from present measurements.

compared with the available data published in the literature (Figure 7). Details for the data are listed in Table 1. All the published data were reprocessed to allow RJSS and Na_{js} to be calculated. To avoid confusion, only one typical set of data is shown in Figure 7 for each study.

Other data sets show similar behaviour and therefore are not shown here. In the case of Wong et al. (1987), two sets of data are shown, one obtained using glass beads as solids and the other using sand particles as the solids phase. The two sets of data from Pantula and Ahmed (1997) were obtained with D/T = 1/3 and 1/2, respectively. The tank size for the data shown varied from 0.15 m (Dutta and Pangarkar, 1995) to 1.2 m (Frijlink et al., 1990). The solids concentration C_v varied from 0.05% (Nienow, 1992) to 20% (present study). Glass beads were used in most of the studies. Sand and quartz particles were used in the studies of Dutta and Pangarkar (1995), Rewatkar et al. (1991) and Wong et al. (1987). The particle size (d_{50}) varied from 23 to 2000 μm. The impeller size was in the range of $0.33 < D/T < 0.5$, while the impeller clearance was in the range $0.25 < C/T < 0.4$.

It is clear that the present correlation represents well all the data to within ±10%. The largest departure from Equation (3) is observed in the data of Frijlink et al. (1990) at small aeration numbers. However, the trend is consistent with that predicted by Equation (3). The good agreement between the present study and the literature supports the validity of Equation (3). The independence of RJSS reflects that the effect of impeller size, solids concentration, solids type, particle size, tank size and other parameters are combined in the relative just suspension speed N_{jsg}/N_{js}, which depends only on the just suspension aeration number. For all the data presented in this paper, the impeller clearance C varied from $0.25T$ to $0.4T$, and there is no marked effect of the impeller location on RJSS. Therefore, it is not unreasonable to claim that RJSS is also independent of impeller location, at least for the range 0.25 ″ C/T ″ 0.4.

The present correlation was obtained with solid particles of a density around 2500~2700 $kg \cdot m^{-3}$. Such a correlation should also be applicable for lighter particles. However, for situations where very light particles (in the order of liquid density) are used, solid suspension is no longer more difficult to achieve than gas dispersion. The correlation should not be applicable, since the gas dispersion is the primary concern (Lehn et al., 1999). Further study is needed to validate the correlation for light solids particles.

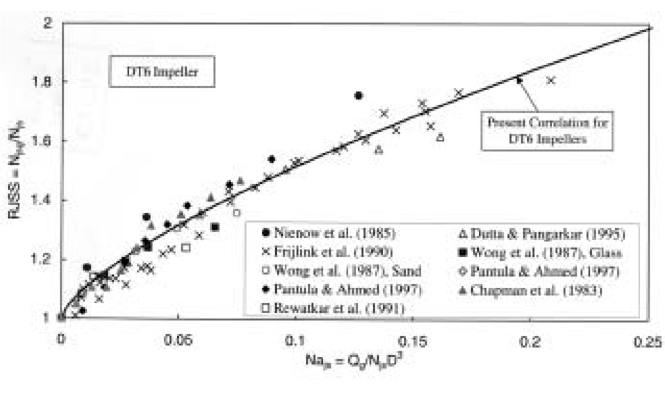

Figure 7. RJSS as a function of Na_{js}: comparison with data published in the literature. The solid line represents Equation (3). Pantula and Ahmed (1997): ◇ $D/T = 1/4$, ◆ $D/T = 1/2$; Wong et al. (1987): ○ glass beads, ● sand particles. Refer to the legend for other symbols.

It should also be mentioned that although the present correlation provides a way of predicting just suspension impeller speed, it does not contradict the findings of Pantula and Ahmed (1997), i.e., that the torque required for achieving solids suspension is independent of the gassing rate and is the same as that in ungassed conditions (see also Lehn et al., 1999). The correlation proposed by Frijlink et al. (1990), i.e.,

$$\frac{Np_{jsg}}{Np_{js}} = \left(\frac{N_{jsg}}{N_{js}}\right)^{-2} \tag{4}$$

also implies constant torque at just suspension conditions. The present torque data for DT6 impellers revealed the same behaviour (data not shown here). The data from Pantula and Ahmed (1997), Lehn et al. (1999) and the present study all indicate that the torque value depends on several parameters, such as solid density, solid concentration and impeller size. Therefore, the application of the constant torque criterion for predicting just suspension speed does not seem to be convenient.

Conclusions

The just off-bottom suspension speed has been studied in three-phase systems with Rushton impellers as agitators. The effects of solids size, solids concentration, impeller size and tank size on the just suspension speed were examined. It has been found that the difference between the just off-bottom suspension speed with and without gas sparging cannot be represented by a linear relationship with the gas sparging rate, and that the relation is system-dependent. The relative just off-bottom suspension speed RJSS = N_{jsg}/N_{js} was found to be dependent only on the just suspension aeration number $Na_{js} = Q_g/N_{js}D^3$. The correlation RJSS = $1 + mNa_{js}^n$ with $m = 2.6$ and $n = 0.7$ represents the present measurements very well. The relation is independent of impeller size, solids size, solids loading and tank size, and can be used to scale up laboratory data to full-scale mixing vessels. Data from different studies support the present findings.

Acknowledgements

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Nomenclature

a	constant
C	impeller clearance, (m)
C_s	sparger clearance, (m)
C_v	solids concentration, (vol%)
d_{50}	median particle size, (μm)
d	impeller disk diameter, (m)
D	impeller diameter, (m)
H	liquid height, (m)
H_B	solids bed height, (m)
L	blade length, (m)
m, n	constants
N	impeller speed, (s^{-1})
N_{js}	just off-bottom speed without gassing, (s^{-1})
N_{jsg}	just off-bottom speed with gassing, (s^{-1})
Na_{js}	just suspension aeration number
Np_{js}	just suspension power number without gassing
Np_{jsg}	just suspension power number with gassing

Q_g	gas sparging rate, (vvm or $m^3 \cdot s^{-1}$)
t	blade thickness
T	tank diameter, (m)
W	blade width, (m)
X	solids concentration, (wt%)

Greek Symbols

ΔN_{js}	N_{jsg}–N_{js} (s^{-1})
ρ_L	liquid density, ($kg \cdot m^{-3}$)
ρ_s	solids density, ($kg \cdot m^{-3}$)

Abbreviations

RJSS	relative just suspension speed, N_{jsg}/N_{js}
VVM	volumetric flow rate of gas per minute per volume of liquid
DT6	disk turbine impeller with six blades

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