RECENT STUDIES ON AGITATED THREE PHASE (GAS-SOLID-LIQUID) SYSTEMS IN THE TURBULENT REGIME

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Earlier work using Rushton turbines and down-(MFD) and up-(MFU) pumping, 45^o-pitched blade turbines at relatively low concentrations of solids of different size and density in vessels up to 1.8 m diameter enabled correlations to be developed for predicting the minimum speed for solid suspension, N_{JSg}. Further work has been conducted with these impellers and with two modern impellers, a Scaba 6SRGT, a typical hollow-blade radial flow impeller and a typical up-pumping, axial flow, wide-blade hydrofoil, the Lightnin' A315, in a vessel of 0.45 m diameter with solids up to 40% by weight. The earlier correlations were validated for the new higher concentration conditions. In all cases, increases in solids concentration increased N_{JSg} and the specific energy dissipation rate required to suspend solids, $(\varepsilon_T)_{JSg}$. On the other hand, the large increase (up to two orders of magnitude) in mixing time found at solids concentration > ~ 15% by weight in two phase systems at N_{JS} as compared to the case without solids, is essentially eliminated in the three phase case. At low gassing rates, Q_{GV} (vvm), down pumping impellers achieve suspension and vertically homogeneous solids distribution at the lowest $(\varepsilon_T)_{JSg}$. However, with increased Q_{GV} up to 3 vvm, N_{JSg} and $(\varepsilon_T)_{JSg}$ increase rapidly, solids maldistribution develops, the flow pattern is very unstable and gross torque fluctuations occur. For the 6SRGT, the operations is very stable and though N_{JSg} and $(\varepsilon_T)_{JSg}$ are both high, they are insensitive to Q_{GV}. This high value of $(\varepsilon_T)_{JSg}$ may not be a disadvantage if high rates of gas-liquid mass transfer are required. For both the 6MFU and especially the A315(U), the flow pattern, N_{JSg} and $(\varepsilon_T)_{JSg}$ are again all very insensitive to Q_{GV} and an homogeneous solids distribution is maintained. For the A315(U), $(\varepsilon_T)_{JSg}$ at high Q_{GV} values is the least amongst the impellers tested, so that wide-blade, up-pumping axial flow hydrofoils are considered to be the optimum impeller when just physical suspension is required or solid-liquid reactions are rate limiting.

Keywords: Solids suspension; gas dispersion; mixing time; mass transfer; impeller choice; scale-up.

INTRODUCTION

Agitated three phase systems (gas dispersion with solid suspension in a liquid) are important industrially for many processes, e.g., catalytic gas-phase reactions and bioleaching of gold ore. The broad-brush issues that need addressing are the choice of agitator type and scale-up. In turn, these topics depend on the ability of different impeller types to disperse gas without flooding and simultaneously suspend solids; on the extent of the spatial distribution of the solids; the homogenisation (mixing time) of the liquid phase; the gas-liquid mass transfer performance in the presence of solids which is intimately connected to the power input from the agitator (or the specific energy dissipation rate, $(\text{å}_T)_g$), so that the gassed power characteristics of the particular impeller type are also important; and the effect of gas on the rate of solid-liquid mass transfer.

This paper is based firstly on earlier work published between 1983-1990 with traditional impellers. These early results are then built on using extensive recent work leading to proposals for the choice of optimum impeller type for these three phase systems and a scale-up strategy. The traditional impellers covered are the radial flow Rushton turbine (RT), the down-pumping 45^o-pitched blade (or mixed-flow) impeller (MFD) with different numbers of blades (4 or 6) and impeller (D)-to-tank-(T) diameter ratio (D/T=0.25 to 0.5) and the equivalent impeller pumping-up (MFU). Of the more modern impellers studied, one is of a radial flow, hollow blade type, viz the Scaba 6SRGT and two are axial flow hydrofoils, the thin-bladed, Chemineer HE3 pumping down, an excellent impeller for solid suspension in two phase systems[1] and the wide-bladed Lightnin A315 pumping-up (an excellent impeller for gas dispersion[2]).

METHODS AND MATERIALS

EXPERIMENTAL

In all the recent three phase work reported here, power input has been measured accurately by strain gauge/telemetry[3] and the speed required to suspend solids, whether the system was gassed or not, has been assessed visually using the 1 to 2 second criterion originally proposed by Zwietering[4]. The vessel size used had standard baffles and was 0.45 m in diameter as was the unaerated liquid height. The impeller sizes are specified in Table 1.

Table 1 Suspension conditions ungassed and gassed for the different impellers in T_{45}.
$(\varepsilon_T)_{JS\ 40\%,\ 0\ vvm}$ or $(\varepsilon_T)_{JS\ 40\%,\ 1.5\ vvm}$ in W/kg (impeller speed in rpm in brackets)

Q_{Gv} [vvm]	SCABA (D/T=0.36)	Rushton (D/T=0.3)	6MFU (D/T=0.5)	6MFD (D/T=0.5)	A315(U) (D/T=0.5)
0	6.4 (722)	10.4 (710)	1.6 (260)	0.84 (246)	1.54 (340)
1.5	6.6 (750)	? (>900)	1.75 (320)	2.1 (413)	1.64 (350)

Mixing times were measured by the iodine/sodium thiosulphate technique[5]. Details of how the proportion of solids in suspension was estimated are given later in the text. Further information is given in the various project reports listed in the references.

RESULTS AND ANALYSIS

GAS DISPERSION AND SOLIDS SUSPENSION CHARACTERISTICS

Down-pumping impellers

All the studies have shown that if the impeller is flooded, then solids cannot be suspended[6-9]. Therefore, for an impeller to be effective for solid suspension under gassed conditions, it must also be a good gas dispersion impeller. Consequently, even though 3 bladed, Chemineer HE3's of D/T = 0.4 have been shown to suspend solids with the lowest specific energy dissipation rates, $(\varepsilon_T)_{JS}$, at D/T ≅ 0.4, they flood very easily. Thus, they were found[8] to require the least energy to suspend glass Ballotini up to a gas flow rate, Q_{GV}, of 0.5 vvm in a vessel, T = 0.29 m, with H = T. However, at higher flow rates, the gas-liquid dispersion was very unstable leading to large torque fluctuations (± 30%) and generally unsatisfactory operating conditions. A similar result was found for small MFD impellers, e.g. 4-bladed, 0.25T and 6 bladed, 0.38T by Chapman *et al.*[6] and Ibrahim[8], respectively.

The performance was much improved if larger, 6-bladed MFD's were employed with D/T = 0.5 (Chapman *et al.*[6]) or 0.52 (Ibrahim[8]) and a large ring sparger, ≅ 0.9D was used. If, when agitating at a speed which just suspends the solids, N_{JS}, a gas flow is begun, the speed is sufficient initially to prevent direct loading of the impeller[10], i.e. the gas is dispersed from the sparger towards the base of the vessel. This dispersion seems to be sufficient to disrupt the regular flow at the base and enables the solids to be suspended at a slightly lower agitator speed, i.e. N_{JSg} is initially lower than N_{JS} up to and including about 0.5 vvm. With a further increase in gassing rate, N_{JSg} has to be increased quite rapidly and again severe torque fluctuations occur (± 30%). Thus, by expressing the gas flow rate in vvm the equation

$$N_{JSg} = N_{JS}(0.83 + 0.31Q_{GV}) \tag{1}$$

for $0.25 \leq Q_{GV} \leq 3.5$ vvm fits the data quite well for vessels up to 1.8 m diameter[8,11] and 40 % solids[9]. N_{JS} is calculated from the Zwietering[4] equation.

Radial flow impellers

Rushton turbines were originally developed for gas dispersion applications[10] and they are generally rather inferior for solid suspension, requiring high values of $(\varepsilon_T)_{JS}$. If, however, they are operating at N_{JS}, the introduction of air leads to the formation of gas filled vortex cavities and a small drop in the liquid flow rate discharged radially from the impeller. This reduction in impeller pumping rate leads in turn to a reduction in liquid velocity near the base and as a result, some solids come out of suspension. Thus, an increase in speed is required to maintain suspension, i.e. $N_{JSg} > N_{JS}$. Further increases in Q_{GV} lead to a growth in cavity size to clinging and then large, 3-3 structures[10], with a commensurate reduction in flow and power leading to the need for a further increase in N_{JSg}. A linear relationship has been found to apply[6,8,11]. Since $(\varepsilon_T)_{JS}$ is less for RT's of D/T = 0.5 compared to D/T = 0.33 (Nienow[1]), so the D/T = 0.5 is also more efficient for three phase systems, giving after combining the data from these three studies

$$N_{JSg} = N_{JS} + 0.85Q_{GV} \tag{2}$$

for vessels up to 1.8m diameter, 20 % solids and 3.5 vvm. Again, N_{JS} can be calculated from the work of Zwietering[4] and Nienow[1]. It is also worth noting that since, as the cavities grow, the power falls typically from an ungassed value, P, to a gassed value, $P_g = 0.5P$, the increase in $(\varepsilon_T)_{JSg}$ compared to $(\varepsilon_T)_{JS}$ is only about 50% for $Q_{GV} = 2.0$ (Ibrahim[8]). A typical data set is shown in Figure 1.

With the Scaba 6SRGT, the hollow blades lead to a very different gassed power characteristic[12]. The initial introduction of gas does not lead to the formation of gas filled cavities but disrupts the smooth flow around the blade so that $P_g \cong 1.1$ P. Possibly, as a result of the extra $(\varepsilon_T)_g$, N_{JSg} is a little less than N_{JS} (see Figure 2). However, overall, increasing Q_{GV} has little effect on P_g ($\cong$ P) or the pumping capacity of the agitator. As a result, N_{JSg} only increases very slightly compared to N_{JS} for solids loading from 10 to 40% (Ciervo[13]).

Up-pumping impellers

Up-pumping impellers, both pitched blade turbines, e.g., 6MFU (Bujalski *et al.*[14]) and especially axial-flow, wide blade, hydrofoils e.g. B2's (Hari-Prajitno *el al.*[15]) are effective at dispersing gas. Both the 6MFU's (Jaworski *et al.*[16]) and hydrofoils (Aubin *et al.*[17]) produce a strong radial component of flow at a clearance off the base, C, of ~ 0.25 to ~ 0.45T. Such a flow pattern also gives a high volumetric flow rate beneath the agitator[18]. However, the local velocities at the base are not so high as when down pumping, so that N_{JS} with the 6MFU is greater than with the 6MFD. On the other hand, when operating at N_{JS} and gas is sparged, the gas-induced liquid flow enhances that produced by the agitator. As a result, there is very little reduction, if any, of volumetric flow at the base. In addition, the formation of gas filled cavities is less with up-pumping than with down-pumping impellers[11]. Therefore, the fall in P_g is reduced. Finally, torque and flow instabilities with 6MFU's are much less than with 6MFD's, very similar to those found with radial impellers.

The overall effect is that 6MFU's are very effective in three phase systems [7,14] with N_{JSg} being rather insensitive to Q_{GV}. Thus, Bujalski *et al.*[11], again using a large sparger ≅ 0.9D with D/T = 0.5 for a 6MFU found:

$$N_{JSg} = N_{JS}(1 + Q_{GV})^{0.11} \qquad (3)$$

for vessels up to 1.8 m diameter and 3.5 vvm. [9] has validated this correlation up to 40 % solids in 0.45 m vessel.

Comparison of performance

Figure 3 compares the sensitivity of N_{JSg} to Q_{GV} for the three traditional impellers RT, 6MFD and 6MFU. Figure 4 and Figure 5 respectively show the insensitivity of N_{JSg} (Monti[19]) and P_g (Hari-Prajitno[2]) to Q_{GV} for the A315(U). The relative performance of these four impellers plus the 6SRGT is also compared in Table 1 and the suspension parameter, S, required to calculate N_{JS} is given in Table 2 for the A315(U) (6.4) and the 6SRGT (9.6).

Table 2 Power number, Po, and S values for the Scaba 6SRGT and the Lightnin' A315(U)

Parameter	SCABA (D/T=0.36)	A315(U) (D/T=0.5)
Po [-]	1.52	0.72
S [-]	9.6 ± 0.17	6.4 ± 0.15

PROPORTION OF SOLIDS SUSPENDED

In addition to N_{JSg}, it is also of interest to know what proportion of solids is suspended at $N < N_{JSg}$ and how sensitive that proportion is to gassing rate. Bujalski *et al.*[20] modified the static head technique of Brucato and Brucato[21] in order to determine this parameter. An U-tube is placed in the vessel and initially the height of liquid in the tube is the same as that in the vessel. As solids become suspended, the height increases by an amount, h. When all are suspended, the increase in height is a maximum, h_{max}, given by the suspension density. The presence of gas does not affect the values of h or h_{max}. Thus, h/h_{max} represents the proportion of solids in suspension.

For the 6SRGT and the 6MFU, the increase in gassing rate had little effect on the proportion of solids suspended. For example, Figure 6a shows data for the 6MFU (Takenaka[9]) and very similar results were obtained for the 6SRGT (Ciervo[13]) (data not shown). It is considered that this insensitivity of the proportion of solids suspended to Q_{GV} can be explained in a similar way to the insensitivity of N_{JSg} to Q_{GV}. This conclusion is supported by the very different solid suspension characteristics found with the 6MFD and RT. Figure 6b shows the results for the 6MFD equivalent to those for the 6MFU (Takenaka[9]). Now, a very significant reduction in proportion of solids suspended with increasing Q_{GV} at a particular speed can be observed. Similar results were found for the RT[13] (data not shown).

SOLIDS DISTRIBUTION AND LIQUID PHASE MIXING

Recent work using a decolorisation technique[20] showed that at solids concentrations > ~ 10% by wt. in solid-liquid systems, the liquid mixing time, θ_m, compared to the single phase was greatly increased. Indeed, the increase in θ_m may be as much as two orders of magnitude whether using down-pumping axial hydrofoils[20] or radial flow[13] 6SRGTs and RT's. The increase is associated with the establishment of a visually-observable clear liquid layer above a relatively-concentrated solid suspension with a sharp interface, height H_i, above the base[22,23]. Without solids, $N\theta_m$ for a particular agitator is constant. A maximum $N\theta_m$ in two phase systems is found when the clear layer is greatest, i.e. H_i is the least[20].

On the other hand, provided the mixing times are compared at equivalent (ε_T) and $(\varepsilon_T)_g$ values, then θ_m in both single liquid phase and two-phase gas-liquid systems is essentially the same, provided, in the gas-liquid case, the impeller is not flooded[10].

In the case of the three-phase system, the gas sparging tends to break-up the formation of the concentrated solid suspension, with bubbles helping transport solids higher up the vessel and enhancing liquid exchange, too. Thus, with the 6SRGT and RT, an increase in mixing time was only found at 30% and 40% solids with a maximum two to three times the single phase case (see Figure 7 for the 6SRGT)[13]. For these impellers once gassed, a clear interface was not observed.

Very similar results were found for the 6MFU and 6MFD[9] and the A315(U)[19] with maximum increases in $N\theta_m$ of 2 to 3 fold. However, with the 6MFD, a solid liquid interface at 40% by wt. glass Ballotini and 1.5 vvm could be seen with $H_i/H \approx 0.6$ even at N_{JSg} in a $T = 0.45$ m vessel[9].

CONSTANT TORQUE AS A PREDICTOR OF N_{JSG}

Pantula and Ahmed[24] have suggested that by adjusting the speed to maintain constant agitator torque on gassing, N_{JSg} would be followed and solid suspension maintained. These recent studies have shown that this concept applies quite well when N_{JSg} is rather insensitive to gassing rate. This insensitivity of N_{JSg} is also associated with P_g being insensitive to Q_{GV} and is particularly found with the 6SRGT, the 6MFU and the A315(U). As an example, Figure 8a shows the relevant data of torque against Q_{GV} for the A315(U)[19]. However, the concept failed for the Rushton turbine[13] and the 6MFD, especially at the highest solids concentration and air flow rate (see Figure 8b as an example[9]).

MASS TRANSFER CHARACTERISTICS

Without solids present, gas-liquid mass transfer rates expressed as k_La were first shown by Van't Riet[25] (and since it has been confirmed by many other workers[10]) to be independent of impeller type. k_La is related to the agitation and gas flow rate conditions by:

$$k_L a = A(\varepsilon_T)_g^{\alpha}(v_s)^{\beta} \tag{4}$$

where v_s is the superficial gas velocity. However, the experimentally-derived constants, A, α and β (and especially A) depend on the liquid composition. Bujalski *et al.*[14] using a two-probe, unsteady state technique validated Equation (4) for both the 6MFD and 6MFU in water and more recently, Vasconcelos *et al.*[26], using the steady state hydrogen peroxide technique, did so for the RT and the up-pumping wide blade Hayward Tyler (formerly APV) B2 hydrofoil.

Chapman *et al.*[27] found Equation (4) applied for three phase systems (water-air-glass beads) for different impeller types. Graves and Loh[28] found a similar result with up to 50 % by wt. Ballotini, even though k_La fell by 50 % compared to water alone. Given the current state of knowledge of k_La in two- and three-phase systems, it seems reasonable to conclude that for a given system, it is independent of impeller type and follows Equation (4).

With respect to solid-liquid reactions, much work indicates that the rate of reaction only increases slowly with $N > N_{JS}$ for systems in which solid-liquid mass transfer controls in two phase systems[1]; or for $N > N_{JSg}$ for three-phase systems[29]. When the solid-liquid reaction is reaction rate controlled, the overall rate does not increase at all beyond N_{JS} or N_{JSg} respectively, i.e. when all the surface area is available for reaction[30].

DISCUSSION AND CONCLUSIONS

Equations have been published previously for calculating the minimum speed for suspending solids up to 10 % by wt. under gassed conditions for RT, 6MFD and 6MFU impellers which have been tested for vessels up to 1.8 m diameter. This recent work, though more limited, indicates that these equations are valid up to 40% by weight of solids. Of these impellers, the 6MFU is least sensitive to aeration rate with respect to flooding[10] and solid suspension. The Scaba 6SRGT (Saito *et al.*[12]) and the up-pumping axial flow hydrofoil, A315 (Hari-Prajitno[2]), are also difficult to flood and lose little power when gassed. Here, it is shown that N_{JSg} is very insensitive to gas flow rate for these two impellers. For all the impellers tested, the very large increase in liquid phase mixing time at high solids concentration found in solid-liquid systems under certain agitation conditions[20] is essentially eliminated when gassing is introduced.

Retrofitting RT's by larger diameter 6SRGT's ($Po \cong 1.5$) or A315's ($Po \cong 0.85$) since they have lower power numbers[10] should enable both impeller types to handle more gas without flooding and with $N_{JSg} \cong N_{JS}$, scale-up and design become relatively easy. Of these two, the 6SRGT has a much higher value of $(\varepsilon_T)_{JSg}$ but if high rates of gas liquid mass transfer along with high gas flow rates are required, it (or another type of hollow blade radial flow agitator) is probably the best option. If solid suspension is all that is required or where the solid-liquid reaction is the rate limiting step, then either the 6MFU, or even better, the A315U (or another wide-blade, axial up pumping hydrofoil) offers distinct energy saving possibilities whilst maintaining equivalent process results. For these latter three impellers, constant torque agitation maintains solids in suspension when gassing.

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NOMENCLATURE

C	impeller clearance of the base	[m]
D	impeller diameter	[m]
h	hydrostatic pressure due to solids being suspended	[mm water]
h_{max}	hydrostatic head when solids all are suspended	[mm water]
H	liquid height	[m]
H_i	height of the cloud/liquid interface	[m]
M	torque	[Nm]
N	speed of the impeller (except when stated as rpm)	[s^{-1}]
P	power input	[W]
Po	power number, $=P/\rho_L N^3 D^5$	[-]
Q_{GV}	gas flow rate	[vvm]
T	diameter of the vessel	[m]
vvm	volume of air/minute per volume of liquid in the vessel	[min^{-1}]
ε_T	specific energy dissipation rate	[Wkg^{-1}]
θ_m	the mixing time	[min or s]
ρ_L	density of liquid	[kgm^{-3}]
ρ_S	density of solids	[kgm^{-3}]

SUBSCRIPTS

g	under gassed conditions
i	interface
JS	at just suspended conditions in ungassed systems
JSg	at just suspended conditions under gassed conditions
max	maximum value of a parameter

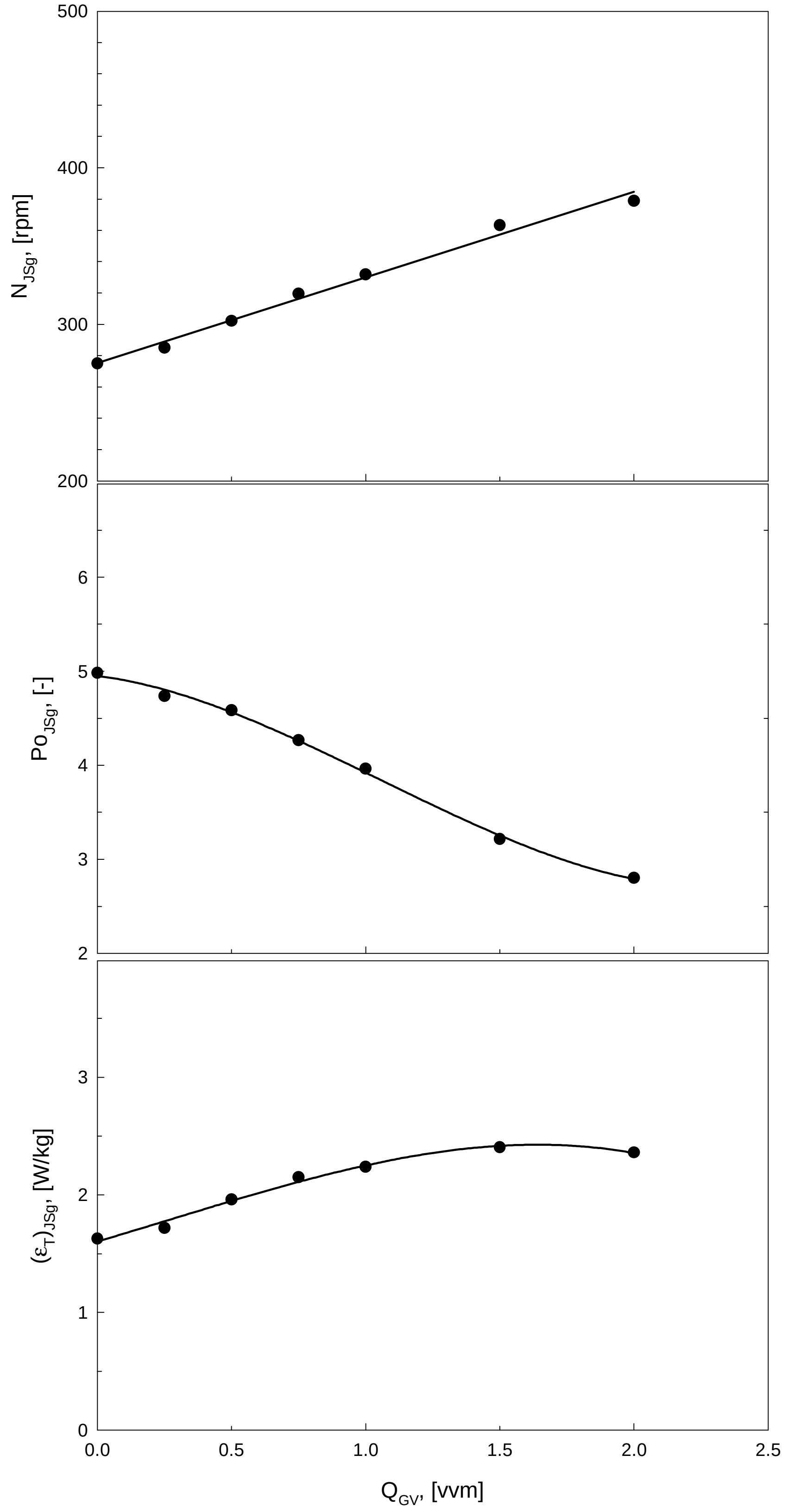

Figure 1 The impact of gassing on the performance of an RT in a three-phase system: a) N_{JSg}; b) Po_{JSg}; c) $(\varepsilon_T)_{JSg}$; (T = 0.29 m; D/T = 0.5; C = T/4; 0.5% by wt., 650 μm glass Ballotini) (Ibrahim)[8].

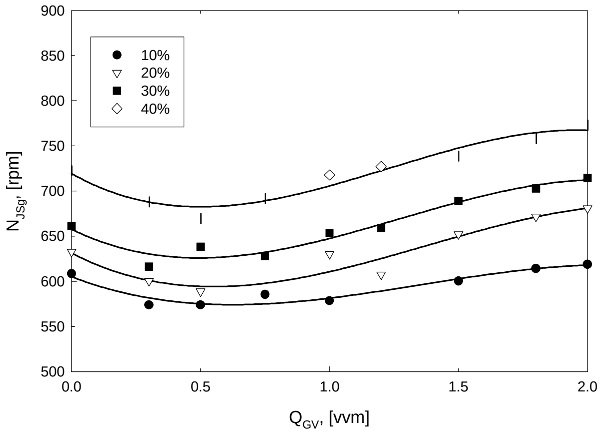

Figure 2 The impact of gassing on N_{JSg} for a Scaba 6SRGT (T = 0.45 m; D/T = 0.36; C = T/4, 255 μm glass Ballotini) (Ciervo[13]).

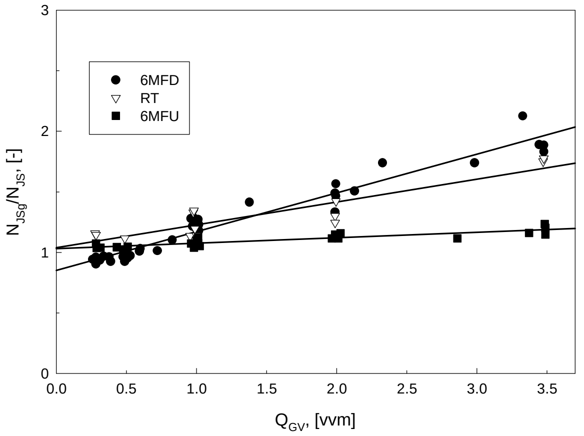

Figure 3 The impact of gassing on N_{JSg} for an RT, 6MFD and 6MFU (D/T = 0.5; C/T = 0.25; 1 % glass Ballotini for vessels of 0.29, 0.45 and 0.61 m diameter) (Bujalski *et al.*[11]).

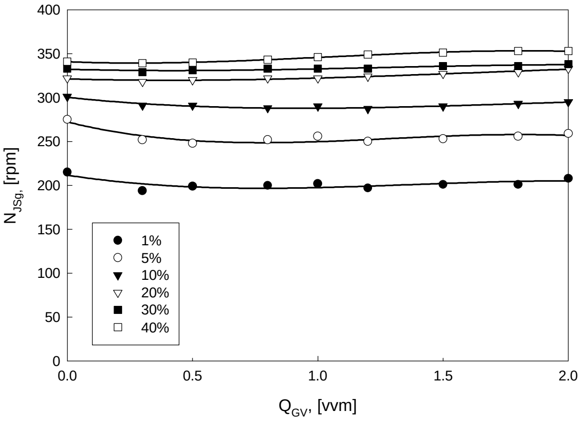

Figure 4 N_{JSg} versus Q_{GV} for a Lightnin A315 pumping up (T = 0.45 m; D/T = 0.5; C = T/4; 255 μm glass Ballotini) (Monti[19]).

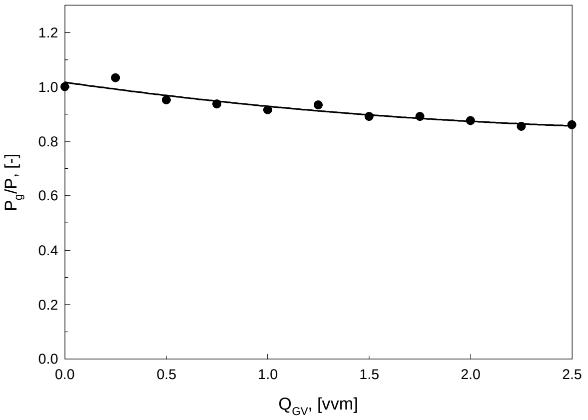

Figure 5 Gassed power characteristic in water for a Lightnin A315(U) (T = 0.61m, D/T =0.43; C/T = 0.25; (ε_T) = 1 W/kg; N = 263 rpm) (Hari-Prajitno[2]).

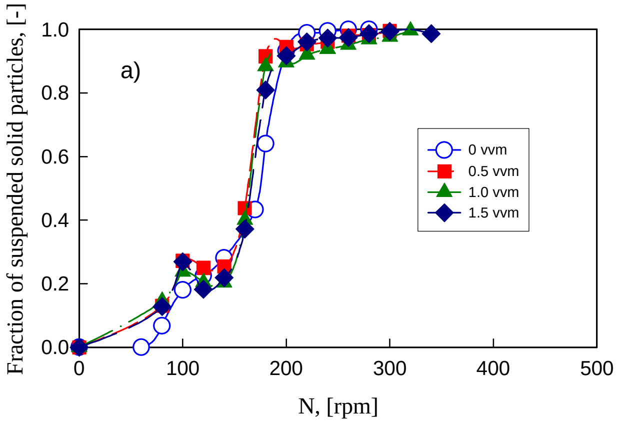

Figure 6 The influence of operating conditions on the proportion of solids suspended in water: a) 6MFU; b) 6MFD (T = 0.45m; D/T = 0.5; C/T = 0.25; 40 % by wt., 255 μm glass Ballotini) (Takenaka[9]).

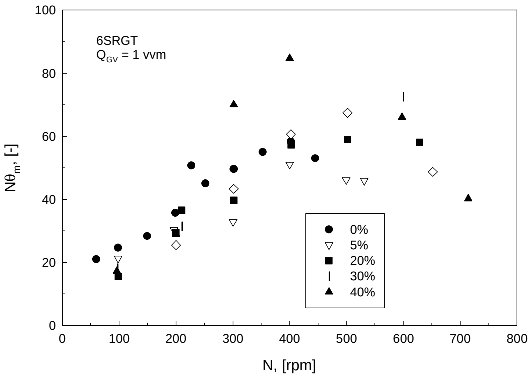

Figure 7 Impact of solids (255 μm glass Ballotini) on mixing time in water with 6SRGT at Q_{GV} = 1.0 vvm (T = 0.45m; D/T = 0.36; C = T/4) (Ciervo[13]).

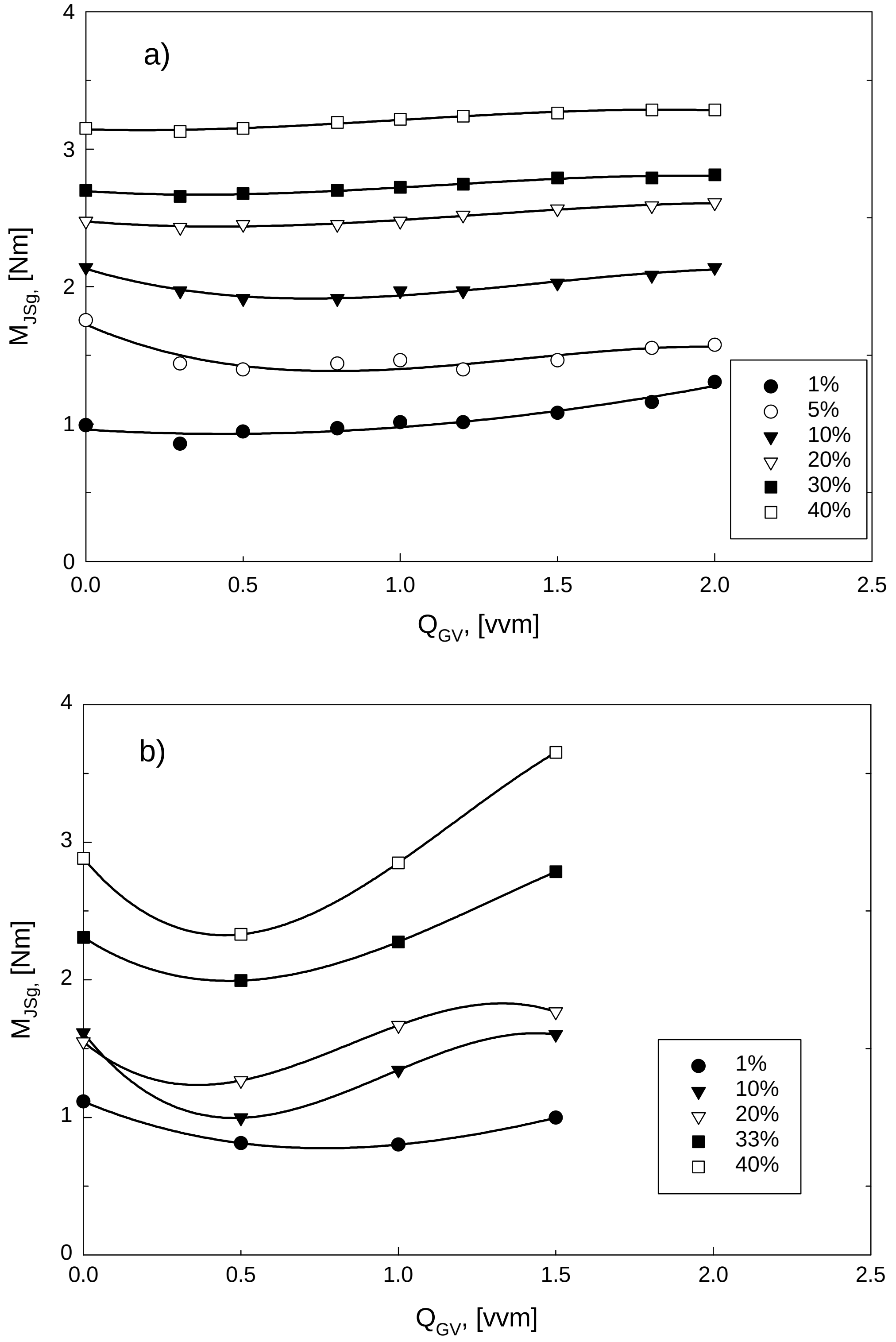

Figure 8 The torque, M_{JSg}, require to keep solids in suspension in water under gassed conditions (T = 0.45m; D/T = 0.5; C/T = 0.25; 255 µm glass Ballotini): a) A315(U) (Monti[19]); b) 6MFD (Takenaka[9]).

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