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SUSPENSION OF SOLID PARTICLES WITH GASSED IMPELLERS

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Abstract—The suspension of settling solids with gassed impellers has been studied taking into account the influence of cavity formation behind the impeller blades in gassed systems. It is shown that the increase of stirrer speed that is required to maintain complete suspension under gassed conditions correlates strongly with the power drop that results from cavity formation. Many different impellers have been compared, both at low and high solids concentrations. Downward pumping types can be used only at very low and stable gassing rates. In most cases a disc turbine will operate satisfactorily at a bottom clearance of about 0.25 tank diameter especially when used in a vessel with a dished bottom. Although the ungassed stirrer speed for complete suspension depends among other things on the particle concentration, the increase with gassing rate is practically independent of the solid phase because the whole process is dominated by the gas–liquid impeller hydrodynamics. Scale up correlations for the just-suspended power consumption are given.

1. INTRODUCTION

Both gas dispersion and solids suspension in mixing vessels are research areas that are still incomplete. Nevertheless in recent years surveys have started on three-phase (gas–liquid–solid) mixing. This field is far from academic: Shah (1979) lists well over 100 industrial three-phase processes with continuous liquid phase and dispersed gas and solid phases, ranging from catalytic oxygenation and hydrogenation to microbial coal desulfurization and immobilized fermentation broths. The role of the particles may vary from reactant or product to catalyst, biocatalyst or support particle. Although attention is generally limited to settling suspensions, there have also been some studies of gassed reactors with floating solids (Bakker and Frijlink, 1989).

This paper considers the hydrodynamic problems associated with the demands of simultaneous gas dispersion and solids suspension with one single impeller. The formation of ventilated cavities behind the impeller blades and the associated decrease of shaft power and pumping capacity play a dominant role in these systems and can lead to partial settling out of the solids with both disc impellers and open ("inclined blade") impellers. As a consequence, increased impeller speeds are required in order to maintain suspension in gassed systems. At very high gassing rates, flooding can lead to complete loss of liquid pumping and gas dispersion with consequent settling out of the solids.

In this work the "just-suspended" criterion (Zwietering, 1958) is used in both gassed and ungassed systems, and the associated stirrer speed is denoted N_{js}. Gassed and ungassed speeds are distinguished with N_{jsg} and N_{jsu}, respectively, where necessary. The effect of particles on gas–liquid mass transfer in various types of equipment will be published separately by Frijlink and Smith (in preparation).

1.1. *Previous work*

Kürten and Zehner (1979) compared some types of suspension reactors, including a stirred vessel with a single disc turbine (see Fig. 1). The power required to maintain complete suspension increased with the superficial gas velocity to the power 0.3. They suggest that the gassed power drop of the impeller can explain these results; however, their data apply mainly to high gassing rates, far beyond the decreasing power range. The authors drew straight lines in the original graphs. In Fig. 1 modified curves are sketched through their data points. The two regimes, not recognized by the authors, are discussed in the following sections.

About 1978 extensive studies with single impeller systems were started by Wiedmann (1982) and Chapman (1981). Both workers covered a wide area.

Chapman (1981) and Chapman *et al.* (1981, 1983a–c) compared a large number of impellers in solid–liquid, gas–liquid and three-phase systems in vessels of up to 1.8 m diameter. Using disc turbines the increase of N_{js} on gassing showed a proportionality with the gas flow rate only and was found to be independent of the solids type and concentration for low gassing rates. They also found that downward pumping impellers require the least energy at low gas flow rates but exhibit unstable behaviour at high gas flow rates. Therefore it is advantageous to use upward pumping impellers at high gas flow rates because these do not show this unstable behaviour.

Wiedmann concentrated on power characteristics, gas hold-up and flooding in similar vessels (0.2 and

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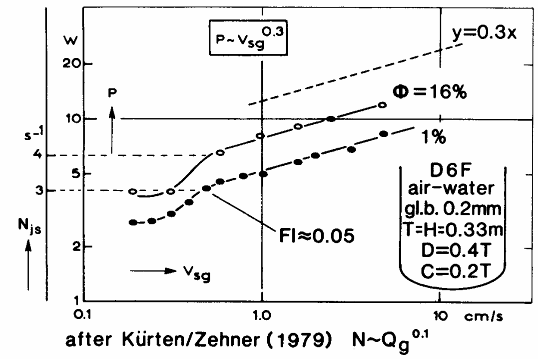

Fig. 1. Data from Kürten and Zehner (1979). The zone of gassed power drop is to the left, the zone with large cavities to the right.

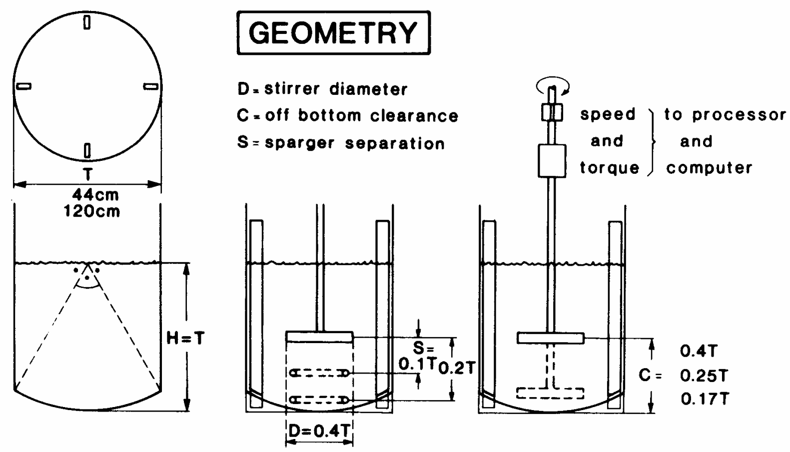

Fig. 2. Vessel and impeller configurations.

0.45 m diameter) with propellers and disc impellers. Neither author discussed the interaction between cavity formation and suspension behaviour of the impellers used.

Warmoeskerken *et al.* (1984a) showed that cavity formation with disc turbines in suspensions does not deviate from that in water, at least with less than 5 mass % of solids. Frijlink *et al.* (1984) discussed the suspension of solids with aereated, downwards pumping pitched blade turbines. They showed the existence of a strong interaction between the gassed impeller characteristics and the suspension performance.

Greaves and Loh (1984) reported power measurements in a 0.20 m diameter vessel with a dished bottom. A non-Newtonian behaviour was found at high solids concentrations. Some of their results suggested an increased size of the ventilated cavities behind the stirrer blades under these circumstances.

Nienow *et al.* (1986) and Bujalski *et al.* (1988) continued the previous work by Chapman. They gave several design correlations for three-phase systems, for upward pumping as well as for downward pumping impellers. They also suggested an optimum geometry and sparger design. All their experiments were carried out in flat bottomed vessels only.

2. EXPERIMENTAL METHODS

2.1. *Vessel geometries and instrumentation*

The vessel geometries are drawn schematically in Fig. 2. A 0.44 m vessel with a dished bottom was used for most of these suspension experiments. Some comparative data were obtained in a 0.44 m vessel with a flat bottom. The latter was also used in scale-up studies because at larger scale only a flat bottomed vessel ($T = 1.20$ m) was available. Liquid height H equalled tank diameter T throughout the work. The width of the four baffles was $0.1T$ with a $0.01T$ separation from the wall. Impeller bottom clearance was varied over a wide range. With downwards pumping open turbines the separation S between ring sparger and impeller was also varied.

In the two 0.44 m vessels torque was measured by

Vibrometer TT 106 instruments. In the 1.20 m tank the torque was determined indirectly by measuring the anchor current of the d.c. motor. This is possible because the torque exerted by a d.c. motor is proportional to the anchor current. Empirical corrections for energy and friction losses in the motor, the gearing and shaft bearings were made. Measuring the power number of a disc turbine gave $Po = 6.37$. Calculating the power number of this disc turbine with the correlation proposed by Bujalski *et al.* (1987) yields $Po = 6.3$. Both data agree fairly well, giving confidence in the power data obtained in this way. In all vessels the stirrer speed was determined with high accuracy from the time of revolution of the shaft.

2.2. *Impellers used*

The D/T ratio was 0.4 for all impellers used. In the 1.20 m vessel only six-bladed impellers were used. Blade and disc thicknesses were scaled with approximately the same factor as the diameter.

Abbreviation description

D6F	Standard disc turbine with six flat blades.
D6C	*Idem* (Fig. 3), with curved blades, $R = D/5$ (van't Riet *et al.*, 1976; Warmoeskerken and Smith, 1989).
D6CC	*Idem*, with increased curvature of the blades, $R = D/10$.
90°/6	Open turbine with six flat blades, radial pumping.
60° ↓ 6 (4)	Open turbine, downwards mode with six (four) flat blades.
45° ↓ 6 (4)	Blade angle to the horizontal 60°, 45°, 30°, respectively.
60° ↑ 6 (4)	*Idem*, pumping upwards.

2.3. *Materials used*

In all experimental work reported here tap water and air were used. The solid materials were glass beads and sand, both with narrow size distributions around 0.12 mm. Solid density was 2500 kg/m^3.

2.4. *Suspension criteria*

Zwietering (1958) proposed that complete suspension is achieved if no particles remain motionless on the vessel bottom for more than 1 s. This situation (stirrer speed N_{js}, just-suspended state and speed) differs considerably from the state of homogeneous suspension, except when the particles are very small or of nearly neutral density. However, in most cases a homogeneous suspension is not required and would be very difficult to realize with rapidly settling particles. The accessibility of all of the surface area of the solid phase and the elimination of the danger of hot spots, etc. has made the just-suspended condition the most useful parameter characterizing suspension operations. It must be noted, however, that the vertical concentration profile $c(z)$ still depends on the nature of the particles if the 1-s criterion is used. Einenkel (1980), who frequently used a 90% bed height criterion, found that relations for stirrer speed and scale-up were of similar form for various suspension criteria.

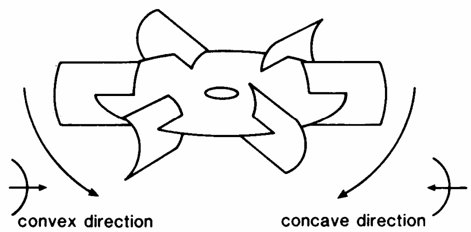

Fig. 3. The disc turbine with curved blades. All experiments with this impeller were conducted with the concave blade faces forward.

The strength and weakness of the 1-s method lie in the need to observe the vessel bottom: a single plane of a three-dimensional system, but doubtless the most important plane. Visual observation is demanding and often impossible. Automation is far from easy, especially since settling out can take place at various places, depending on flow pattern, geometry, gassing rate, etc. This is illustrated for a disc turbine at two clearances in Fig. 4. A persistent spot of particles in the centre of the bottom (with a dished bottom) or behind the baffles (with a flat bottom) is often only suspended after a redoubling of impeller speed, which is not always possible in industrial equipment. The interaction between clearance and impeller diameter on the one hand and liquid circulation and suspension performance on the other has already been discussed by Nienow (1968) for flat bottomed vessels equipped with a disc turbine.

The geometry problem is further illustrated by the following comment made by Chapman *et al.* (1983c) on work by Wiedmann *et al.* (1980): "their absolute data values imply particle suspension was achieved at speeds 50% lower than this work or that of Zwietering or Nienow would predict and must therefore be regarded as slightly suspect". It can easily be shown, however, that the differences are associated with the geometry. Chapman *et al.* used only flat bottomed vessels that are known to be unfavourable for solid suspension. Wiedmann *et al.* used dished bottoms with the gas pipe to the ring sparger entering in the centre of the bottom, just where a stagnant spot of particles might occur. Bottom geometries like this that eliminate the danger of solids build up are relatively favourable: many vessels used for suspension have some kind of cone in the centre of the bottom (Bourne and Sharma, 1974). From this point of view the difference cited above is by no way surprising. Similar results were found in this study [see, for example, Fig. 14(a) and (b)].

3. EFFECT OF SOLIDS ON GAS DISPERSION PERFORMANCE

3.1. *General approach*

In a stirred multiphase system the hydrodynamic condition of the impeller is of major importance. In a

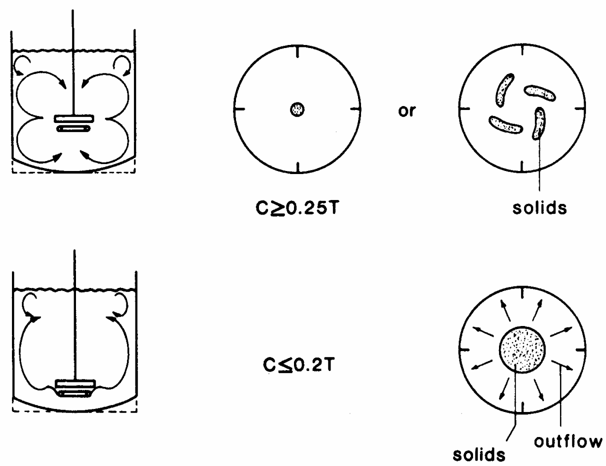

Fig. 4. Different patterns of settled solids at stirrer speeds just below N_{js} (disc turbine).

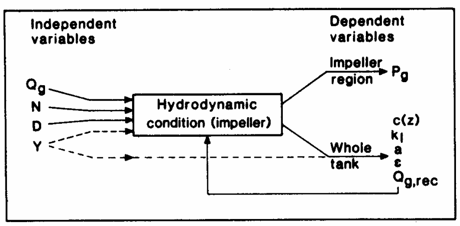

Fig. 5. Schematic view of the relations between dependent and independent variables, showing that particles may affect the impeller hydrodynamics as well as the bulk conditions. Here ε is the gas fraction.

gas–liquid dispersion, the performance is largely controlled by the impeller zone, more specifically by the formation of ventilated cavities behind the stirrer blades. These cause a decrease of shaft power. In his extensive study of these phenomena, Warmoeskerken (1986) showed that three independent variables determine the hydrodynamic condition of the impeller: the gas flow rate Q_g, the stirrer speed N and the geometry, characterized by impeller diameter D. Figure 5 illustrates that all other variables, like gassed power P_g or interfacial area "a" depend on these three design parameters. From these the dimensionless flow number $Fl = Q_g/ND^3$ comes forward as a single quantity for characterization, correlation and scale-up of gassed systems. Unfortunately, this expectation is not fulfilled because both the recirculating gas flow $Q_{g,rec}$ and the maximum cavity size depend on the stirrer speed N at constant values of the flow number Fl. Consequently, the description of gassed systems is very complicated and reliable scale-up rules for the dependent variables have not yet been established.

If solid material is introduced in the gassed stirred system a new parameter has to be defined, which characterizes the settling properties of the particle swarm in the gas–liquid system. The symbol Y in Fig. 5 refers to a property group of the type introduced by Zwietering (1958):

$$Y = \nu^{0.1} d^{0.2} \left(\frac{g\Delta\rho}{\rho_l}\right)^{0.45} B^{0.13}. \qquad (1)$$

This group has repeatedly been found to characterize the settling behaviour effectively. B (also denoted as X) is the ratio of solids mass to liquid mass (%).

A new dependent quantity on the right hand side in Fig. 5 is the vertical concentration profile $c(z)$ of the suspended solid phase. The solid particles will affect the dependent variables partly via the impeller hydrodynamics and partly via processes occurring in the bulk of the vessel (e.g. via increased coalescence).

The gas–liquid system may serve as a starting point for the examination of three-phase systems if the effect of the particles on the impeller hydrodynamics is negligible or very small. If, on the contrary, the solid phase changes the impeller hydrodynamics sharply, then an alternative approach must be found.

Solids can be expected to influence the impeller performance as a result of modification of viscosity, local density or vortex structures in the vicinity of the impeller blades. It is well known that in concentrated suspensions with non-Newtonian properties the circulation around the impeller blades changes drastically. It has also been reported that stable gas cavities may form behind the blades in viscous Newtonian and non-Newtonian fluids (van't Riet, 1975). As well as this, any unsuspended solids may form a false bottom, effectively reducing clearance and in most geometries also affecting power consumption.

If a gas flow Q_g is introduced, leading to the formation of large ventilated cavities, the shaft power will decrease some 50% or more and the effective density, clearance and viscosity experienced by the impeller may all change significantly.

In an ungassed suspension, the effective density ρ_{eff} experienced by the impeller will depend on the physical system Y, impeller clearance C and the stirrer speed N and will generally not be equal to the mean density or to the liquid density ρ_l. For the power consumption one may write:

$$P = 2\pi NM = Po\,\rho_{eff} N^3 D^5 = Po^* \rho_l N^3 D^5. \quad (2)$$

Here P and M are shaft power and torque, respectively, and Po is the power number. The modified power number Po^* accounts for the ratio ρ_{eff}/ρ_l.

When gassing it is difficult to decide whether a change in power consumption must be associated with cavity formation alone, or includes density and rheology modifications. This requires careful examination of the experimental data. Therefore, in three-phase systems a similar apparent power number Po_g^* is defined that reflects all the effects mentioned above.

3.2. *Disc turbines*

Warmoeskerken *et al.* (1984a) detected the transition from six clinging to three large and three clinging cavities in various suspensions with a spring steel strain gauge probe that was placed in the impeller discharge stream. Figure 6 contains their data and some more recent extensions using the same apparatus. This change of cavity structure is found at $Fl = 0.03$ for both liquids and suspensions up to 25 mass % (10 vol %) sand.

Further evidence that the gas–liquid impeller hydrodynamics do not change drastically in suspensions is found in the extensive flooding measurements reported by Steiff and Weinspach (1982).

Finally the power drawn at constant stirrer speed and increasing gas flow rate was measured in pure liquids and suspensions. Warmoeskeren *et al.* (1984a) showed that small solids concentrations (0.5–5 mass %; 0.2–2 vol %) did not change the characteristics of these curves. In Fig. 7 the upper curves show the effect of 10 vol % sand at 6 s^{-1} stirrer speed and a large clearance ($C = 0.36T$). The apparent power number Po^* with solids is about 5% larger at zero gas flow and this situation is approximately maintained when the gas flow rate increases.

The three lower curves are measured with small clearance, $C = 0.17T$, when the lower circulation loop is suppressed (see Fig. 4). With 0 and 2 vol % nearly identical curves are found. The relative power drop at this clearance is larger than in the first case. A rather steep part of both curves at $Fl = 25 \times 10^{-3}$ indicates a less gradual transition from clinging to large cavities. With 10 vol % solids the ungassed value of Po^* is 10% higher as a result of the high local density. The reduction of gassed power with increasing flow number is very rapid in this case and the steepest zone occurs at $Fl = 20 \times 10^{-3}$.

In Fig. 8 results are presented for both clearances at a stirrer speed of 3 s^{-1}. This low stirrer speed results in considerable density stratification. The two upper curves (large clearance) compare solid-free data and those for 10 vol % sand. With the incompletely suspended solids Po^* is increased by 10% at $Fl = 0$, decreases more rapidly than without solids and approaches a constant value for high gassing rates. The curves for $C = 0.17T$ show a very steep decrease of gassed power at $Fl = 25 \times 10^{-3}$. The minimum in both curves (0 and 2 vol % sand) has not been reported before, and again indicates that the cavity

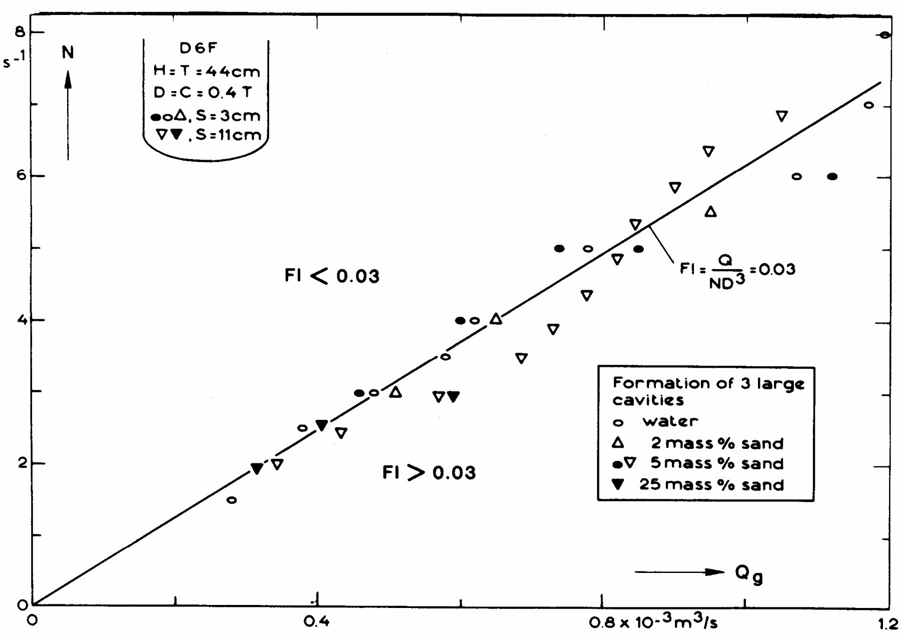

Fig. 6. Transition from six clinging cavities to three large and three clinging cavities in pure liquid and in suspensions.

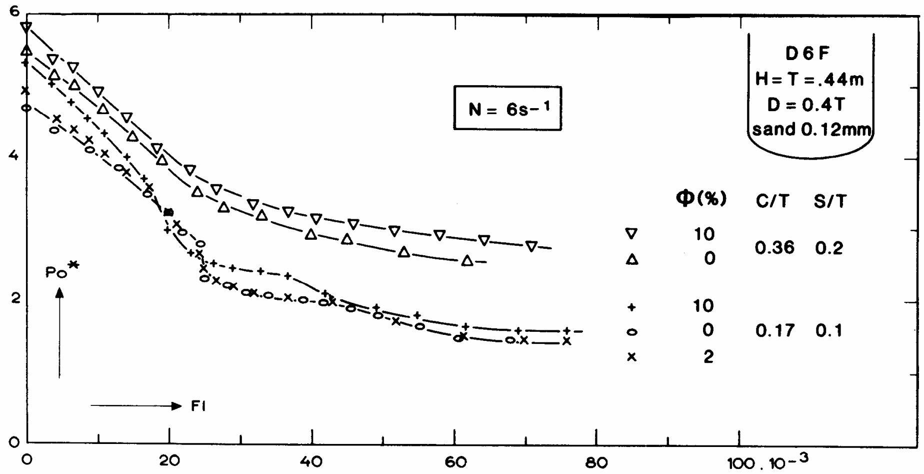

Fig. 7. Effect of solids concentration on Po^* at $N = 6\ s^{-1}$ for large and small clearance.

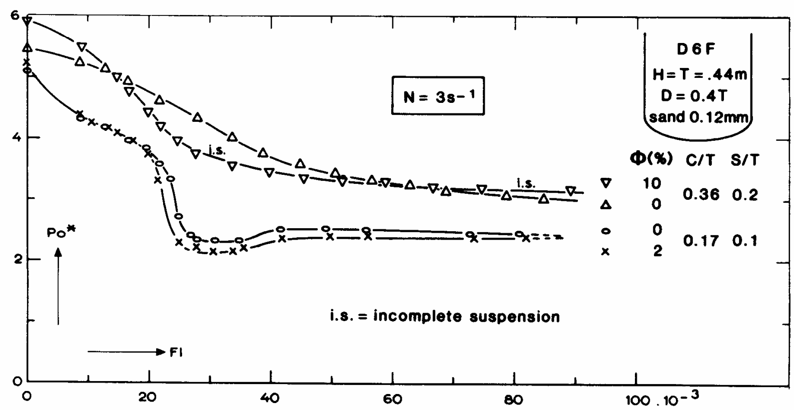

Fig. 8. As Fig. 7, but with a stirrer speed of $3\ s^{-1}$.

formation regimes at this impeller position may be quite different from the description given by Warmoeskerken (1986) for large clearances. To summarize, these results indicate that high local solids concentrations in the impeller zone cause the gassed power to decrease faster and at smaller gas flow numbers than without solids, although the general characteristics of the gas–liquid system are still very well recognized.

3.3. *Inclined blade turbines* (*gas–liquid*)

Gas–liquid dispersion using downwards pumping impellers with flat, inclined blades has been discussed by Chapman *et al.* (1983b), Nienow *et al.* (1986) and Warmoeskerken *et al.* (1984b). These authors all made a distinction between two flow regimes: indirect loading [Fig. 9(a)], when gas is carried downwards from the sparger and can reach the impeller zone only by recirculation; direct loading [Fig. 9(c)], when the bubble cloud rises directly to the impeller and the liquid flow leaves the impeller zone more radially.

Frijlink *et al.* (1984) showed that the impeller–sparger separation distance S had a strong influence on this indirect–direct loading transition. Obviously this was associated with modification of the gas recirculation rate [see Fig. 9(b)]. They also showed that the use of a pipe sparger on the centre line of the vessel yields a steep power drop at low gas rates, because in this case [illustrated in Fig. 9(a)] the gas can easily move upwards via the small recirculation loops directly below the impeller.

Some of the data published by Frijlink *et al.* (1984) are shown in Fig. 10. With ring spargers the power curves coincide up to $Fl = 0.02$ at stirrer speeds of $3\ s^{-1}$ and $6\ s^{-1}$. With a large separation S the growth of the cavities is postponed until—at larger gas flow rates—the hold-up in the sparger zone increases so much that bubbles enter the flow loops close to the

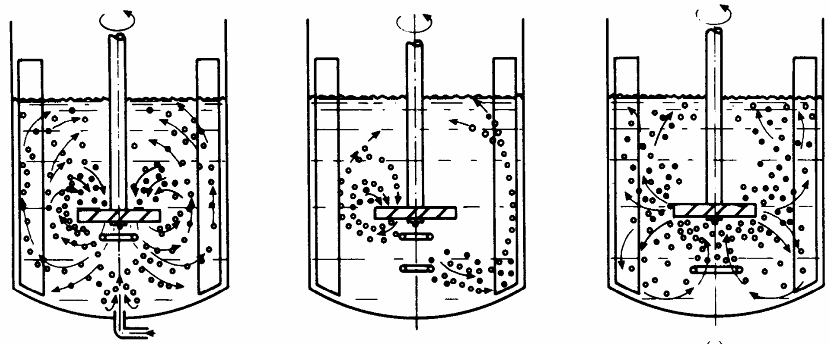
(a) (b) (c)

Fig. 9. Two-phase flow characteristics of downwards pumping open turbines.

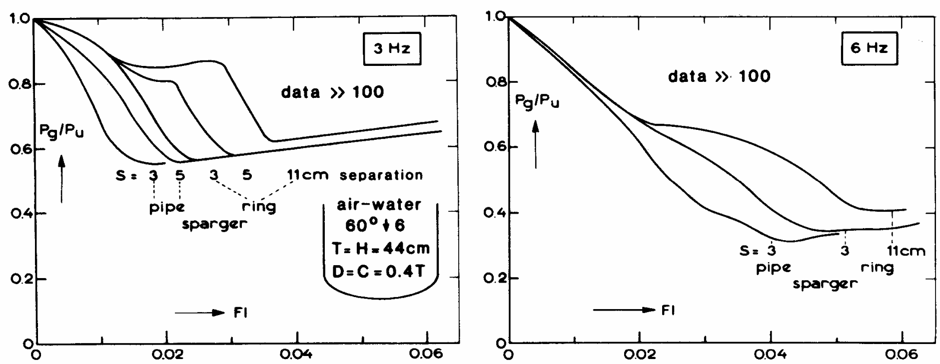

Fig. 10. Effect of sparger geometry on the transition between direct and indirect loading.

centre line. The increase of the cavity size then results in a further reduction of shaft power and pumping rate and finally in direct loading. This transition has been located visually by different experimenters at the point where the power drop is completed and the curves flatten. Because similar results are found at all stirrer speeds, it is unlikely that the transition takes place when the downward liquid velocity happens to equal the rising velocity of the bubble cloud. Attempts to explain the phenomena on the basis of an air lift effect were also unsuccessful.

Operation of an agitated system in the transition zone is undesirable because of the large torque fluctuations that may cause mechanical damage. A point of interest for three-phase applications is that tracer particles are observed to move outwards on the bottom at low gassing rates, but move inwards at higher gas flow, when the impeller is directly loaded and the downwards velocity component is so far reduced that the resulting outflow is more like that of a radial pumping impeller [Fig. 9(c)].

The unstable character of the gassed downwards pumping impeller is avoided when the direction of rotation is reversed so that the impeller is pumping upwards. The cocurrent gas and liquid flows lead to a reduced cavity size, resulting in a smaller power drop on gassing if compared with downward pumping impellers. This stable gas handling behaviour can be advantageous in three-phase systems, as pointed out by Bujalski *et al.* (1988).

Figure 11 shows a comparison of two-phase gassed power curves at a stirrer speed of $4\,s^{-1}$ for different blade angles and blade numbers, pumping downward (a) and upward (b). It is remarkable that the differences between four- and six-blade impellers are small, both gassed and ungassed, although the passed power drop always occurs at lower gassing rates with the four-blade impeller. This strongly suggests that the gas handling capacity is associated with the apparent gas flow per impeller blade.

3.4. *Inclined blade turbines* (*effect of solids*)

The effect of solid particles on the power drawn at constant stirrer speed is illustrated in Fig. 12. The diagrams a–c (left side) show the effect of clearance on gassed power at $6\,s^{-1}$ with and without solids. At $C = 0.36T$ the value of Po^* with 10 vol % sand increases almost uniformly as compared with the solid-free system. At the smaller clearances, however, the effective particle concentration in the impeller zone is larger and may increase further when the power drops.

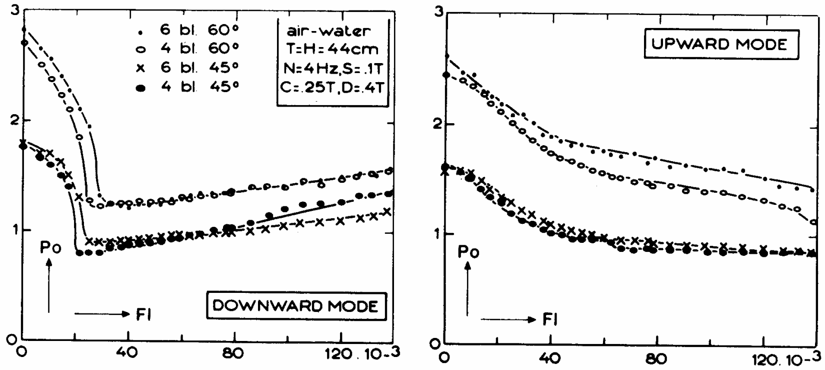

Fig. 11. Power demand for gassed inclined blade impellers for various blade angles and numbers of blades. In the upwards pumping mode the transition from indirect to direct loading is avoided.

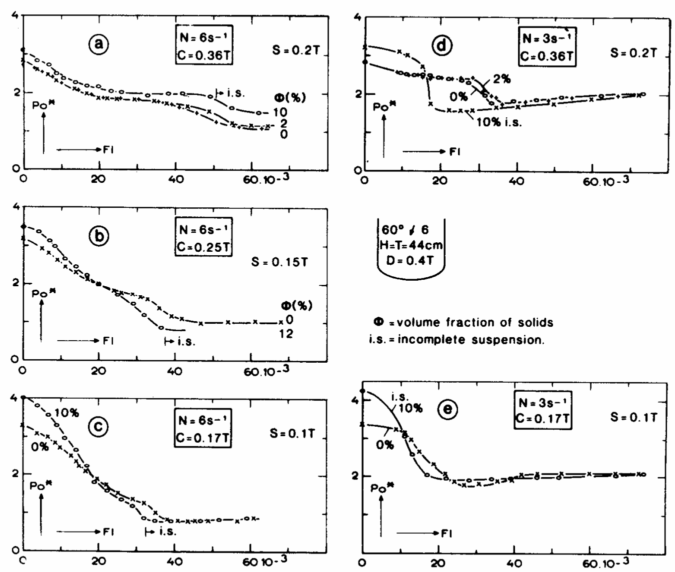

Fig. 12. Effect of solids on Po^* at two stirrer speeds and various clearances using inclined blade impellers.

Nevertheless, Po^* decreases to lower values than in the gas–liquid system. This leads to the conclusion that much larger cavities are developed behind the impeller blades in a concentrated suspension. This result is similar to that reported by van't Riet (1975) in viscous liquids. Figure 12(d) and (e) shows the effect of solids for two clearances at 3 s^{-1} stirrer speed. Incomplete suspension of solids is present here and false bottom effects play a role. Just as with disc turbines a steeper power drop is observed at lower flow numbers.

Again it is concluded that the two-phase gas–liquid system provides a reasonable starting point for the description of the dispersion of gases in suspensions, although it is very difficult to explain results like those in Fig. 12 in full detail.

4. COMPLETE SUSPENSION WITH GASSED DISC TURBINES

4.1. *Effect of particle concentration*

Gassed disc turbines do not develop the dramatic change of flow patterns shown by downwards pumping impellers. The only unexpected effect is the small decrease of the just-suspended stirrer speed that is sometimes observed at low gas flow rates. In that case the introduction of gas that is recirculated in the lower flow loop disturbs the sedimentation zones on the bottom and so helps to fulfil the Zwietering condition. As soon as vortex cavities change into clinging cavities the effect disappears. Figure 13 shows the effect of particle concentration for $C = 0.4T$. It is remarkable that the overall character of the curves does not depend significantly on the mass fraction.

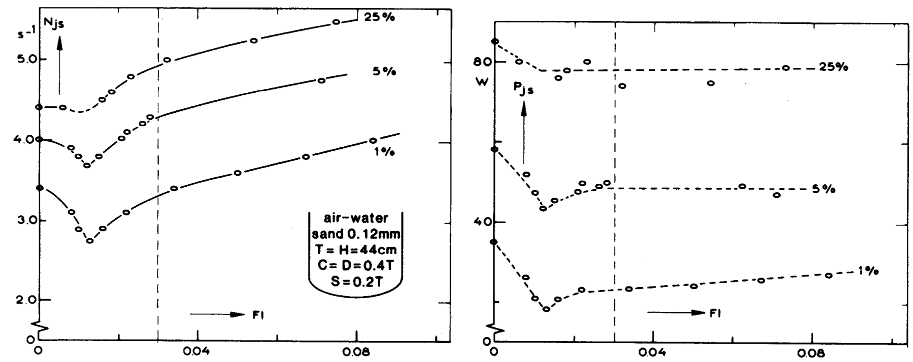

Fig. 13. Stirrer speed and power consumption for complete suspension with disc turbine at a large clearance (1%, 5%, 25% mass).

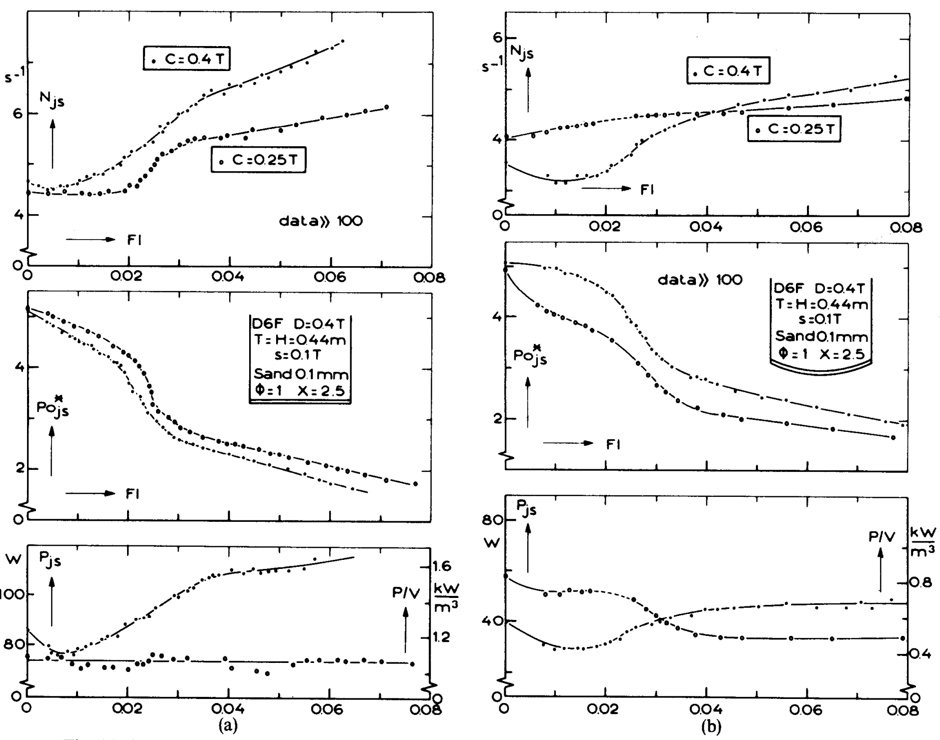

Fig. 14. Just-suspended condition with a gassed disc turbine in flat and curved bottomed vessels. Stirrer speed and power number show a distinct relation. P/V is lowest with the rounded bottom.

The initial differences in the ungassed systems are preserved and the power consumption does not change very much with an increase of gassing rate. These results agree with those obtained by previous authors, e.g. Chapman *et al.* (1981).

4.2. *Effect of gassing on stirrer speed* N_{js}

Extensive measurements at low solids concentration are presented in Fig. 14 for two vessels of 0.44 m diameter, one with a flat bottom, the other with a curved bottom. Stirrer speeds N_{js}, power numbers Po^* and specific power consumption are shown to be strongly correlated. The increase of N_{js} follows the decreasing Po^* in detail. The power consumption is essentially constant with the curved bottom at both clearances and also with the smaller clearance in the flat bottomed vessel. Note that the power consumptions for flat and curved bottoms differ by more than a factor of two (see Section 2.4).

These results may be summarized as follows: any increase of stirrer speed N_{js} on gassing serves primarily to keep the power consumption at a constant level, provided that the vessel geometry is more or less optimal and impeller efficiency does not change on gassing.

4.3. *Effect of scale*

Similar measurements to those reported above were carried out in the 1.20 m diameter steel vessel with a flat bottom (1.36 m^3). For practical reasons only small mass fractions of glass beads (typically 1%) were used in this case. Several 10 cm diameter windows were mounted flush in the bottom and the side walls. One of these, located in the bottom at half the vessel radius, halfway between two baffles was found to be appropriate for determination of complete suspension. A video camera was used for observation.

The results shown in Fig. 15 are similar to those in the 0.44 m vessel [Fig. 14(a)]. The effect of impeller hydrodynamics is clear again. The relative increase of N_{js} vs flow number Q_g/ND^3 is similar at both scales. This aspect is discussed in some detail in Section 7.

Buurman *et al.* (1986) pointed out that when using inclined blade impellers in unaerated vessels the impeller blade thickness can have a remarkable influence on solids suspension. In Fig. 15 suspension data are plotted for two values of disc and blade thickness ($x = 3$ mm and 5 mm) of a disc turbine. It is clear that in a gassed system no significant effect on N_{js} arises from these differences. Therefore the ideas expressed by Buurman *et al.* cannot easily be extended to our three-phase systems.

5. COMPLETE SUSPENSION WITH GASSED INCLINED BLADE IMPELLERS

5.1. *Effect of gassing and solids concentration*

Using downwards pumping impellers the drop in gassed power is rather dramatic. This is reflected in the relations between the gas flow number, Fl, P_{js} and N_{js}, respectively [Fig. 16(a) and (b)]. Moreover, the sparger–impeller separation S has been shown to be a very important parameter. From Fig. 16(a) it is seen that with a small sparger separation $S = 0.1T$ the stirrer speed has to be increased significantly from the lowest gassing rates to maintain complete suspension. With a larger distance between sparger and impeller the slope of the curve is less at low gassing rates, but close to $Fl = 0.045$ a sharp increase of N_{js} is required. These phenomena reflect the differences in the gassed power curves shown in Fig. 10. Note that with $S = 0.2T$ the two curves of Fig. 16(a) show a sharp increase in N_{js} at $Fl = 0.045$, although the solids concentrations differ by a factor of 5. This is further evidence that the properties of the slurry have little influence on the hydrodynamic performance of gassed impellers.

The results for the power consumption in Fig. 16(b) can be interpreted with the aid of Fig. 9(a) and (c). The reversing flow pattern below the impeller at the transition from indirect to direct loading creates two different regimes separated by a barrier where particle suspension is inefficient. A comparison of Figs 10 and 16 indicates that the transition coincides with the formation of large cavities at the impeller blades.

The liquid flow near the bottom is obviously reduced when the two flow regimes are in competition. This leads to the performance barrier shown in the figures. This behaviour may also serve as a proof that sufficient liquid flow along the bottom is the primary requirement for the suspension of solid particles.

A comparison between upwards and downwards pumping impellers in a 0.29 m diameter vessel is shown in Fig. 17. The differences between the gassed power curves of Fig. 11 are clearly reflected in these suspension data. The modest effect of gas-filled cavities in the upward mode results in a relatively flat curve of N_{js} vs gassing rate. The instabilities of flow pattern are eliminated and the system operates very effectively, especially at high gas flow rates where the power consumption is lower than in the downward mode. This confirms the earlier work by Chapman *et al.* (1983) and Bujalski *et al.* (1988). More data concerning the upward pumping mode will be presented in the following sections.

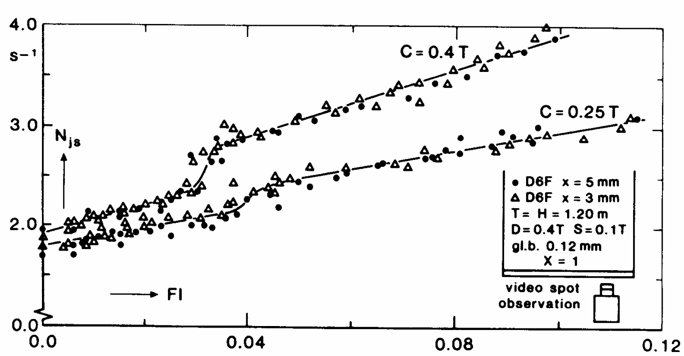

Fig. 15. Stirrer speed N_{js} for two disc turbines with different disc and blade thickness x in the 120 cm flat bottomed vessel. Video observation of a limited area of the vessel bottom.

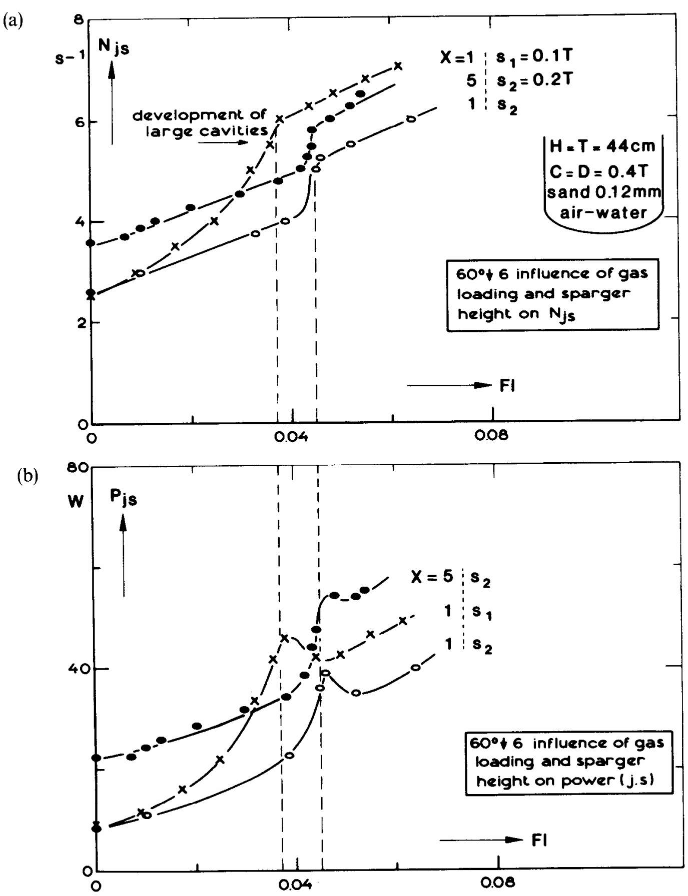

Fig. 16. (a) Stirrer speed for complete suspension at different sparger separations s and solids concentrations. (b) Power drawn at the just suspended condition with downwards pumping inclined blade turbine, showing the performance barrier at the gas loading transition.

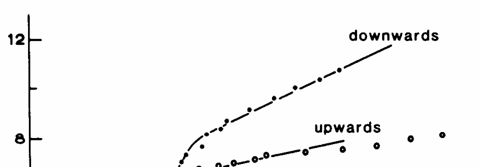

Fig. 17. Complete suspension with upwards and downwards pumping impeller in a gassed system.

5.2. *Effect of scale*

Figure 18 shows results in the 1.20 m vessel with the 60°, six-bladed impeller. Again, the ungassed impeller speed N_{js} is highest for the upwards pumping configuration. Only the six-bladed 60° blade angle impellers can be used up to moderately large flow numbers, preferably at a clearance as low as $C = 0.25T$. Four-blade impellers are far less suited because of the higher gas load per blade (see Section 6). Performance with an impeller clearance $C = 0.4T$ is very much inferior to that with $0.25T$.

6. COMPARISON OF TWELVE IMPELLERS AT A HIGH SOLID CONCENTRATION

From the foregoing sections the conclusion can be drawn that a clearance $C = 0.25T$ is a good compromise for most impellers and vessels, in agreement with Chapman *et al.* (1983c). A comparison of all selected impellers was made with this clearance in a 12 vol % (25 mass %) sand–water suspension. For all these tests the sparger to impeller separation S was $0.1T$. The results are presented in Fig. 19. In order to avoid confusion the data for downwards pumping impellers are presented on the right side and those for

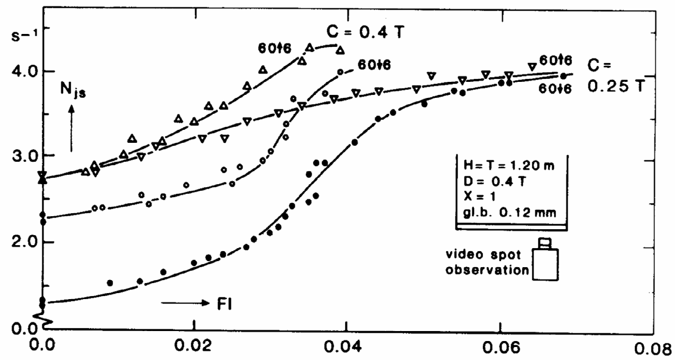

Fig. 18. Complete suspension with upwards and downwards pumping impeller in a gassed system at different impeller–bottom clearances.

upwards and radial pumping configurations on the left side.

The radial pumping impellers appear to be most economical, except at very low gassing rates, and show only weak increases of the required speed and power for complete suspension. The curved bladed disc impellers with the concave side moving forward are very effective in systems of this kind. At this solids concentration the upwards pumping configurations require higher power input than the radial ones; only the 60° six-blade type can be used up to high flow numbers. The remarkable fact is observed that for most inclined blade impellers a maximum value of *Fl* is reached when the relative increase of stirrer speed for complete suspension becomes larger than that of the gas flow rate. This leads to impractical increases in speed and power.

Downward pumping open turbines are economical at small gas flow rates but the strong variations of Po^*_{js}, N_{js} and $(P/V)_{js}$ lead to the conclusion that radial impellers should be preferred. Moreover, in most industrial applications the small gassing rate range is not very important and variations of gas flow rate during a process are quite usual. These may cause unstable performance in the downward mode.

Interesting details with respect to these results are: (i) The differences between four- and six-bladed types of the same angle are small in the ungassed system (cf. Fig. 11). (ii) Deviations start immediately when gassing begins. The 45° blade impeller changes place with the 60° four-blade type, showing that the gas loading per impeller blade is a key parameter with downwards pumping turbines in gassed systems.

7. DATA INTERPRETATION

7.1. *General interpretation*

A large number of measurements, repeated several times, has established that the effect of gassing on the critical impeller speed N_{js} can be largely explained by changes of the gassed power, irrespective of the nature and volume fraction of the solid phase involved.

The following regimes can be distinguished:

(i) Low gas flow rates ($Fl < 0.02$). A small reduction of N_{js} and P_{js} may occur, possibly as a result of gas recirculation along the bottom that disturbs sedimentation patterns and leads to the decision that the 1-s criterion is more easily satisfied. The effect is not caused by gas-induced liquid flow because it has been observed with downwards pumping impellers as well.

(ii) Transition region ($0.02 < Fl < 0.05$). As a result of changing impeller hydrodynamics and flow patterns N_{js} is sometimes not very reproducible. An increase of N_{js} is observed that correlates very well with the decrease of the apparent power number Po^*.

(iii) Large gas flow rates ($Fl > 0.05$). Only radial pumping impellers and some upward pumping configurations continue to operate stably and efficiently. The power consumption is constant or increases slowly with gas flow rate. Downward pumping configurations are generally unsatisfactory at these high gas loadings. None of those studied was able to suspend solids at gas flow numbers above $Fl = 0.08$.

The transition from clinging to large cavities, which is associated with the major part of the so-called gassed power drop, is particularly clearly reflected in the curves of N_{js} vs flow number *Fl*. Generally, the increase of speed required is larger than would be necessary to account for the power drop, so it must be assumed that the efficiency of various impeller configurations to suspend off the bottom also decreases when the cavity configuration—and subsequently the flow pattern—changes. This holds dramatically for downward pumping open turbines. The less sensitive an impeller is to the effect of gassing, the more constant is the power drawn for complete suspension, e.g. the curved bladed disc turbines which are reported to be very stable (Warmoeskerken and Smith, 1989). Most of the present results support the conclusion that, providing that allowance is made for possible changes in impeller efficiency in gassed systems, "con-

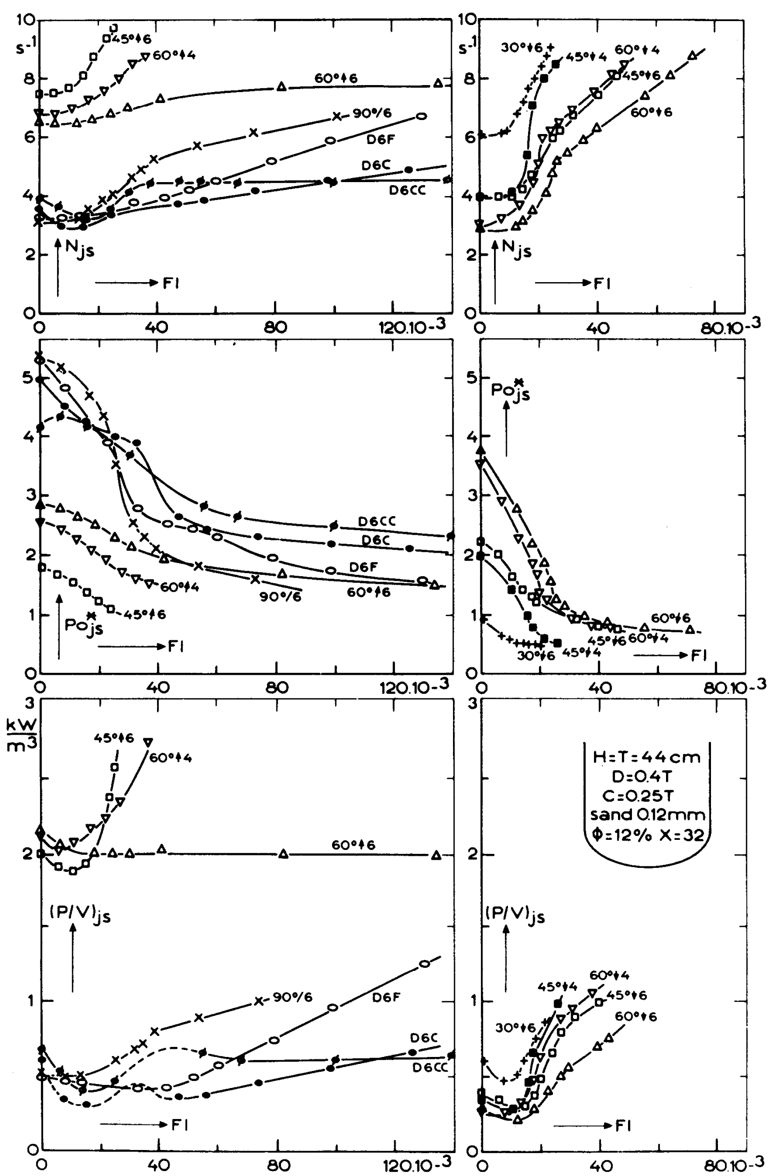

Fig. 19. Comparison of four radial pumping, five downwards and three upwards pumping configurations in the same sand–water system. Complete suspension could not be achieved with upwards pumping 30° and four-blade 45° impellers. The downwards pumping impellers are on the right side in order to avoid confusion. Key to impellers: see section 2.2.

stant power" provides a sensible basis for the design of three-phase systems.

7.2. *Relation between* N_{jsg} *and power consumption*

It has been mentioned several times that the increase of N_{js} at increasing gassing rate correlates very well with the decrease in gassed power number. This can be explored in more detail by plotting the relative decrease of the gassed power number vs the relative increase in N_{js} for the impellers studied (Figs 20 and 21). By doing so the following relation is found for disc turbines and upward pumping impellers:

$$\frac{Po^*_{jsg}}{Po^*_{jsu}} \sim \left(\frac{N_{jsg}}{N_{jsu}}\right)^{-2} \tag{3}$$

It is very interesting to compare the performance of the disc turbine and the inclined blade impellers. With an upward pumping impeller the data scatter around the Rushton line with no significant difference between the data obtained in the 0.44 m and the 1.20 m

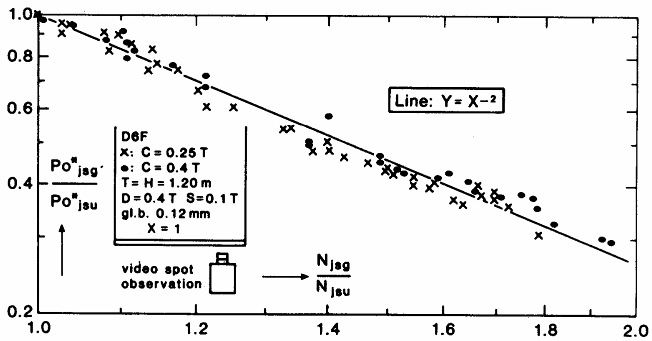

Fig. 20. The relative decrease of the just-suspended power number plotted as a function of the relative increase in the just-suspended stirrer speed for the disc turbine in the 1.20 m flat bottomed vessel.

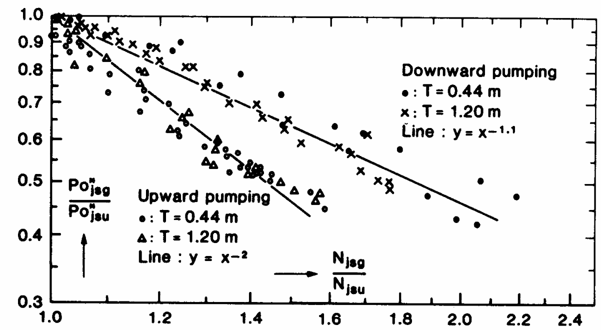

Fig. 21. The relative decrease of the just-suspended power number plotted as a function of the relative increase in the just-suspended stirrer speed for the inclined blade impellers in the 0.44 m and 1.20 m flat bottomed vessels.

tank (Fig. 21). The explanation for the similar behaviour of the disc turbine and the upward pumping impeller in these plots is probably the fact that with both impeller types the introduced gas reinforces the cross-bottom liquid flow.

With a downward pumping impeller the curve is much flatter and though there is a tendency for the data at the two scales to be separated a line of

$$\frac{Po^*_{jsg}}{Po^*_{jsu}} \sim \left(\frac{N_{jsg}}{N_{jsu}}\right)^{-1.1} \quad (4)$$

fits the data to within about 10%. Relationships (3) and (4) cover the whole gassing range. It is clear that the behaviour of downward pumping impellers differs significantly from that of the disc turbine and upward pumping impellers, but in general it can be concluded that the decrease in power consumption associated with cavity formation interacts with the just-suspended impeller speed for all kinds of impellers.

8. SCALE-UP

8.1. *Scale-up conventions for the gas flow rate*

Scale-up is a very important subject in the study of three-phase systems. Until now several scale-up conventions for the gas flow rate are used. These are: scaling up at constant gas flow number *Fl*, constant superficial gas velocity v_{sg} and constant gassing rate in v.v.m. None of these scale-up conventions always work satisfactorily.

It is clear that the flow number *Fl* is not very well suited for design correlations because it contains both stirrer speed and gas flow rate. If the former increases more rapidly than the latter, unpredictable changes of flow number with increasing gas flow rate may be obtained (e.g. Fig. 19). It is impossible to express the effect of increasing gassing rate independently in this way. Moreover, the (changing) stirrer speed appears on both the vertical and the horizontal axis which is again undesirable. Although very helpful to clarify basic hydrodynamic phenomena in the impeller region, the flow number is not applicable for scale-up (Section 3.1) nor for design calculations in the field of three-phase mixing.

German authors (Kürten and Zehner, 1979) prefer to use the superficial gas velocity v_{sg} for correlating data. Correlations that contain the specific power input and the superficial gas velocity are sometimes successful in gas–liquid systems. This approach is, however, not easily transferred to the various interactions in gassed suspensions.

Following a convention in the fermentation industries, British workers (Chapman *et al.*, 1981, 1983b, c; Greaves and Loh, 1984) introduced the vvm (volume per volume per minute):

$$Q_g(\text{vvm}) = 60 Q_g / V_1 . \quad (5)$$

Scaling up at constant Q_g (vvm) is equivalent to keeping a constant ratio between gassing rate and liquid volume. Both the v_{sg} and Q_g (vvm) approaches suffer the problem that the role of the impeller is now practically invisible, although the effect of gassing on a suspension can be quite different, depending on the particular impeller operating conditions.

8.2. *Scaling up at constant* Q_g *(vvm)*

In the literature several design correlations containing the gas flow rate in vvm are given for three-phase systems, e.g. Chapman *et al.* (1983b), Nienow *et al.* (1986) and Bujalski *et al.* (1988). Mainly for reasons of comparison it was decided to follow this approach.

When using constant gassing rate in vvm as a scale-up criterion it was found that in our small and large vessels the relative increase in just-suspended stirrer speed scales as follows:

$$\frac{N_{jsg}}{N_{jsu}} \sim D^{0.2}. \quad (6)$$

This relation holds for the radial pumping disc turbine as well as for the axial pumping inclined blade impellers (upward pumping as well as downward pumping) for gassing rates larger than 0.5 vvm. Scaling up from the 0.44 m vessel to the 1.20 m vessel using this equation can be done with 10% accuracy.

Our results indicate that with disc turbines the ungassed stirrer speed N_{jsu} obeys Zwietering's (1958) correlation:

$$N_{jsu} \sim D^{-0.85}. \quad (7)$$

Combining eqs (6) and (7) gives:

$$N_{jsg} \sim D^{-0.65} \quad (8)$$

for the disc turbine.

If Po_{jsg} were independent of scale, the power per unit volume $\varepsilon_{jsg} = P_{jsg}/V$ would be proportional to $N^3 D^2$ and, from eq. (8), would be practically constant. However, because of the altered hydrodynamic conditions Po_{jsg} is not independent of scale when scaling up at constant Q_g (vvm). Combining eqs (3) and (6) gives:

$$\frac{Po^*_{jsg}}{Po^*_{jsu}} \sim D^{-0.4}. \quad (9)$$

This decrease of the relative power number of scaling up can be explained since, as stated before, these equations are valid only for scaling up at constant Q_g (vvm). Because N_{jsg} decreases when scaling up, the corresponding flow number ($Fl \sim Q_g$ (vvm)$/N_{jsg}$) increases. From Figs 14 and 19 it can be seen that Po^*_{jsg}/Po^*_{jsu} decreases with increasing flow number.

Furthermore, by definition:

$$\frac{P_{jsg}}{P_{jsu}} = \frac{Po^*_{jsg}}{Po^*_{jsu}} \left(\frac{N_{jsg}}{N_{jsu}}\right)^3 . \quad (10)$$

Combining eqs (6), (9) and (10) gives:

$$\frac{P_{jsg}}{P_{jsu}} \sim D^{0.2}. \quad (11)$$

If the *ungassed* power number can be assumed to be independent of scale, combining eqs (2) and (7) yields:

$$P_{jsu} \sim D^{2.45}. \quad (12)$$

Combining eqs (11) and (12) results in:

$$\varepsilon_{jsg} = P_{jsg}/V \sim D^{-0.35} \quad (13)$$

for disc turbines. Thus, the power per unit volume decreases slightly when scaling up at constant Q_g (vvm).

Different scale-up rules must be applied for inclined blade impellers. In ungassed systems, the just-suspended stirrer speed scales as follows for downward pumping impellers:

$$N_{jsu} \sim D^{-0.7}. \quad (14)$$

Using eqs (4) and (14) and repeating the above manipulations results in:

$$\varepsilon_{jsg} \sim D^{0.3}. \quad (15)$$

For upward pumping impellers:

$$N_{jsu} \sim D^{-0.6}. \quad (16)$$

For the specific power consumption this results in:

$$\varepsilon_{jsg} \sim D^{0.4}. \quad (17)$$

Equations (14)–(17) hold for scaling up at constant Q_g (vvm) using inclined blade impellers, downward and upward pumping, respectively. It can be seen that the specific power ε_{jsg} increases slightly on scale-up when using this kind of impeller. These results are in reasonable agreement with those reported by Chapman *et al.* (1983c).

9. CONCLUSIONS

For general purposes it is recommended to use six- or eight-bladed disc impellers at a clearance of $0.25T$. In this way a good and stable gas handling capacity is combined with adequate suspension performance. Inclined blade impellers pumping downwards show unstable behaviour at high gassing rates. Upward pumping impellers, which were recommended by Chapman *et al.* (1983c) and Bujalski *et al.* (1988), may be advantageous because of the stable behaviour on gassing but show insufficient suspension performance with high concentrations of dense solids.

The suspension performance can further be improved by using dished tank bottoms instead of flat bottoms. In this way the liquid flow near the bottom is increased and the just-suspended impeller speed decreases significantly. This was already known from two-phase studies but has not earlier been reported for three-phase systems.

When using disc turbines the disc and blade thickness do not significantly influence the suspension characteristics of the system.

When scaling up at constant Q_g (vvm) the specific just-suspended power consumption ε_{jsg} increases when using an inclined blade impeller and decreases when using a disc turbine. This corresponds fairly well with the results of Chapman *et al.* (1983c).

The drop in power consumption caused by the formation of cavities behind the impeller blades corresponds to an increase in the required just-suspended impeller speed. This holds for disc turbines as well as for inclined blade impellers. The effect is less for impellers which are less sensitive to gassing, like upward pumping impellers and concave-bladed radial impellers. Therefore, further research should be concentrated in this area.

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NOTATION

Upper case

- B mass ratio of solid to liquid phase in suspension × 100
- C impeller clearance
- D impeller diameter
- H liquid height
- M impeller torque
- N impeller speed
- P power
- Q flow rate
- R radius of curved blade
- S vertical separation between impeller and sparger
- T tank diameter
- V volume
- X see B
- Y suspension parameter

Lower case

- a interfacial area between gas and liquid per unit volume
- c concentration
- d particle diameter
- g acceleration due to gravity
- k mass transfer coefficient
- v velocity
- x blade and disc thickness for a disc turbine
- z vertical coordinate

Greek letters

- ε power input per unit volume
- ϕ, Φ solids volume fraction
- ν kinematic viscosity
- ρ density
- $\Delta\rho$ density difference
- ΔN difference of impeller speeds

Non-dimensional quantities

- Po impeller power number ($= Ne = N_p$ defined as $P/(\rho_{eff} N^3 D^5)$
- Po^* apparent power number in gassed suspensions, using ρ_1 as the density. It includes both the effect of gassing and local density modification that results from inhomogeneous solids distribution
- Fl gas flow number, $Fl = Q_g/ND^3$

Subscripts

- b bottom
- eff effective
- g gas(sed)
- js just-suspended
- l liquid
- rec recirculated
- sg superficial (gas)
- u ungassed

REFERENCES

Bakker, A. and Frijlink J. J., 1989, *Chem. Engng Res. Des.* **67**, 208–210.

Bourne, J. R. and Sharma, R. N., 1974, *First Eur. Conf. on Mixing*, Cambridge, U.K., Paper B3. BHRA, Cranfield.

Bujalski, W., Nienow., A. W., Chatwin, S. and Cooke, M., 1987, *Chem. Engng Sci.* **42**, 317–326.

Bujalski, W., Konno, M. and Nienow, A. W., 1988, *Proc. 6th Eur. Mixing Conf.*, Italy, pp. 389–398. AIDIC/BHRA Fluid Engineering, Cranfield.

Buurman, C., Resoort, G. and Plaschkes, A., 1986, *Chem. Engng Sci.* **41**, 2865–2871.

Chapman, C. M., 1981, Dissertation, University of London.

Chapman, C. M., Nienow, A. W. and Middleton, J. C., 1981, *Trans. Inst. Chem. Engrs* **59**, 134–137.

Chapman, C. M., Nienow, A. W., Cooke, M. and Middleton, J. C., 1983a, *Chem. Engng Res. Des.* **61**, 71–81.

Chapman, C. M., Nienow, A. W., Cooke, M. and Middleton, J. C., 1983b, *Chem. Engng Res. Des.* **61**, 82–95.

Chapman, C. M., Nienow, A. W., Cooke, M. and Middleton, J. C., 1983c, *Chem. Engng Res. Des.* **61**, 167–181.

Einenkel, W. D., 1980, *German Chem. Engng* **3**, 118–124.

Frijlink, J. J., Kolijn, M. and Smith, J. M., 1984, *Inst. Chem. Engrs Symp. Ser.* **89**, 49–58.

Greaves, M. and Loh, V. Y., 1984, *Inst. Chem. Engrs Symp. Ser.* **89**, 69–96.

Kürten, H. and Zehner, P., 1979, *Chem. Ing. Tech.* **51**, 227–229 (*German Chem. Engng* **2**, 220–227, 1979).

Nienow, A. W., 1968, *Chem. Engng Sci.* **23**, 1453–1460.

Nienow, A. W., Konno, M. and Bujalski, W., 1986, *Chem. Engng Res. Des.* **64**, 182–185.

Riet, K. van't, 1975, Dissertation, Delft University of Technology.

Riet, K. van't, Boom, J. M. and Smith, J. M., 1976, *Trans. Inst. Chem. Engrs* **54**, 124–131.

Shah, Y. T., 1979, *Gas–Liquid–Solid Reactor Design.* McGraw-Hill, New York.

Steiff, A. and Weinspach, P. M., 1982, *Chem. Ing. Tech.* **54**, 526–527.

Warmoeskerken, M. M. C. G., 1986, Dissertation, Delft University of Technology.

Warmoeskerken, M. M. C. G. and Smith, J. M., 1989, *Chem. Engng Res. Des.* **67**, 193–198.

Warmoeskerken, M. M. C. G., Houwelingen, M. C. van, Frijlink, J. J. and Smith, J. M., 1984a, *Chem. Engng Res. Des.* **62**, 197–200.

Warmoeskerken, M. M. C. G., Speur, J. A. and Smith, J. M., 1984b, *Chem. Engng Commun.* **25**, 11–29.

Wiedmann, J. A., 1982, Dissertation, University of Dortmund.

Wiedmann, J. A., Steiff, A. and Weinspach, P. M., 1980, *Chem. Engng Commun.* **6**, 245–256.

Zwietering, Th. N., 1958, *Chem. Engng Sci.* **8**, 244–253.