Cite this article as: Ibrahim, S., Wong, S. D., Baker, I. F., Zamzam, Z., Sato, M., & Kato, Y. (2015). Influence of geometry and slurry properties on fine particles suspension at high loadings in a stirred vessel. *Chemical Engineering Research and Design*, *94*, 324-336. DOI: http://doi.org/10.1016/j.cherd.2014.08.008

Influence of geometry and slurry properties on fine particles suspension at high loadings in a stirred vessel

S. Ibrahim[a,*], S.D. Wong[a], I.F. Baker[a], Z. Zamzam[b], M. Sato[b], Y. Kato[b]

a Department of Civil Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia
b Mixing Technology Laboratory, SATAKE Chemical Equipment MFG. LTD., Japan

Highlights

- Suspension of fine low-density particles at high solids loading in a stirred reactor.
- Comparing the performance of SUPERMIX® axial and radial impellers to conventional geometries.
- Effects of fine particle size, solids loading and impeller clearance on just-suspension energy.

Abstract

Particle size, solids loading and impeller clearance from the base were all found to have significant effects on the just-suspension of fine particles in a stirred tank. At the higher end of particles size studied, where there is greater difference in settling velocities between particle sizes, the smaller the particles the less specific energy, ε_{js} is required for just-suspension. But at the low end of particle size range, changes in the settling velocity are small while continued reduction in particle size corresponds to substantial increase in total particle surface area, leading to increased ε_{js} possibly due to particles interactions. Just-suspension of PMMA particles of diameter 195.5 µm required higher ε_{js} than for 75.3 µm particles, whereas ε_{js} for 75.3 µm particles was lower than that for 18.0 µm diameter particles. Experiments were conducted in water in a 15.5 cm cylindrical tank at an aspect ratio of 1:1 over a range of loadings from 5 to 40% by weight. The HR100 and HS604 SUPERMIX® impellers manufactured by SATAKE, generally showed better efficiencies compared to the conventional 4 pitched-blade turbine and 3-blade propeller, in addition to being less affected by changes in operational parameters. The HS604 performance proved that a radial impeller can be comparable to or better than a downward axial impeller in solid–liquid suspension if used at very low clearance. *S* factor values under different experimental conditions are presented.

Keywords

- Fine particles;
- SUPERMIX® impellers;
- High solids loading;
- Particle size;
- Impeller clearance;
- Just-suspension

Nomenclature

c_w
solids loading (%)

N_{js}
just-suspension speed

ε_{js}
power per unit mass of slurry (W/kg)

N_p	power number
b_w	baffle width
wt%	weight percent
vol%	volumetric percent
ρ_s	solid density (kg m^{-3})
ρ_l	liquid density (kg m^{-3})
C	off-bottom clearance
D	impeller diameter (cm)
H	mixing height (cm)
S	Zwietering's N_{js} coefficient
T	tank diameter (cm)
V_y	terminal velocity (m s^{-1})
d_p	particle diameter (µm)
$d_{18.0}$	solid particles with diameter 18.0 µm
$d_{75.3}$	solid particles with diameter 75.3 µm
$d_{195.5}$	solid particles with diameter 195.5 µm

1. Introduction

The suspension of solids in stirred tanks is governed by various parameters, namely the impeller-to-tank configuration, solids loading and solid/liquid properties. Changes in these variables will affect the speed and energy required to achieve the desired level of suspension; and there are multitude possible combinations of these parameters.

Zwietering's (1958) pioneering work to obtain an empirical correlation relating the just-suspension speed, N_{js} to other variables, is arguably the most highly cited literature on the subject. Subsequent studies using glass beads (Nienow, 1968 ; Ibrahim and Nienow, 1996), quartz (Rao et al., 1988), bronze particles (Machado et al., 2012), ion exchange resins (Ayranci and Kresta, 2011), lead shots and the neutrally buoyant Cytodex microcarrier particles (Ibrahim and Nienow, 1996 ; Ibrahim and Nienow, 2004) have shown the range over which Zwietering's correlation can be applied; and alternative correlations have also been proposed.

Cite this article as: Ibrahim, S., Wong, S. D., Baker, I. F., Zamzam, Z., Sato, M., & Kato, Y. (2015). Influence of geometry and slurry properties on fine particles suspension at high loadings in a stirred vessel. *Chemical Engineering Research and Design*, *94*, 324-336. DOI: http://doi.org/10.1016/j.cherd.2014.08.008

In scaling up or changing from one system to another, the power or specific energy at just-suspension, ε_{js} has been commonly used to compare the efficiencies of different systems. Nienow and Miles (1977) reported that specific power for just suspension was always less in larger vessels of geometrically similar impeller to tank configuration. Ochieng and Lewis (2006) stressed that while bulk fluid flow represented by impeller tip speed may cause particles suspension at low solids loadings, turbulence intensity is what governs the particles suspension at high loadings, thus the use of power per unit volume as a scale up factor is recommended. Bubbico et al. (1998) explained that particles gain kinetic energy as they are moved by stirring, and this energy is dissipated in particle–liquid friction and particle–particle or particle–equipment collisions; causing either attrition of the particles or elastic deformation that will release heat energy when the particles recover their shape. Ayranci and Kresta (2011) explained that hard particles can transfer momentum through collisions, while introducing a second solid phase in the system would significantly affect the suspension, especially in mixtures above 20 wt% solids as the particle–particle interactions becomes important. For bimodal solids in liquid Ayranci et al. (2012) proposed a new power model to predict N_{js} for solid particles of different physical properties with experiments up to 27 wt%, when the Zwietering correlation could only give accurate prediction up to 10%. In ultra-high solids loading (50 vol%), Wang et al. (2012) reported that similar amount of specific energy is required to suspend 70 µm and 120 µm particles.

On the effect of geometry, Nienow and Miles (1977) found with the radial Rushton and 2-flat blade paddles, that larger impellers and lower clearances were more efficient for suspension. And the 45° pitched-blade impellers were better than the radial impellers. Armenante and Nagamine (1998) stated that axial and mixed-flow impellers are more energy efficient to suspend particles as compared to radial-flow impellers. But Wu et al. (2002) found that at high solids loading it was more efficient to use radial flow impellers, particularly with unbaffled tanks. Chapple et al., 2002 reported the pitched blade geometry having strong interactions with the tank walls, such that changes in the impeller position can have a significant impact on the power number, as opposed to a radial impeller for which form drag dominates the power consumption, hence the impeller details are important.

Kumaresan and Joshi (2006) using hydrofoils, pitched blade and disc turbines, reported how the flow patterns generated from varying the impeller design, impeller diameter, number of blades, blade angle, blade width, blade twist, and pumping direction can have impact on suspension; and suggested tailoring the flow pattern to enhance mixing. Jirout and Rieger (2011) reported that all hydrofoils have similar efficiency when compared at optimum clearance, and they are more efficient than the standard 45° pitched-blade impellers which are more sensitive to changes in impeller clearance. They also found that the pitch angle for pitched-blade impellers has minimum effect on the suspension efficiency in the region of relatively fine particles. Ayranci et al. (2012), employing two Lightnin A310 impellers of diameters of $T/3$ and $T/2$ discovered that turbulence is dominant for suspending solids with the $T/3$ impeller while for the $T/2$ impeller some combination of turbulence and mean flow is required; and the former is more efficient in solids suspension.

This work employs lightweight PMMA particles of diameters lower than those usually studied, over a wide range of loadings from 5 to 40 wt% by weight, using SATAKE SUPERMIX® impellers and the conventional pitched-blade and 3-blade propeller in a 15.5 cm cylindrical tank. The objective is to obtain data on solids suspension requirements under those conditions not reported before.

2. Materials and methods

Experiments were carried out in a fully baffled cylindrical, flat-based transparent Perspex tank of internal diameter, T = 15.5 cm. The tank was placed in a rectangular tank that was filled with water to allow undistorted view of the stirred tank content. A mirror placed at a 30° angle below the tank facilitates visual observation of the tank base in ascertaining the state of particles suspension. The visual observation was additionally aided with the shine of a white LED lights, a 10× magnifier and glare-shades to reduce reflection.

The solids employed were poly(methyl methacrylate) (PMMA) particles of density, $\rho_s = 1300$ kg m^{-3} and Sauter Mean diameters 18.0 µm, 75.3 µm and 195.5 µm (hereinafter referred to as $d_{18.0}$, $d_{75.3}$ and $d_{195.5}$, respectively), while the liquid was tap water ($\rho_l = 1000$ kg m^{-3}). The Sauter Mean diameter of the PMMA particles (Refractive Index 1.49) is measured with a Malvern Mastersizer (Hydro MU 2000). Microscopic images of the particles presented in Fig. 1, show that the particles are spherical. The solids loadings were 5%, 10%, 15%, 20%, 30% and 40%, all by weight. Particle and slurry properties are provided in Table 1a ; Table 1b.

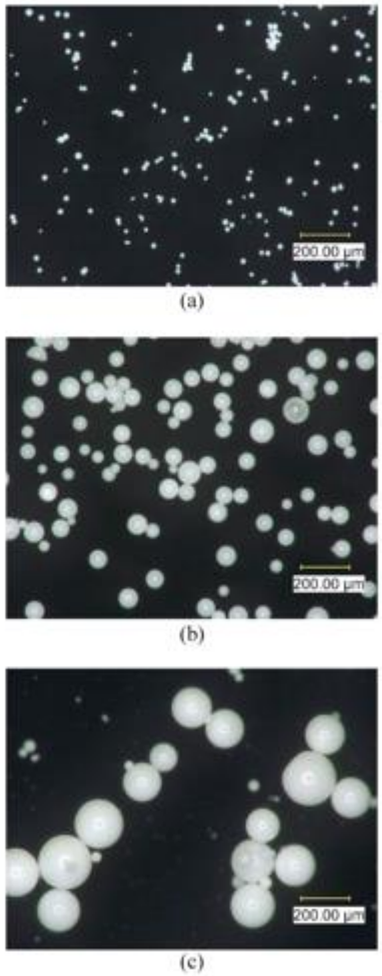
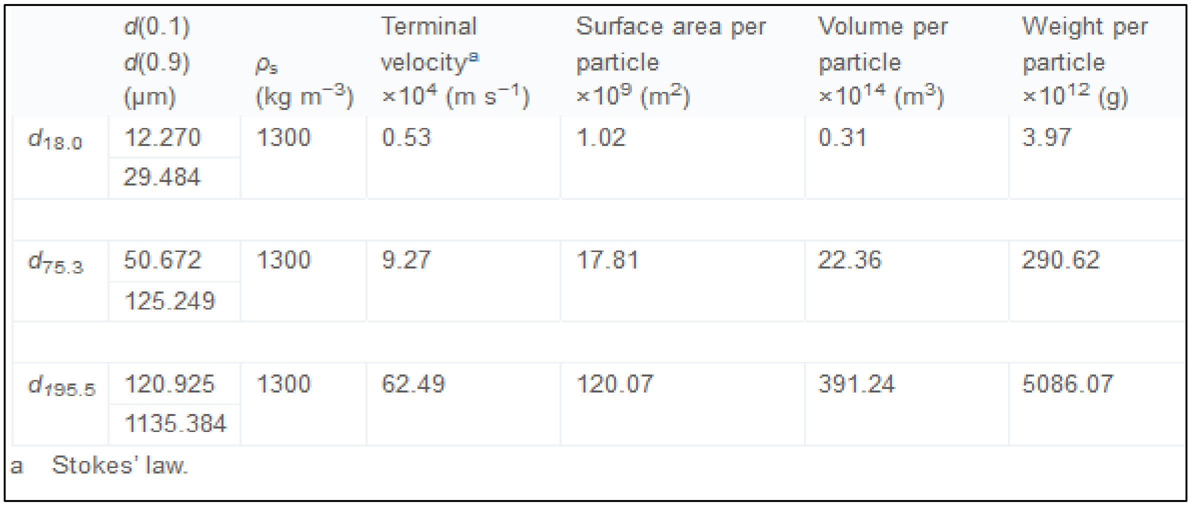


Fig. 1. Microscopic images of PMMA particles (a) 18.0 µm; (b) 75.3 µm; (c) 195.5 µm.
Provided by SATAKE

Cite this article as: Ibrahim, S., Wong, S. D., Baker, I. F., Zamzam, Z., Sato, M., & Kato, Y. (2015). Influence of geometry and slurry properties on fine particles suspension at high loadings in a stirred vessel. *Chemical Engineering Research and Design*, *94*, 324-336. DOI: http://doi.org/10.1016/j.cherd.2014.08.008

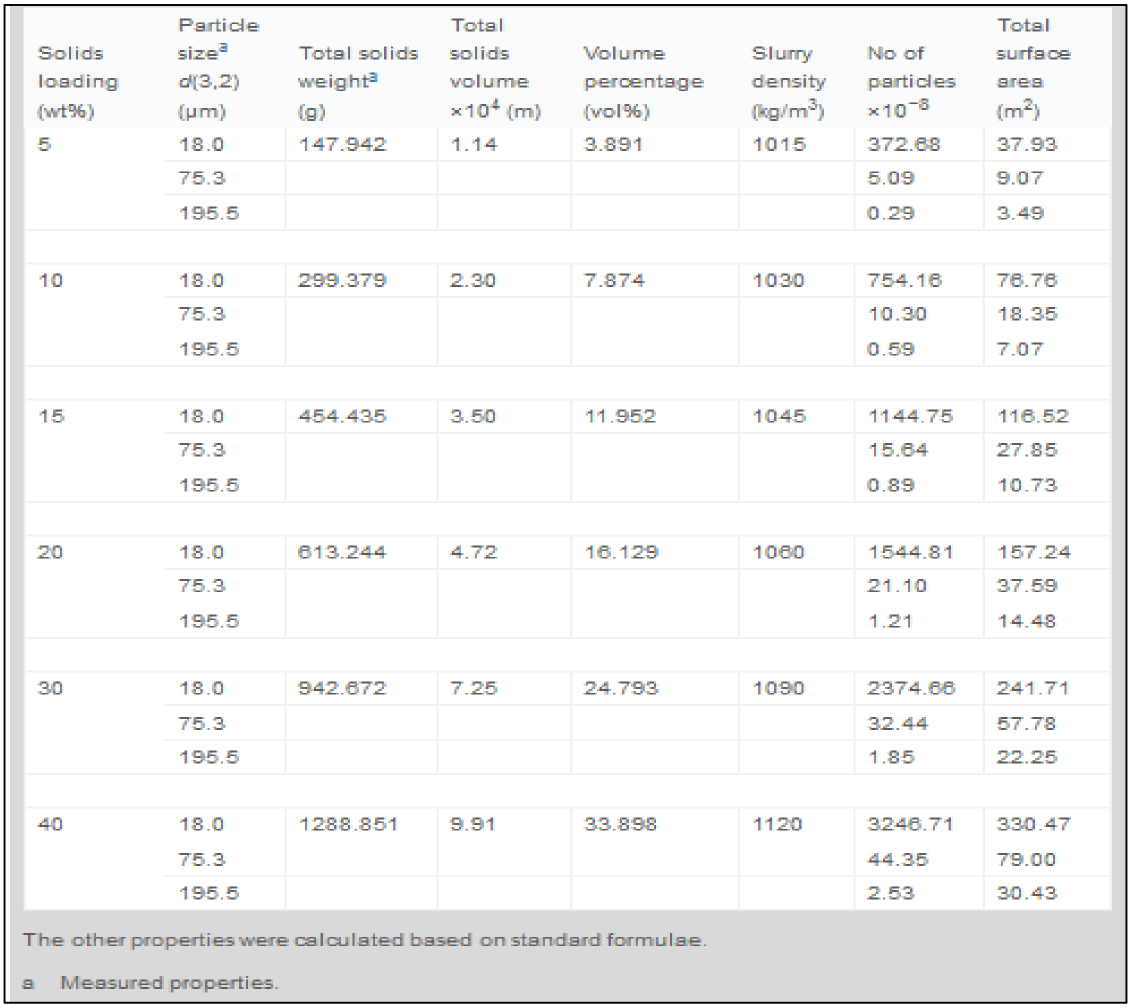
Table 1a. Properties of solid particles.



	d(0.1) *d*(0.9) (μm)	ρ_s (kg m^{-3})	Terminal velocity[a] ×10^4 (m s^{-1})	Surface area per particle ×10^9 (m^2)	Volume per particle ×10^{14} (m^3)	Weight per particle ×10^{12} (g)
$d_{18.0}$	12.270 29.484	1300	0.53	1.02	0.31	3.97
$d_{75.3}$	50.672 125.249	1300	9.27	17.81	22.36	290.62
$d_{195.5}$	120.925 1135.384	1300	62.49	120.07	391.24	5086.07

a Stokes' law.

Table 1b. Slurry properties.



Solids loading (wt%)	Particle size[a] *d*(3,2) (μm)	Total solids weight[a] (g)	Total solids volume ×10^4 (m)	Volume percentage (vol%)	Slurry density (kg/m^3)	No of particles ×10^{-8}	Total surface area (m^2)
5	18.0	147.942	1.14	3.891	1015	372.68	37.93
	75.3					5.09	9.07
	195.5					0.29	3.49
10	18.0	299.379	2.30	7.874	1030	754.16	76.76
	75.3					10.30	18.35
	195.5					0.59	7.07
15	18.0	454.435	3.50	11.952	1045	1144.75	116.52
	75.3					15.64	27.85
	195.5					0.89	10.73
20	18.0	613.244	4.72	16.129	1060	1544.81	157.24
	75.3					21.10	37.59
	195.5					1.21	14.48
30	18.0	942.672	7.25	24.793	1090	2374.66	241.71
	75.3					32.44	57.78
	195.5					1.85	22.25
40	18.0	1288.851	9.91	33.898	1120	3246.71	330.47
	75.3					44.35	79.00
	195.5					2.53	30.43

The other properties were calculated based on standard formulae.

a Measured properties.

The cylindrical tank was filled with the mixture of water and PMMA particles of a given solids loading, to a total height equal to the tank inner diameter, giving an aspect ratio of 1:1.

The N_{js} determination was based on Zwietering's (1958) criterion, who described, "*It was difficult to determine this point exactly and objectively, because even at high stirrer speed streaks of solid particles are always visible at the bottom. At the border between incomplete and complete suspension there are particles which settle temporarily at the bottom and remain for a short time in a fixed position relative to each other. When such a small pile remained* ***at rest*** *longer than 1 or 2 seconds before being broken up the suspension was judged incomplete*".

In order to reach N_{js} in this work, the impeller speed was slowly increased while particles movement on the tank base were scrutinized through the inclined mirror. When the bed is mostly lifted, the last layer of particles remaining on the base tended to suspend and settle at a steady rate, as implied by Zwietering (1958). The speed had to be increased further slightly to ensure particles were resuspended from the base within 1–2 s. Due to the subjective nature of this method, a variation of ±5 to 10 rpm in N_{js} is acceptable.

The stirrer motor is connected to an inbuilt SATAKE mixing torque transducer ST-3000II and the impeller speed could be adjusted over the range 10–1500 rpm. A 10 min average of the torque value is measured at N_{js}, to calculate power and specific energy, ε_{js} (W/kg), which are used in the plots to compare the effects under different conditions.

The impellers employed (Fig. 2) are down-pumping 4PBT with four 45° pitched blades, 3-blade propeller (3P), and two SUPERMIX® impellers from SATAKE Chemical Equipment MFG. LTD., namely the axial HR100 and radial HS604. Specifications of the impellers are as given in Table 2. Except for the HS604 which was used at clearance $C/D = 0.04$, all the other impellers were used at four different clearances of $C/D = 0.25$, 0.5, 0.75, and 1.0.

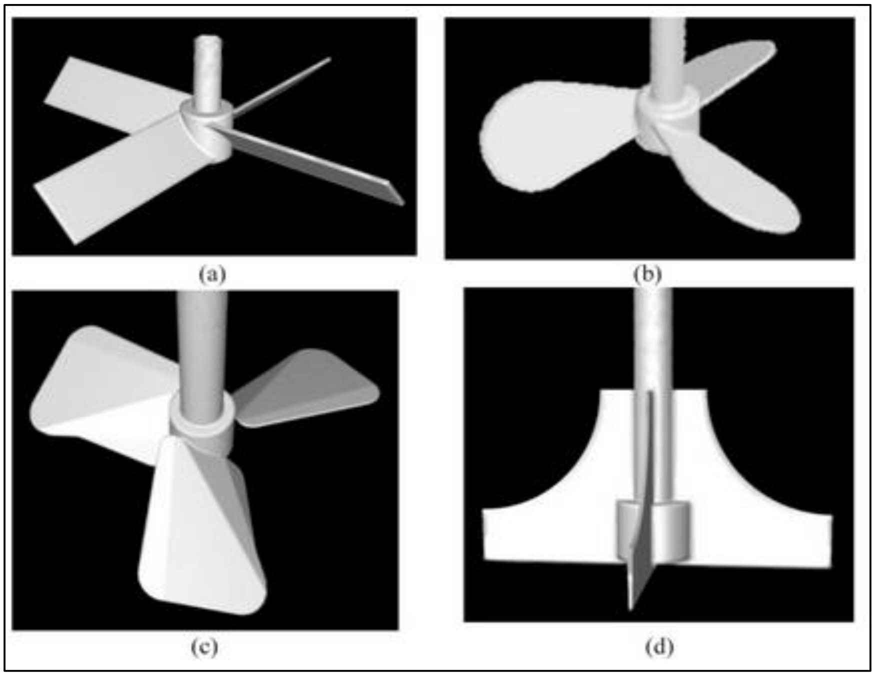
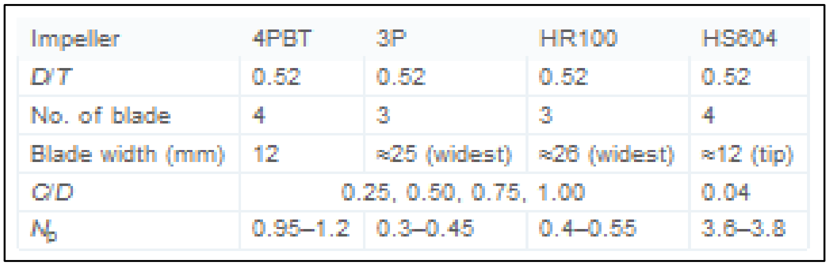


Fig. 2. Impellers (a) 4PBT; (b) 3P; (c) HR100; (d) HS604.

Table 2. Impeller specifications.



Impeller	4PBT	3P	HR100	HS604
D/T	0.52	0.52	0.52	0.52
No. of blade	4	3	3	4
Blade width (mm)	12	≈25 (widest)	≈26 (widest)	≈12 (tip)
C/D	0.25, 0.50, 0.75, 1.00			0.04
N_p	0.95–1.2	0.3–0.45	0.4–0.55	3.6–3.8

The HR100 is a unique design of 3 angular blades that are wider at the tips, diagonally and progressively bent from the mid-width towards the front side to create a “tapering inclination angle”. The HR100 geometry produces low shear with high downward discharge, and is recommended for uniform suspension of fragile or lightweight particles and emulsified micro-capsules.

HS604 is a four-blade impeller that must be mounted very close to the base to create strong radial flow on the tank floor. The flow continues forcefully upwards along the tank wall and return to the impeller from the top through the centre. The effect is a large circulation loop from a strong discharge flow, which ensures flow stability in the stirred tank even if liquid surface changes. This enhances uniformity of solids distribution in a solid–liquid system. Its unique but relatively simple blade profile and very low clearance mounting make the HS604 ideal for processes that requires uniformity and when liquid level changes are critical.

3. Results and discussion

In solid–liquid mixing the main task for the impeller is to create flow with sufficient energy to lift all the particles from the tank bottom and sustain them in suspension. Although the general effects of the variables can be predicted, such as ε_{js} increasing with higher solids loading or higher impeller clearance, the extent of the effects vary considerably depending on the condition or values of other influencing parameters. For example, to what extent solids loading affects suspension will depend on the impeller geometry, clearance, and the particle size. Hence, under any condition there is a combined influence of all the parameters.

Table 3 ; Table 4 show the N_{js} and ε_{js} values under all the experimental conditions. Selected cases are graphically presented to illustrate the effects of the different parameters.

Cite this article as: Ibrahim, S., Wong, S. D., Baker, I. F., Zamzam, Z., Sato, M., & Kato, Y. (2015). Influence of geometry and slurry properties on fine particles suspension at high loadings in a stirred vessel. *Chemical Engineering Research and Design*, *94*, 324-336. DOI: http://doi.org/10.1016/j.cherd.2014.08.008

Table 3. N_{js} (rpm) under different experimental conditions.

C/D	wt%	4PBT			3P (d80)			HR100			HS604		
		$d_{18.0}$	$d_{75.3}$	$d_{195.5}$	$d_{18.0}$	$d_{75.3}$	$d_{195.5}$	$d_{18.0}$	$d_{75.3}$	$d_{195.5}$	$d_{18.0}$	$d_{75.3}$	$d_{195.5}$
0.04	5										125	100	140
	10										135	115	155
	15										145	125	170
	20										160	135	175
	30										180	150	190
	40										215	205	220
0.25	5	160	145	165	195	195	185	175	155	165			
	10	185	165	205	240	210	230	190	165	185			
	15	195	175	235	250	225	235	210	180	205			
	20	210	180	265	260	235	250	225	200	235			
	30	240	190	310	280	265	305	250	225	295			
	40	265	200	345	295	275	400	270	240	375			
0.5	5	170	135	160	245	185	235	200	165	190			
	10	195	145	195	285	200	290	230	175	240			
	15	220	155	225	320	210	310	255	195	250			
	20	240	160	260	345	225	375	280	215	275			
	30	270	175	305	370	245	420	310	240	330			
	40	290	180	335	405	265	440	340	250	390			
0.75	5	210	195	230	290	220	260	235	190	215			
	10	235	220	280	330	250	330	265	195	265			
	15	270	225	310	370	265	340	295	205	280			
	20	295	245	340	395	285	390	325	235	315			
	30	340	270	435	425	305	450	360	250	375			
	40	390	280	510	475	340	510	400	285	420			
1.00	5	255	255	275	385	305	345	245	205	230			
	10	285	260	360	430	320	410	275	210	280			
	15	325	265	405	475	340	440	310	240	295			
	20	375	285	440	510	390	510	340	250	325			
	30	430	335	555	555	430	650	380	275	395			
	40	485	350	680	600	465	790	425	305	490			

Table 4. Comparing ε_{js} ×10 (W/kg) under different experimental conditions.

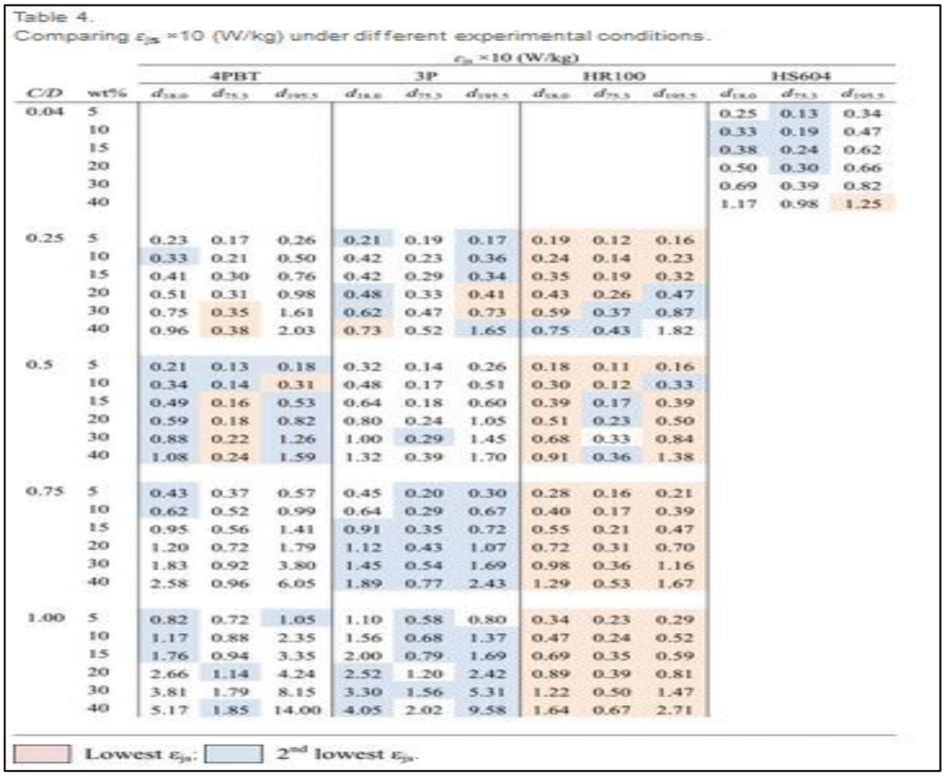


Table 4.

Comparing ε_{js} ×10 (W/kg) under different experimental conditions.

		ε_{js} ×10 (W/kg)											
		4PBT			3P			HR100			HS604		
C/D	wt%	$d_{18.0}$	$d_{75.3}$	$d_{195.5}$	$d_{18.0}$	$d_{75.3}$	$d_{195.5}$	$d_{18.0}$	$d_{75.3}$	$d_{195.5}$	$d_{18.0}$	$d_{75.3}$	$d_{195.5}$
0.04	5										0.25	0.13	0.34
	10										0.33	0.19	0.47
	15										0.38	0.24	0.62
	20										0.50	0.30	0.66
	30										0.69	0.39	0.82
	40										1.17	0.98	1.25
0.25	5	0.23	0.17	0.26	0.21	0.19	0.17	0.19	0.12	0.16			
	10	0.33	0.21	0.50	0.42	0.23	0.36	0.24	0.14	0.23			
	15	0.41	0.30	0.76	0.42	0.29	0.34	0.35	0.19	0.32			
	20	0.51	0.31	0.98	0.48	0.33	0.41	0.43	0.26	0.47			
	30	0.75	0.35	1.61	0.62	0.47	0.73	0.59	0.37	0.87			
	40	0.96	0.38	2.03	0.73	0.52	1.65	0.75	0.43	1.82			
0.5	5	0.21	0.13	0.18	0.32	0.14	0.26	0.18	0.11	0.16			
	10	0.34	0.14	0.31	0.48	0.17	0.51	0.30	0.12	0.33			
	15	0.49	0.16	0.53	0.64	0.18	0.60	0.39	0.17	0.39			
	20	0.59	0.18	0.82	0.80	0.24	1.05	0.51	0.23	0.50			
	30	0.88	0.22	1.26	1.00	0.29	1.45	0.68	0.33	0.84			
	40	1.08	0.24	1.59	1.32	0.39	1.70	0.91	0.36	1.38			
0.75	5	0.43	0.37	0.57	0.45	0.20	0.30	0.28	0.16	0.21			
	10	0.62	0.52	0.99	0.64	0.29	0.67	0.40	0.17	0.39			
	15	0.95	0.56	1.41	0.91	0.35	0.72	0.55	0.21	0.47			
	20	1.20	0.72	1.79	1.12	0.43	1.07	0.72	0.31	0.70			
	30	1.83	0.92	3.80	1.45	0.54	1.69	0.98	0.36	1.16			
	40	2.58	0.96	6.05	1.89	0.77	2.43	1.29	0.53	1.67			
1.00	5	0.82	0.72	1.05	1.10	0.58	0.80	0.34	0.23	0.29			
	10	1.17	0.88	2.35	1.56	0.68	1.37	0.47	0.24	0.52			
	15	1.76	0.94	3.35	2.00	0.79	1.69	0.69	0.35	0.59			
	20	2.66	1.14	4.24	2.52	1.20	2.42	0.89	0.39	0.81			
	30	3.81	1.79	8.15	3.30	1.56	5.31	1.22	0.50	1.47			
	40	5.17	1.85	14.00	4.05	2.02	9.58	1.64	0.67	2.71			

🟥 Lowest ε_{js}; 🟦 2^{nd} lowest ε_{js}.

Cite this article as: Ibrahim, S., Wong, S. D., Baker, I. F., Zamzam, Z., Sato, M., & Kato, Y. (2015). Influence of geometry and slurry properties on fine particles suspension at high loadings in a stirred vessel. *Chemical Engineering Research and Design*, *94*, 324-336. DOI: http://doi.org/10.1016/j.cherd.2014.08.008

3.1. Effect of solids loading

In a tank of fixed operating volume, higher solids loading means higher slurry mass that the impeller has to pump and keep in suspension; which would naturally require higher speed and energy since power is directly related to the slurry density. But Bubbico et al. (1998) stated that prediction of the suspension power cannot depend on the suspension density alone, because the solid phase is in fact responsible for the dissipation of the supplied energy through solid–liquid friction and particle collisions. Ayranci and Kresta (2011) reported for binary solids mixture that particle–particle interactions dominate at very high solids loading of >25 wt%, leading to significant increase in specific energy requirement.

Fig. 3(a)–(c) shows ε_{js} increasing with solids loading for 3P and HR100 at C/D = 0.5 and 1.0, and the effect is greater with the 3P at a higher clearance and for $d_{195.5}$, the largest particles used, with an increase in ε_{js} of more than 10 times in going from 5% to 40% loading. Correspondingly the N_{js} also increases with solids loading as shown in Fig. 4(a) for 3P and HR100 with $d_{195.5}$, and Fig. 4(b) for HS604. The increase in solids loading for any given particle size and density means an increase in the number of particles and the total particles surface area; and this can subsequently lead to higher particle–particle interactions, as suggested by previous workers. Table 1b shows the increase in number of particles and total surface area associated with each particle size, as the solids loading is increased for the cases studied here. The more pronounced effect of solids loading at a higher clearance for 3P can be attributed to greater momentum loss, as the fluid has to be pumped a greater distance, while having to sustain the suspension of higher mass of particles. Solids loading effects are generally less drastic with the medium-sized $d_{75.3}$ particles except with the HS604 that was used at a very low clearance. More on the effects of clearance, particle size and impeller geometry are discussed below.

Cite this article as: Ibrahim, S., Wong, S. D., Baker, I. F., Zamzam, Z., Sato, M., & Kato, Y. (2015). Influence of geometry and slurry properties on fine particles suspension at high loadings in a stirred vessel. *Chemical Engineering Research and Design*, *94*, 324-336. DOI: http://doi.org/10.1016/j.cherd.2014.08.008

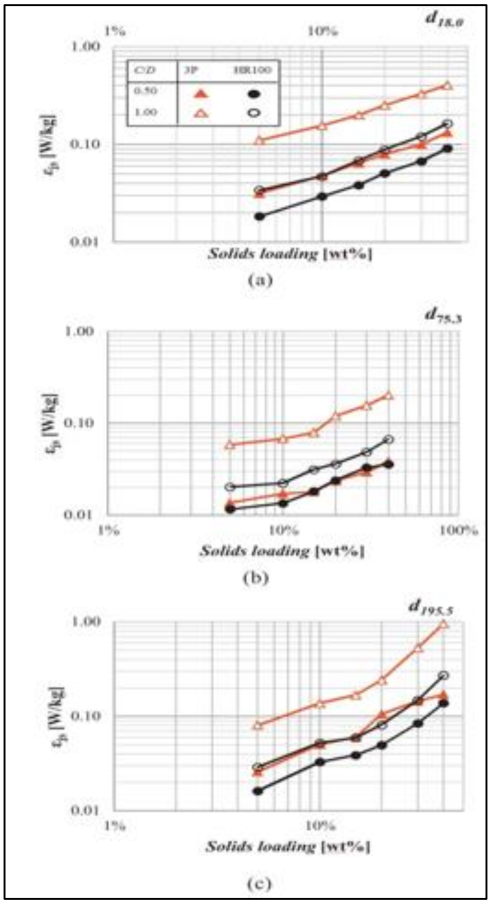


Fig. 3. The effect of concentration on specific energy ε_{js} (W/kg) at just suspension for HR100 and 3P.

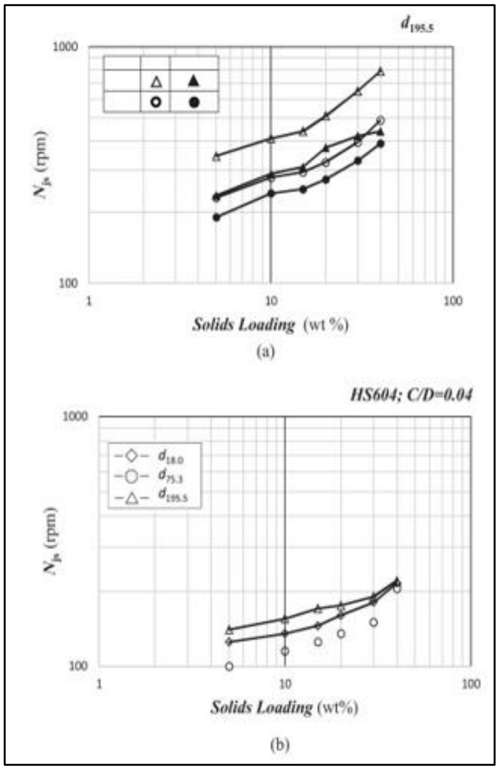


Fig. 4. The effect of solids loading on just suspension speed, Njs (rpm) for (a) 3P and HR100 with d195.5, (b) HS604.

3.2. *Effect of particle size*

All the impellers are affected by changes in particle size, as shown in Table 3 ; Table 4. ε_{js} for 3P and 4PBT can increase by more than 300% in going from $d_{75.3}$ to $d_{195.5}$ at high solids loadings and high impeller clearance. Interestingly, while the highest N_{js} and ε_{js} are needed to suspend the largest particles, i.e. $d_{195.5}$, the next highest N_{js} and ε_{js} are required by the smallest particles, $d_{18.0}$, and the lowest N_{js} and ε_{js} are for the middle-sized $d_{75.3}$ particles. In other words, going from $d_{75.3}$ to $d_{18.0}$ corresponds to an increase in N_{js} and ε_{js}; and ε_{js} for the $d_{18.0}$ could be twice as high as that for $d_{75.3}$.

Plots of ε_{js} as a function of particle diameter given in Fig. 5(a)–(e) for the 3P and HR100 impellers at C/D = 0.25 and 0.75, and the HS604 at C/D = 0.04 show minimum points occurring at the middle particle diameter of $d_{75.3}$, although the effect is relatively less for HS604.

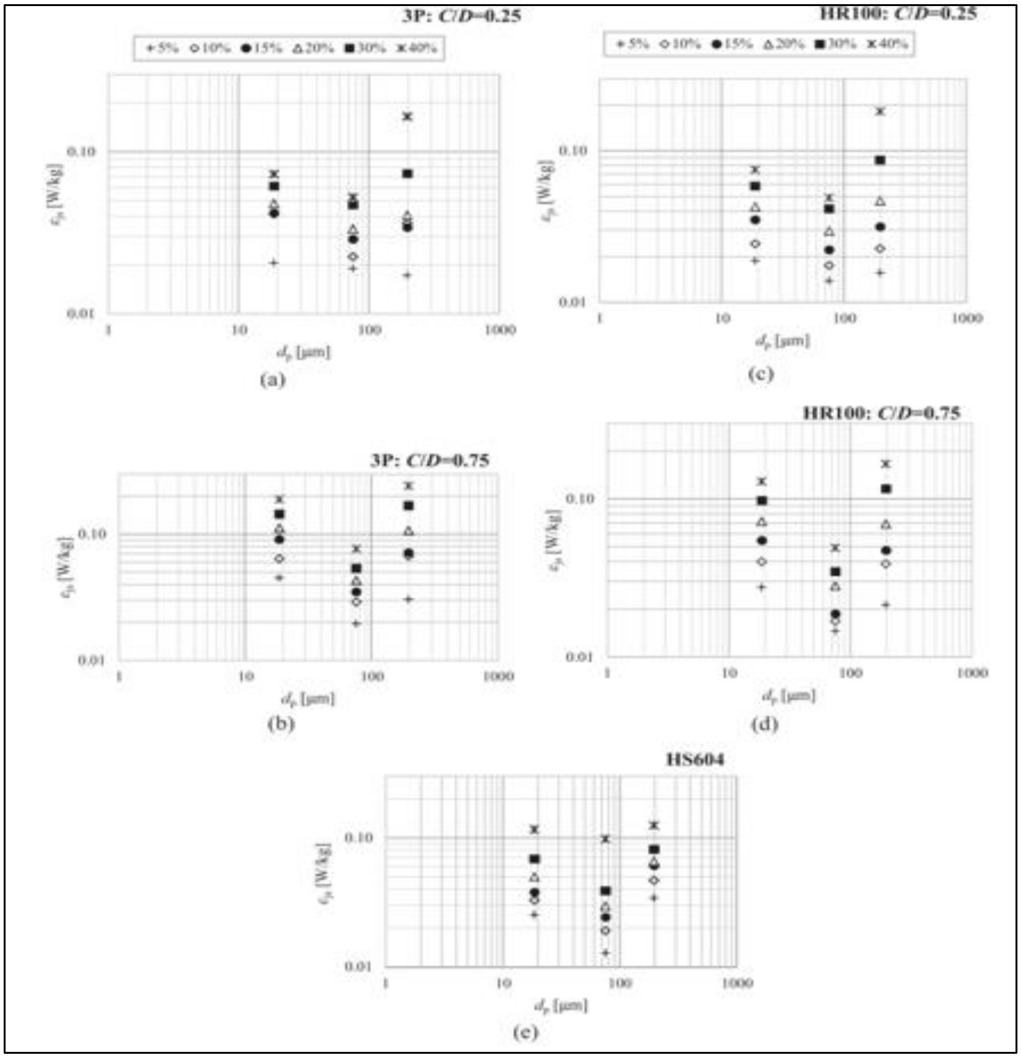


Fig. 5. The effect of particle size on specific energy εjs (W/kg) at just suspension. (a) 3P, C/D = 0.25; (b) 3P, C/D = 0.75; (c) HR100, C/D = 0.25; (d) HR100, C/D = 0.75; (e) HS604, C/D = 0.04.

Higher N_{js} and ε_{js} with increasing particle size as demonstrated by going from $d_{75.3}$ to $d_{195.5}$ can be explained by the higher particle settling velocity with bigger particle diameter (Atiemo-Obeng et al., 2004). But Wang et al. (2012), in studying the effect of particle size between 70 μm and 320 μm with radial and axial impellers in baffled and unbaffled tanks, has reported that as d_p reduced below 150 μm, ε_{js} did not continue to decrease with decrease in particle size, but came towards a plateau. This could hint a possibility of ε_{js} increasing if particle diameter was decreased even further.

In the present work, having the lowest N_{js} and ε_{js} at $d_{75.3}$ could be attributed to opposing effects of particle size on terminal velocity and particle–particle interactions, respectively. As shown in Table 1a ; Table 1b larger diameter particles have higher settling velocity and higher surface area per particle, but smaller diameter particles have far greater number of particles which in turn, make the total surface area multifold higher. The number of particles for $d_{18.0}$ is two and three orders of magnitude greater than the particle numbers for $d_{75.3}$ and $d_{195.5}$ particles, respectively. And the total surface area is at least one order of magnitude higher for the $d_{18.0}$ particles compared to the other two sizes, whereas for $d_{75.3}$ and $d_{195.5}$ the total surface area are of the same order of magnitude.

The increase in N_{js} and ε_{js} in going from $d_{75.3}$ to $d_{195.5}$ can be related to the increase in terminal velocity, and this is congruous with the grainy consistencies of both the $d_{195.5}$ and $d_{75.3}$ slurry mixtures. On the other hand, when the particle diameter reduced to $d_{18.0}$ from $d_{75.3}$, and ε_{js} increased instead of decreasing, it is likely linked to the multifold increase in particles interactions and friction losses that could arise from greater particle numbers resulting in higher total surface area. Indeed the $d_{18.0}$ mixture was found to be smoother and pastier in texture. The $d_{18.0}$ slurry was more compact, and a longer time was required to loosen the solids bed before N_{js} could be ascertained. Getting the settled $d_{18.0}$ solids to move was a challenge, particularly at high solids loading. The impeller had to first be set at a higher clearance to move the top layer of the solids bed, and only after the bed had been loosened was the impeller lowered down to the desired operating C/D. If the impeller was buried in the settled $d_{18.0}$ particles at high loadings and low clearance, it is not possible to get it to rotate. But once suspended the fine $d_{18.0}$ particles took a long time to settle due to low settling velocity.

Fig. 6(a) and (b), respectively, shows plots of calculated values of total particles surface area and particle terminal velocity, v_t, as a function of Sauter mean diameter, clearly showing the values and slope decreasing with decrease in particle size for v_t, but increasing with decrease in particle size for total surface area. The $d_{75.3}$ particles being least affected by solids loading is because they fall in the range of particle size where particles interactions are not dominating and the settling velocity is decreasing to a low plateau. This opposing trends with respect to the effect of particle size result in a range of particle size where both the total surface area and terminal velocity are at the lowest points. Particles belonging in this size range, such as the $d_{75.3}$ are therefore the easiest to be suspended under most conditions, thus maintaining a relatively low speed and energy requirement for just suspension.

Cite this article as: Ibrahim, S., Wong, S. D., Baker, I. F., Zamzam, Z., Sato, M., & Kato, Y. (2015). Influence of geometry and slurry properties on fine particles suspension at high loadings in a stirred vessel. *Chemical Engineering Research and Design*, *94*, 324-336. DOI: http://doi.org/10.1016/j.cherd.2014.08.008

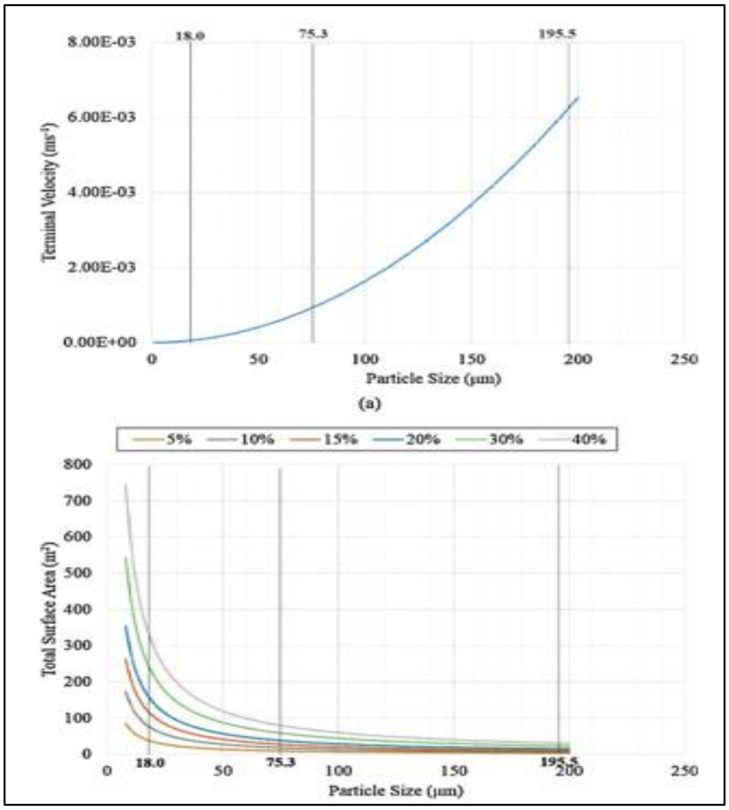


Fig. 6. (a) Calculated terminal velocity as a function of particle size. (b) Calculated surface area as a function of particle size.

Preliminary viscosity measurements of the slurries at the highest loadings indicated higher viscosity values compared to that of water, but rheological characteristics were not ascertained in detail to relate them to the changes in suspension requirement with different particle sizes or solids loading.

3.3. Effect of clearance

It is generally expected that increasing the impeller clearance from the tank base would require higher speed and energy to achieve suspension, because the fluid has to travel a greater distance to reach the base after being discharged from the impeller, and some momentum would be lost through turbulence dissipation. In Fig. 7(a)–(c) for the 4PBT going from the lowest *C*/*D* of 0.25 to 0.5 caused almost no increase, or even a slight decrease in N_{js} and ε_{js}, but increasing the clearance to 0.75 and 1.0 led to significantly greater increase in N_{js} and ε_{js}.

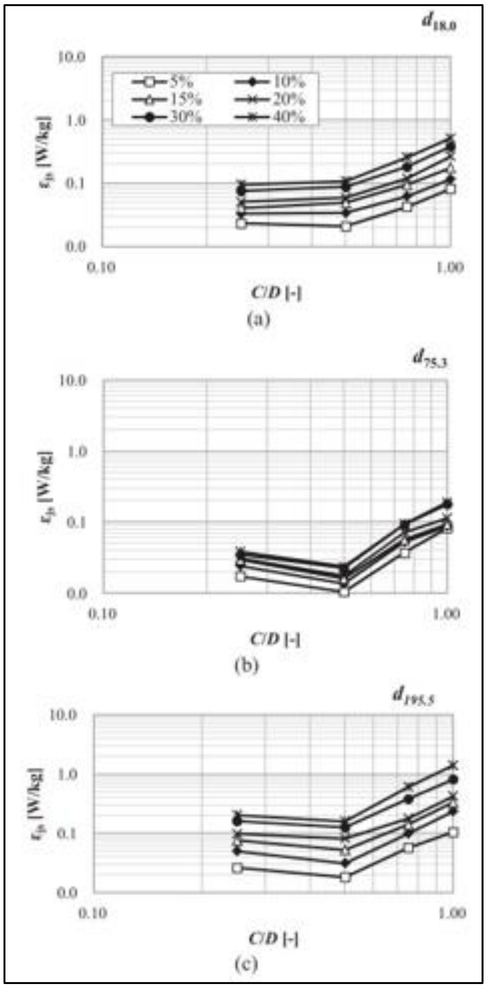


Fig. 7. The effect of clearance on specific energy at just suspension εjs (W/kg) for 4PBT.

It was observed that as clearance from the base increased to *C*/*D* = 0.75 the primary discharge for 4PBT did not reach the base. Instead, a secondary circulation loop is formed in the opposite direction such that the overall flow pattern changes to that depicted in Fig. 9(a). At *C*/*D* = 1.0 a double-loop pattern could clearly be observed. Sharma and Shaikh (2003) has reported a similar double-loop flow pattern for axial impellers at a clearance *C*/*T* > 0.35 (≈0.70*D*).

By comparison, given the same changes in clearance for HR100, the axial flow generated by the blades of the HR100 was maintained regardless of the impeller clearance, as illustrated in Fig. 9(b) at *C*/*D* = 0.75, and correspondingly increases in N_{js} and ε_{js} are less than for the other impellers (Fig. 8(a)–(c)). The ability to sustain the axial discharge all the way to the base even at high clearances of *C*/*D* = 1.0, makes the HR100 advantageous to clear particles that accumulate in the central region. This is also the main reason for the stability of the HR100 power requirement with respect to its position from the tank base. Of the three impellers studied at different clearances, the HR100 is least affected by change in *C/D.*

Cite this article as: Ibrahim, S., Wong, S. D., Baker, I. F., Zamzam, Z., Sato, M., & Kato, Y. (2015). Influence of geometry and slurry properties on fine particles suspension at high loadings in a stirred vessel. *Chemical Engineering Research and Design*, *94*, 324-336. DOI: http://doi.org/10.1016/j.cherd.2014.08.008

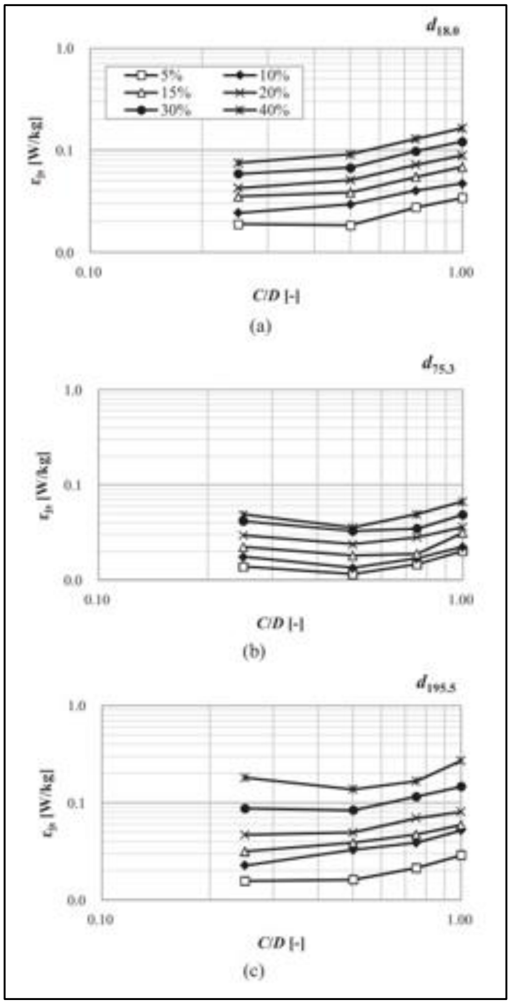


Fig. 8. The effect of clearance on specific energy εjs (W/kg) at just suspension for HR100.

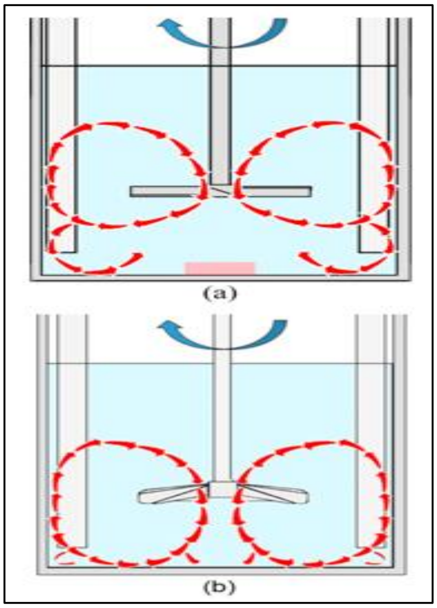


Fig. 9. Observed flow patterns at C = 0.75D, for (a) 4PBT; (b) HR100.

Other studies have also shown that the conventional impeller designs are more sensitive to clearance from the base. Ayranci and Kresta (2011) reported the hydrofoil Lightnin A310 and 4PBT having similar N_{js}, but the ε_{js} of 4PBT ranged from twice that of the A310 at the lowest clearance investigated, to four-fold more at the highest clearance. Jirout and Rieger (2011) reported among the impellers used in their study, the propeller is most sensitive to impeller clearance.

The effect of clearance is more pronounced at higher solids loading, particularly with the 4PBT and 3P, as the additional energy is needed to move through the greater distance that is now filled with the mass of particles. Ochieng and Lewis (2006) have found that the presence of solids resulted in a decrease in the axial velocity component of the impeller pumping.

3.4. Comparing the impellers

Table 3 shows that the HR100 has the lowest specific energy requirement at just-suspension under most experimental conditions (as highlighted), with a few exceptions at C/D = 0.25 and 0.50 where the 4PBT and 3P performed with lower ε_{js}. The HS604, which was used at a C/D of 0.02, when compared to the other impellers at the C/D of 0.25 is the next most efficient impeller after HR100 at the lower solids loading and with $d_{18.0}$ and $d_{75.3}$. When solids loading was increased the particles were observed to accumulate longer on the side of the base, but interestingly at the highest solids loading of 40% for $d_{195.5}$ the HS604 drew 10% less energy than the HR100, making it the most efficient under this condition.
In addition to the lower energy requirement for the HR100 and HS604, these impellers have also shown the advantage of being more stable to changes in the operating parameters, particularly solids loading and impeller clearance, in the case of HR100; while the effect of particle size is less for the HS604.

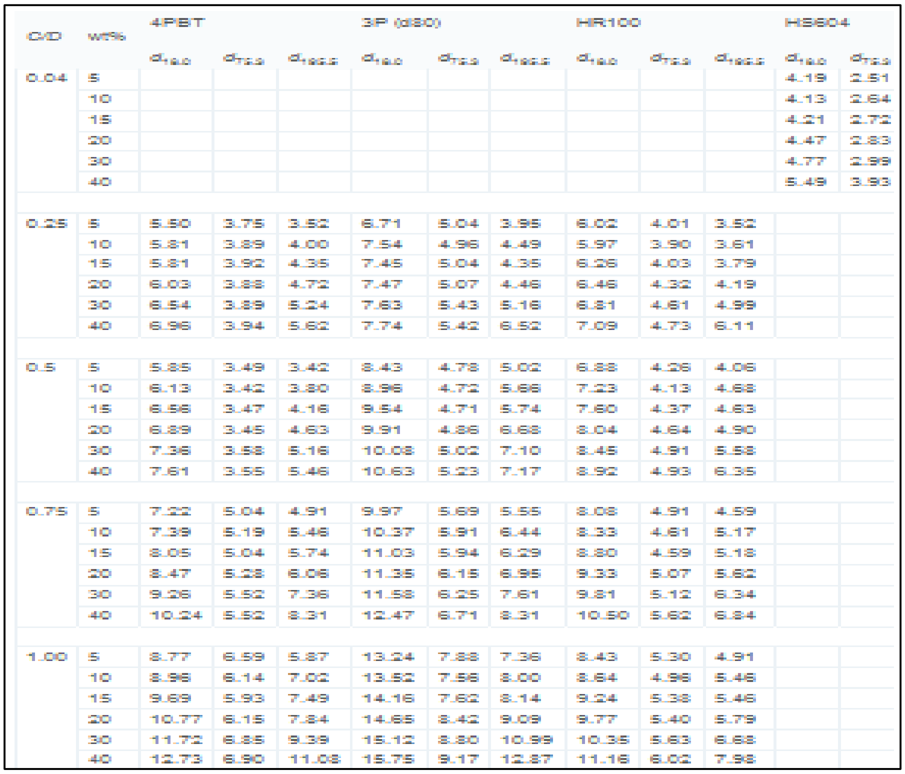
On the effect of clearance, the HR100 angled-blade design has been shown to maintain an axial flow pattern through the range of C/D used while the 4PBT and 3P axial flow were dampened at higher clearance. This led to the significant increase in N_{js} and ε_{js} for the conventional geometries for suspension at high *C*/*D*. However these advantages could also be attributed to the larger blade width for the SATAKE impellers compared to the 4PBT and 3P impellers.

The HS604 also has relatively low N_{js} compared to the other impellers, particularly at high solids loading. This could be attributed to the very low clearance setting of the impeller. The pumping action towards the side in the radial direction and the shearing action at the blade tip, combined with very low clearance possibly created such a strong force that could push the particles regardless of the size and consistency.

3.5. S values

The values of *S* factor in Zwietering's equation have been calculated from the N_{js} values under the different experimental conditions and are shown in Table 5. Impeller clearance, particle size and solids loading can all lead to significant changes in *S* values, thus the importance of using correct *S* factors in Zwietering's correlation to avoid large discrepancies in predicting N_{js}. Changes in *S* values of less than 10% is seen for the low clearance of 0.25 and solids loading of 20% or less. At higher clearances and loadings the difference in *S* values can be higher than 70%. The HR100 and HS604 impellers show relatively smaller changes in *S* as the operating conditions were varied. Fig. 10(a)–(c) compares *S* values for various types of 3-bladed and 4-bladed impellers obtained from previous and current studies, albeit under different conditions of solids properties, solids loading, impeller-to-tank geometries, and scale. *S* values from the present work at the lowest solids loading of 5% are plotted along with those of A310 and HE3 impellers with 0.5% glass beads (Ibrahim and Nienow, 1996). The effects of particle size on the *S* factor are clearly evident for the HR100, 3P and 4PBT of the present work.

Table 5. S values.



C/D	wt%	4PBT			3P (d80)			HR100			HS604	
		$d_{18.0}$	$d_{73.9}$	$d_{165.5}$	$d_{18.0}$	$d_{73.9}$	$d_{165.5}$	$d_{18.0}$	$d_{73.9}$	$d_{165.5}$	$d_{18.0}$	$d_{73.9}$
0.04	5										4.19	2.51
	10										4.13	2.64
	15										4.21	2.72
	20										4.47	2.83
	30										4.77	2.99
	40										5.49	3.93
0.25	5	5.50	3.75	3.52	6.71	5.04	3.95	6.02	4.01	3.52		
	10	5.81	3.89	4.00	7.54	4.96	4.49	5.97	3.90	3.61		
	15	5.81	3.92	4.35	7.45	5.04	4.35	6.26	4.03	3.79		
	20	6.03	3.88	4.72	7.47	5.07	4.46	6.46	4.32	4.19		
	30	6.54	3.89	5.24	7.63	5.43	5.16	6.81	4.61	4.99		
	40	6.96	3.94	5.62	7.74	5.42	6.52	7.09	4.73	6.11		
0.5	5	5.85	3.49	3.42	8.43	4.78	5.02	6.88	4.26	4.06		
	10	6.13	3.42	3.80	8.96	4.72	5.66	7.23	4.13	4.68		
	15	6.56	3.47	4.16	9.54	4.71	5.74	7.60	4.37	4.63		
	20	6.89	3.45	4.63	9.91	4.86	6.68	8.04	4.64	4.90		
	30	7.36	3.58	5.16	10.08	5.02	7.10	8.45	4.91	5.58		
	40	7.61	3.55	5.46	10.63	5.23	7.17	8.92	4.93	6.35		
0.75	5	7.22	5.04	4.91	9.97	5.69	5.55	8.08	4.91	4.59		
	10	7.39	5.19	5.46	10.37	5.91	6.44	8.33	4.61	5.17		
	15	8.05	5.04	5.74	11.03	5.94	6.29	8.80	4.59	5.18		
	20	8.47	5.28	6.06	11.35	6.15	6.95	9.33	5.07	5.62		
	30	9.26	5.52	7.36	11.58	6.25	7.61	9.81	5.12	6.34		
	40	10.24	5.52	8.31	12.47	6.71	8.31	10.50	5.62	6.84		
1.00	5	8.77	6.59	5.87	13.24	7.88	7.36	8.43	5.30	4.91		
	10	8.96	6.14	7.02	13.52	7.56	8.00	8.64	4.96	5.46		
	15	9.69	5.93	7.49	14.16	7.62	8.14	9.24	5.38	5.46		
	20	10.77	6.15	7.84	14.65	8.42	9.09	9.77	5.40	5.79		
	30	11.72	6.85	9.39	15.12	8.80	10.99	10.35	5.63	6.68		
	40	12.73	6.90	11.08	15.75	9.17	12.87	11.16	6.02	7.98		

Cite this article as: Ibrahim, S., Wong, S. D., Baker, I. F., Zamzam, Z., Sato, M., & Kato, Y. (2015). Influence of geometry and slurry properties on fine particles suspension at high loadings in a stirred vessel. *Chemical Engineering Research and Design*, *94*, 324-336. DOI: http://doi.org/10.1016/j.cherd.2014.08.008

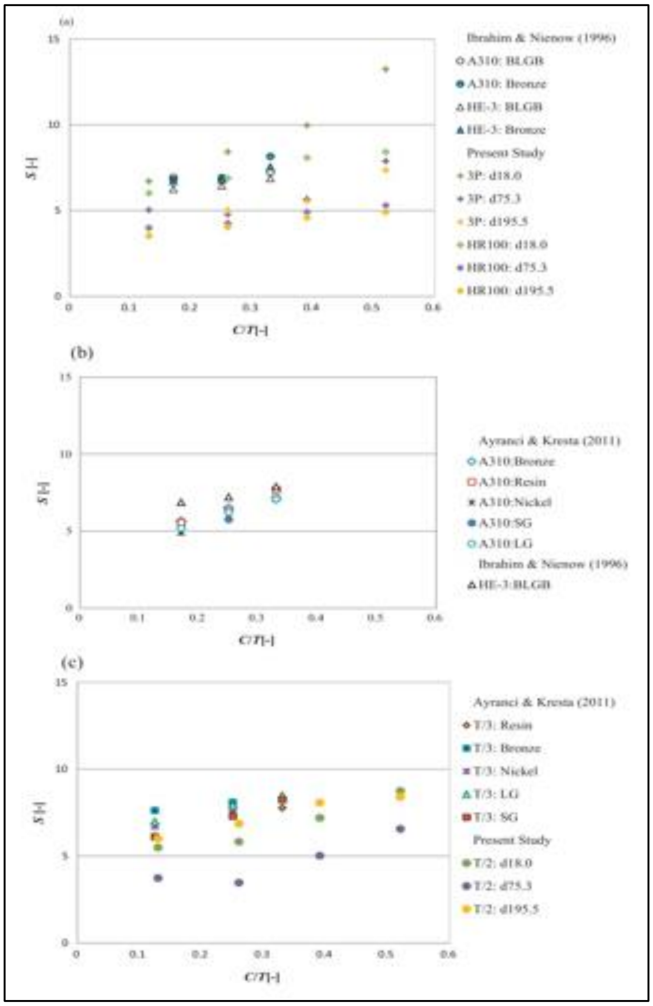


Fig. 10. (a) Comparing S values for 3-bladed impellers, D/T ≈ 1/2. Ibrahim and Nienow (1996) uses 0.5% solids, present study 5% solids. (b) Literature S values for 3-bladed impellers, D/T ≈ 1/3. 0.5% solids for Ibrahim and Nienow (1996) and 1.5% Ayranci and Kresta (2011). (c) Experimental and literature S values of 4PBT for D ≈ T/2 and T/3. Ayranci and Kresta (2011) uses 1.5% solids, present study uses 5% solids loading.

4. Conclusions

The influence of spherical particle diameter, solids loading and impeller clearance on the suspension of fine PMMA particles in water, in a 15.5 cm diameter cylindrical stirred tank was investigated using a 4PBT, 3P and HR100 and HS604 impellers by SATAKE. Solids loading ranged from 5 to 40 wt%, Sauter mean particle diameters of 18.0, 75.3 and 195.5 µm, and impeller clearance from C/*D* = 0.25–1.0.

Higher N_{js} and ε_{js} are required to suspend slurries with higher solids loading, and the effect is enhanced with higher clearance and in using the conventional impeller geometries. $d_{195.5}$ particles demand the highest ε_{js}, followed by the $d_{18.0}$ particles while the $d_{75.3}$ particles has lowest ε_{js} under any condition. This phenomenon is attributed to the fact that the particle terminal velocity decreases with reduction in particle size, while total surface area decreases with increase in particle size for the same mass of solids of any size. The $d_{75.3}$ particle size fall within the range of these opposing trends where both the particle terminal velocity and the particle total surface area are at their respective low ends; such that the $d_{75.3}$ particles become relatively easily suspended under any condition.

The SATAKE impeller designs demand less N_{js} and ε_{js} under many cases studied, and are less affected by variations in the particle size, solids loading and impeller clearance. This is attributed to the strong discharge created by the specific blade geometries and dimensions of these SUPERMIX® impellers that could dampen the effects of the other operational parameters. The radial HS604 impeller, used at an extremely low clearance of C/D = 0.04 showed comparable performance to the axial impellers. This is in line with the report by Armenante and Nagamine (1998) that the difference between radial and axial impellers is less pronounced at very low clearances.

The use of Zwietering's equations to predict the just-suspension speed under the conditions studied could lead to some discrepancies in N_{js} because the results obtained here show that the S factor does not only change with geometry, but vary significantly with changes in other operating parameters.

Acknowledgments

This work has been part of the programme supported by SATAKE Chemical Equipment MFG. LTD and the University of Malaya Research Grant (RG168-12SUS). Input from Professor E.C. Abdullah and Dr R. Karim are duly acknowledged.

References

P.M. Armenante, E.U. Nagamine. Effect of low off-bottom impeller clearance on the minimum agitation speed for complete suspension of solids in stirred tanks. Chem. Eng. Sci., 53 (9) (1998), pp. 1757–1775.

V.A. Atiemo-Obeng, W.R. Penney, P. Armenante. Solid–liquid mixing Handbook of Industrial Mixing, Science and Practice, John Wiley & Sons, Inc., New Jersey (2004), pp. 543–584.

I. Ayranci, S.M. Kresta. Design rules for suspending concentrated mixtures of solids in stirred tanks. Chem. Eng. Sci. Des., 89 (10) (2011), pp. 1961–1971.

I. Ayranci, M.B. Machado, A.M. Madej, J.J. Derksen, D.S. Nobes, S.M. Kresta. Effect of geometry on the mechanisms for off-bottom solids suspension in a stirred tank. Chem. Eng. Sci., 79 (2012), pp. 163–176.

R. Bubbico, S. Di Cave, B. Mazzarotta. Agitation power for solid–liquid suspensions containing large particles. Can. J. Chem. Eng., 76 (1998), pp. 428–432.

D. Chapple, S.M. Kresta, A. Wall, A. Afacan. The effect of impeller and tank geometry on power number for a pitched blade turbine. Trans. IChem., 80 (2002), pp. 364–372.

S. Ibrahim, A.W. Nienow. Particle suspension in the turbulent regime: the effect of impeller type and impeller/vessel configuration. Chem. Eng. Res. Des., 74 (6) (1996), pp. 679–688.

Cite this article as: Ibrahim, S., Wong, S. D., Baker, I. F., Zamzam, Z., Sato, M., & Kato, Y. (2015). Influence of geometry and slurry properties on fine particles suspension at high loadings in a stirred vessel. *Chemical Engineering Research and Design*, *94*, 324-336. DOI: http://doi.org/10.1016/j.cherd.2014.08.008

S. Ibrahim, A.W. Nienow. Suspension of microcarriers with axial flow impellers. Trans. IChemE., 82 (2004), pp. 1082–1088.

T. Jirout, F. Rieger. Impeller design for mixing suspensions. Chem. Eng. Res. Des., 89 (2011), pp. 1144–1151.
T. Kumaresan, J.B. Joshi. Effect of impeller design on the flow pattern and mixing in stirred tanks. Chem. Eng. J., 115 (2006), pp. 173–193.

M.B. Machado, J.R. Nunhez, D. Nobes, S.M. Kresta. Impeller characterization and selection: balancing efficient hydrodynamics with process mixing requirements. AIChE J., 58 (8) (2012), pp. 2573–2588.

A.W. Nienow. Suspension of solid particles in turbine agitated baffled vessels. Chem. Eng. Sci., 23 (12) (1968), pp. 1453–1459.

A.W. Nienow, D. Miles. The effect of impeller/tank configurations on fluid-particle mass transfer. Chem. Eng. J., 15 (1977), pp. 13–24.

A. Ochieng, A.E. Lewis. Nickel solids concentration distribution in a stirred tank. Miner. Eng., 19 (2006), pp. 180–189.

W. Rao, V.B. Rewatkar, J.B. Joshi. Critical impeller speed for solid suspension in mechanically agitated contactors. AIChE J., 34 (1988), pp. 1332–1340.

R.N. Sharma, A.A. Shaikh. Solids suspension in stirred tank with pitched blade turbines. Chem. Eng. Sci., 58 (2003), pp. 2123–2140.

S. Wang, D.V. Boger, J. Wu. Energy efficient solids suspension in an agitated vessel-water slurry. Chem. Eng. Sci., 74 (2012), pp. 233–243.

J. Wu, Y.G. Zhu, L. Pullum. Suspension of high concentration slurry. AIChE J., 48 (6) (2002), pp. 1349–1352.

T.N. Zwietering. Suspending of solid particles in liquid by agitators. Chem. Eng. Sci., 8 (1958), pp. 244–253.