

Article

Critical impeller speeds for a gas-inducing stirring tank loaded with solid particles☆

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ABSTRACT

The influence of solid particles size, density and loading on the critical gas-inducing impeller speed was investigated in a gas–liquid–solid stirring tank equipped with a hollow Rushton impeller. Three types of solid particles, hollow glass beads with diameters of 300 μm , 200 μm , 100 μm , and 60 μm , silica gel and desalting resin, were used. It was found that the adding solid particles would change the critical impeller speed. For hollow glass beads and silica gel, whose relative densities were less than or equal to 1.5, the critical impeller speeds increased with the solid loading before reaching the maximum values, and then decreased to a value even lower than that without added solids. The size of the solids also had apparent influence on the critical impeller speed, and larger solid particles correspond to a smaller critical impeller speed. The experimental data also showed that the gas-inducing was beneficial to the suspension of the solid particles.

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1. Introduction

Gas-inducing impellers are widely used in many industry operations, such as hydrogenation, oxidation reactors, etc. This type of impellers can simultaneously help with gas induction, gas dispersion and solid dispersion for a gas–liquid–solid contactor without using either external compressor or external pump [1], and save the process energy consumptions. However, the performances of this type of impellers are dependent on several structural and operational conditions, and the comprehensive understanding of their operation principles is highly desired.

A lot of research work has been devoted to develop design principles for self-inducing impeller, most of which concerns about gas–liquid phase systems. Martin [2] measured the local pressure around the pitched orifices on the blade and gave a correlation to calculate the gas induction rate. Bacziewicz and Michalski [3] published an empirical correlation to calculate the maximum gas induction rate. Evans *et al.* [4,5] and Rielly *et al.* [6] corrected and extended the previous work to give more accurate results. Forrester and Rielly [7] successfully predicted the gas induction rate for concave blade impellers with a single orifice. Then, Forrester *et al.* [8] studied the cases of multiple orifice impellers. Deshmukh *et al.* [9] proposed a self-induction mechanism for the case of hollow pitched blade down flow turbines and gave the calculation method for the gas side, liquid side pressure losses and the pressure driving force. Poncin *et al.* [10] selected a viscous and a low viscosity system, proposed the correlations of the rate of gas induction.

The gas induction rate closely depends on the impeller speed. When the stirred speed exceeds a critical value, the gas induction happens. Many models have been developed by considering different liquid submergences [4,5,11,12]. Different types of impellers, liquid level, physical properties (viscosity and density) of the liquid and size of the vessel have also been found to influence the critical gas-induction impeller speed [13–15]. Gas holdup is also an important factor which affects the mixing in multi-phase reactive units. Saravanan and Joshi [13] measured the fractional gas holdup for different types of impeller. The instability of gas holdup was found in some regions over a certain range of impeller speeds, but would be eliminated by using multi-impellers [16,17].

Solid is frequently encountered in modern industrial applications, taking solid catalyst as an example. Compared with gas–liquid two-phase system, gas–liquid–solid systems received less attention due to the complexities of this kind of systems. Murthy *et al.* [1] selected PBTD60, PBTD45 and PBTD30 self-inducing impellers to investigate the effect of impeller designs and operational conditions. CFD was also used to predict the contours of solid volume fraction [18]. They provided the critical gas-inducing impeller speeds for four levels of solid loading. The data showed that the critical gas-inducing impeller speeds increased with the increase of solid loading.

Critical gas-induction impeller speed is a very important parameter when we design a gas-inducing impeller. Rushton impeller provides a simple radial flow pattern with an upper and a lower circulation loops. It is commonly used in reactors and other devices requiring intense mixing. So far, there is no study on the effect of type and size of loaded solid particles on the critical gas-induction impeller speed. However, little has been reported on gas-inducing Rushton impellers. In this work, the Rushton impeller with hollow axes and blades was adopted.

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The locations of the orifice on the blades were designed with the help of CFD. The effects of density, size and solid content on the critical impeller speeds as well as on the suspension of the solid phase were investigated experimentally.

2. Impeller Design by CFD

The CFD method was conducted for a tank full with water to find a better design of the position of gas-induction holes. In the literature, holes were drilled on the top [8] or bottom of the blades [9]. The tank was 0.288 m in diameter and equipped with four wall baffles and a Rushton impeller, whose details were given in Zhang *et al.* [19]. The thickness of the hollow impeller blades was 8 mm. The k -epsilon model was employed to model the turbulence. To simplifying the numerical simulation, single-phase liquid flow was simulated, based on the idea that the location on the blade surface with the lowest pressure will give the highest rate of gas suction. The governing equations for incompressible fluid were listed as follows:

Mass and momentum conservation equations,

$$\frac{\partial}{\partial x_k}(\rho u_k) = 0 \quad (1)$$

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_k}(\rho u_k u_i) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_k} \left(\mu_t \frac{\partial u_k}{\partial x_i} \right) + \Delta \rho g_i \quad (2)$$

$$\tau_{ij} = \mu_t \left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j} \right) - \frac{2}{3} \mu_t \delta_{ij} \frac{\partial u_j}{\partial x_j} \quad (3)$$

Kinetic energy and dissipation conservation equations,

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_k}(\rho u_k k) = \frac{\partial}{\partial x_k} \left(\frac{\mu_t}{\sigma_k} \frac{\partial k}{\partial x_i} \right) + (G - \rho \varepsilon) \quad (4)$$

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_k}(\rho u_k \varepsilon) = \frac{\partial}{\partial x_k} \left(\frac{\mu_t}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial x_i} \right) + \frac{\varepsilon}{k} (C_1 G - C_2 \rho \varepsilon) \quad (5)$$

$$\mu_t = C_\mu \frac{k^2}{\varepsilon} \quad (6)$$

where G is the turbulence generation rate. $C_\mu = 0.09$, $\sigma_k = 1.0$ and $\sigma_\varepsilon = 1.3$ are empirical constants recommended by Launder and Spalding [20].

FLUENT 14.3 was adapted in the work to compute a stirred tank with a traditional Rushton impeller. The SIMPLE algorithm was used for pressure and velocity coupling, and the QUICK differencing scheme was used for the transportation equations. The tank was divided into three different grids with 420000, 570000, or 640000 cells. Fig. 1 gave the radial distributions of the tangential velocity at the two axial heights computed over these three grids. It showed that the tangential velocities for 570000 and 640000 cells were very close. So, the mesh having 640000 cells was used in the following simulations.

The pressure distribution on the surface of the impeller obtained under an impeller speed of $300 \text{ r} \cdot \text{min}^{-1}$ was shown in Fig. 2. The largest value could be found at the tip of the blades through which the momentum was transferred to the water. The low pressure region located on the top and bottom faces of the blades.

According to the results of the CFD simulation, 3 orifices to be drilled on the bottom faces of the blades were designed, through which gas could be induced into the tank (Fig. 3). Thus, the gas enters into the tank from the bottom of the blades, and will be dispersed into the tank much well. The orifices were 2 mm in diameter and evenly distributed along the radial direction of the blade. The detailed structures of the impeller can be seen in Fig. 3.

3. Experimental

The tank used in experiment was the same as that dealt in CFD. The tank had four baffles. The diameter of the tank (H) is 0.288 m which equals its diameter (D). Four wall baffles were standard with a width of 29 mm. The diameter of the impeller was 0.096 m. The impeller off-bottom clearance was 0.096 m. The speed of the impeller was adjusted by controlling the motor. A scale was attached to the wall of the tank for reading the level of liquid level under agitation. The scale was with a minimum scale of 1 mm. The impeller speed can be read from the motor control panel at the precision of $5 \text{ r} \cdot \text{min}^{-1}$.

Critical impeller speed measurement procedure: In each experimental run, water was filled into the tank first until the surface of the water reached a certain value. For example, if the solid load was 1.0%, this value was 259.2 mm. Then, solids were filled until the surface of the water reached the height of 288 mm. Keep stirring the water slowly until no little bubble generated due to dissolved air was found present in the bulk water phase. Slow agitation can accelerate the degassing of water in the tank. This procedure guarantees the accuracy that later the observed bubbles are from the gas induction only. Then, slowly increase the impeller rotating speed. The lowest speed, under which a

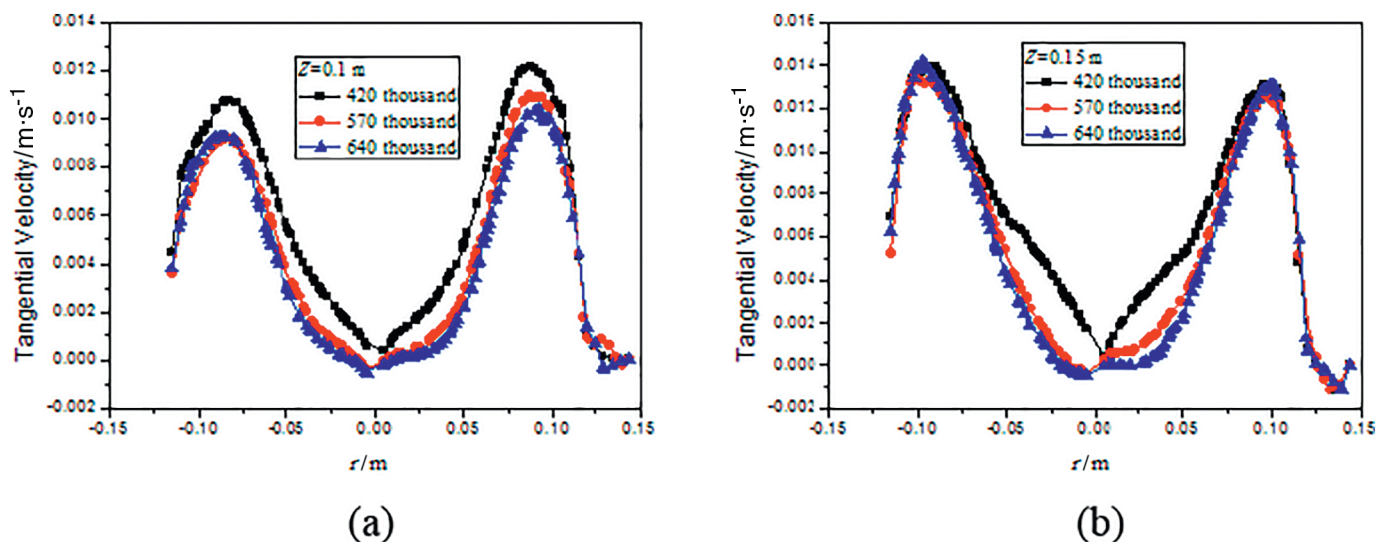


Fig. 1. Radial distributions of the tangential velocity ($N = 300 \text{ r} \cdot \text{min}^{-1}$); (a) $z = 0.1 \text{ m}$ (0.004-m above impeller); (b) $z = 0.15 \text{ m}$ (0.054-m above impeller).

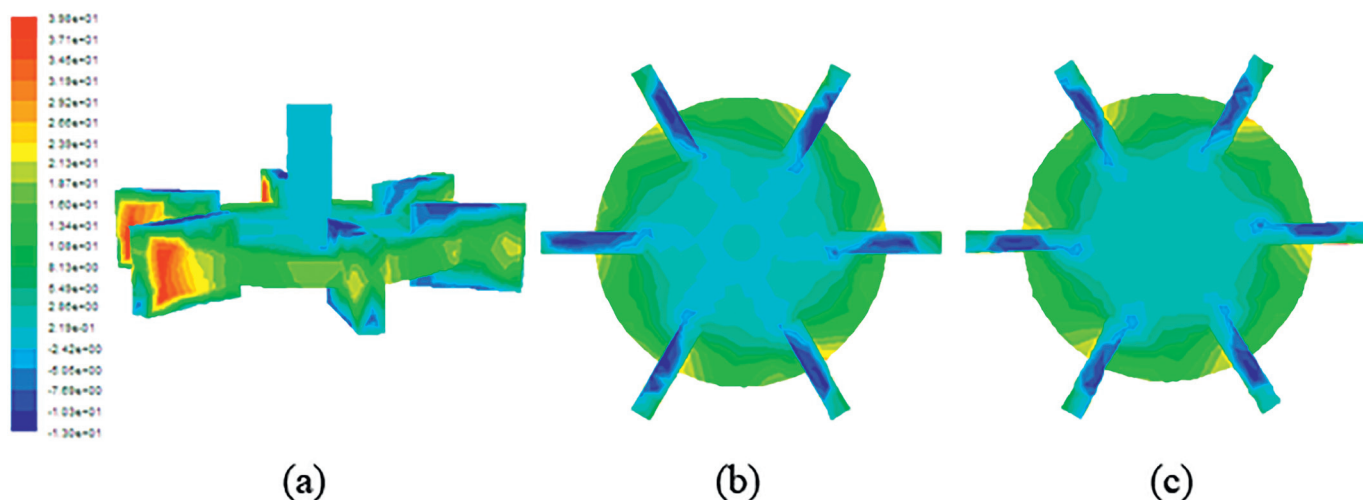


Fig. 2. Contours of the pressure distribution (640000 cells); (a) whole surface of the impeller; (b) top surface of the impeller; (c) bottom surface of the impeller.

large number of air bubbles were sucked into the tank, was recorded as the critical gas-inducing impeller speed.

For spherical particles, the terminal settling velocity in Newtonian liquids is calculated by

$$u = \frac{gd_s^2(\rho_s - \rho_l)}{18\mu} \quad (7)$$

where ρ_s is the density of the solid particle, and ρ_l is the density of the liquid phase.

Hollow glass beads, desalting resin and silica gel were used in this work and their physical properties were listed in Table 1. Four different hollow glass beads with the diameter in the range of 60–300 μm were selected to study the effect of the particle size on the critical impeller speed. The solid content in water was set at 11 different levels ranging from 1.1 % to 12.1%(v/v) to investigate the effect of solid loading while the total volumes of systems were kept at constant with the solid–liquid mixture height.

4. Results and Discussion

4.1. Critical impeller speed

Without the adding of solid into the water, when the impeller speed attained $450 \text{ r} \cdot \text{min}^{-1}$, about dozens of small bubbles, about 2 mm in

diameter, appeared in the tank. They moved slowly and randomly. With further increasing of the impeller speed, there was no obvious change except that the speed of bubble overflow was accelerated until it increased to $530 \text{ r} \cdot \text{min}^{-1}$. At that time, a large number of bubbles entered the tank from the small holes on the bottom surface of the blades. The diameter of the bubble was about 5–8 mm, and the flow of a large number of bubbles caused the strong turbulence of the liquid surface. The induced bubbles strongly enhanced the turbulence of the water, which made the water looked like boiling. With solids added, no random little bubbles could be observed at low rotation speed. When the gas induction occurred, there was loudly voice because of the movement of the bubbles and solid in the water. Fig. 4 showed the flow patterns in the tank for different systems. The bubbles can be seen clearly in the gas–liquid phase (Fig. 4(a)). Water becomes cloudy due to the existence of the desalting resin and hollow glass beads (Fig. 4(b), (c)).

Fig. 5 showed the measured critical impeller speeds for hollow glass beads with different sizes at eleven solid loading levels. It was found that the critical impeller speeds decrease uniformly with the increasing of solid loading for all the four particles with different diameters when the loading was less than 10.0%. The particle size also had large influence on the critical impeller speed. The smaller particle sizes used in the experiment, the higher critical speed would be observed. The maximum critical impeller speeds were obtained at a 1.1% (v/v) loading of hollow glass beads with a 60- μm diameter. When the solid loading exceeded a certain amount, 2.2%, 4.4%, 5.5% and 8.8% for hollow glass

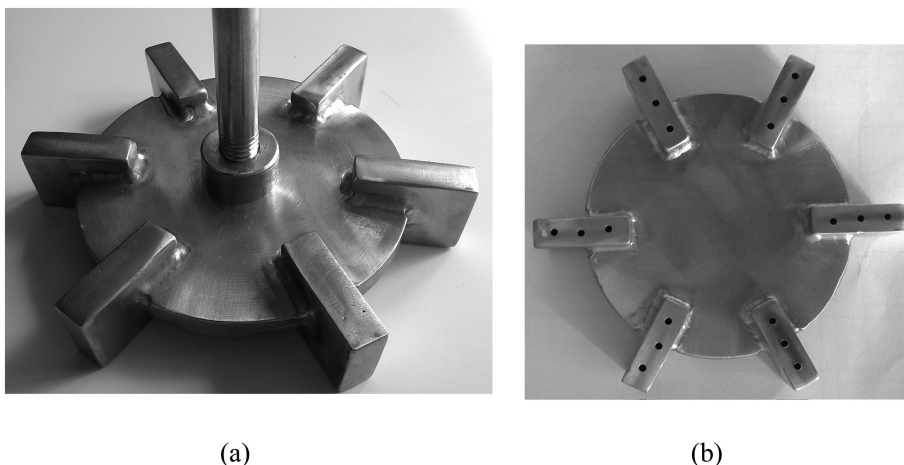


Fig. 3. The structures of self-inducing impeller used in the experiment: (a) hollow Rushton impeller; (b) distribution of the orifices.

Table 1
Physical property of the solids

	Desalting resin	Silica gel	Hollow glass bead #1	Hollow glass bead #2	Hollow glass bead #3	Hollow glass bead #4
Density $\times 10^{-3}/\text{kg}\cdot\text{m}^{-3}$	1.17	2.6	1.5	1.5	1.5	1.5
Diameter/ μm	~680	3000	300	200	100	60
Terminal setting velocity/ $\text{m}\cdot\text{s}^{-1}$	0.04	7.85	0.02	0.01	0.003	0.001

beads with 60, 100, 200 and 300 μm respectively, the critical impeller speeds for the gas–liquid–solid phase was lower than that for gas–liquid phase.

N_c is closely related to the physical properties of the liquid, impeller type and its submergence. For gas–liquid two phase system, N_c can be obtained theoretically by [8]

$$N_c = \left(\frac{gh}{2(\pi R_o(1-K))^2(C_p-1)} \right)^{0.5} \quad (8)$$

$$C_p = \frac{2(P_s - P_o)}{\rho_l U^2} \quad (9)$$

where h is the gas outlet orifices submersion depth; R_o is the orifice radial distance from the impeller axis; K is a blade slip factor; P_s is the pressure at the front stagnation point on the blade surface; P_o is the pressure at the outlet orifice on the blade surface, and U is the liquid velocity upstream of the orifice relative to the orifice velocity.

K is the function of the blade design and vessel geometry [21], and they were unchanged in this study. Therefore, the value of K was content, so N_c was only affected by C_p . Increasing the loading of particles would increase the apparent density of the fluid, which made N_c increasing. On the other hand, U and P_s are also dependent on the loading of particles. High loading of particles also makes the relative velocity increase but the influence of solid particles on the pressure drop seems unclear. When the solids loading exceeded 9.9%, N_c remained unchanged, possibly because no much solid particles were suspended up to the current speed in the liquid phase. The result was different from the conclusion obtained by Murthy *et al.* [1] that the critical gas-induction impeller speed was increased with the adding of solid loading and the particle size (100, 350 and 700 μm) with the particle density of 2400 $\text{kg}\cdot\text{m}^{-3}$.

The factors that affect the critical gas-induction impeller speed are very complex. The impeller type, the just suspended speed of the solid–liquid system might be the reasons of the differences.

Three pitched impellers and one kind of modified double disk were equipped in [1]. The measured values of the critical impeller speeds varied greatly. The critical gas-induction impeller speeds for modified double disk was about twice those for PBTD30. The influence of solid loading on the critical gas-induction impeller speeds was only investigated on one kind of impeller PBTD45 with the solid loading of 3%(wt), 5%(wt) and 7%(wt). The results show that, as the amount of particles increased, in the critical gas-induction impeller speeds increased and finally reached a stable value. These results suggested that the difference of the impeller type might be one of the main

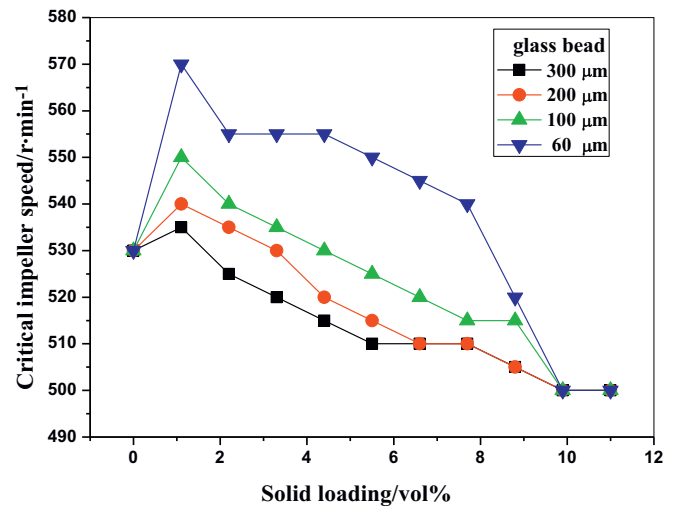


Fig. 5. Critical impeller speeds of hollow glass bead in different solid loading rate (four different sizes).

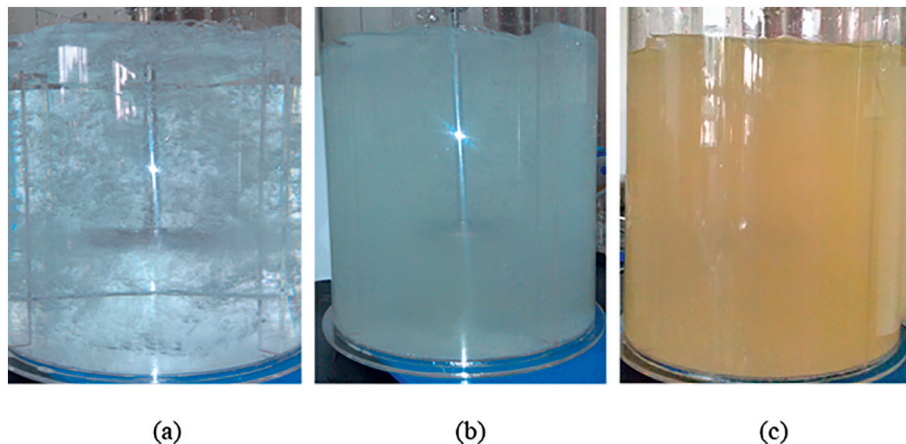


Fig. 4. Flow patterns in gas-inducing tanks. (a) Gas–liquid two-phase system, $N = 540 \text{ r}\cdot\text{min}^{-1}$; (b) gas–liquid–solid (hollow glass bead) system, $N = 550 \text{ r}\cdot\text{min}^{-1}$, 1.1vol%, $d_p = 100 \mu\text{m}$; (c) gas–liquid–solid (desalting resin) system, $N = 560 \text{ r}\cdot\text{min}^{-1}$, 2.0vol%.

causes leading to the difference of the critical gas-induction impeller speeds.

The just suspended speed, usually expressed in N_{js} , is the function of impeller, tank geometry and physical properties of the solid particle and the liquid. It can be defined as [22]

$$N_{js} = \left(\frac{g(\rho_s - \rho_l)}{\rho_l} \right)^{0.45} \frac{C_s^{0.13} d_s^{0.2} \nu^{0.1}}{D^{0.85}} \quad (10)$$

where C_s is the solid loading; D is the impeller diameter, and ν is the kinematic viscosity of liquid. In the case of same material of solid and the impeller type, the increase in size and density of solid particles will lead to an increase in N_{js} . At the same time, there is a negative correlation between N_{js} and C_s . The diameter of impeller in [1] was 0.25 m while the diameter of impeller used in our study was 0.096 m. According to Eq. (10), a large size impeller is beneficial to the suspension of solid particles. Therefore, the just suspended speed might be a factor that has a significant impact on the critical gas-induction impeller speeds.

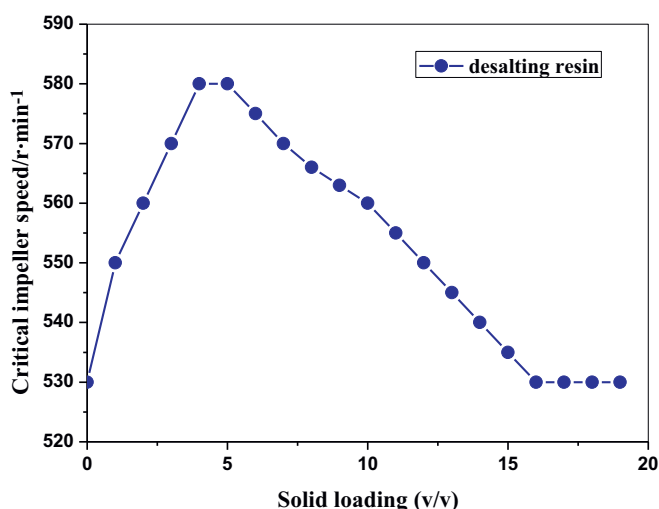


Fig. 6. Critical impeller speeds for desalting resin.

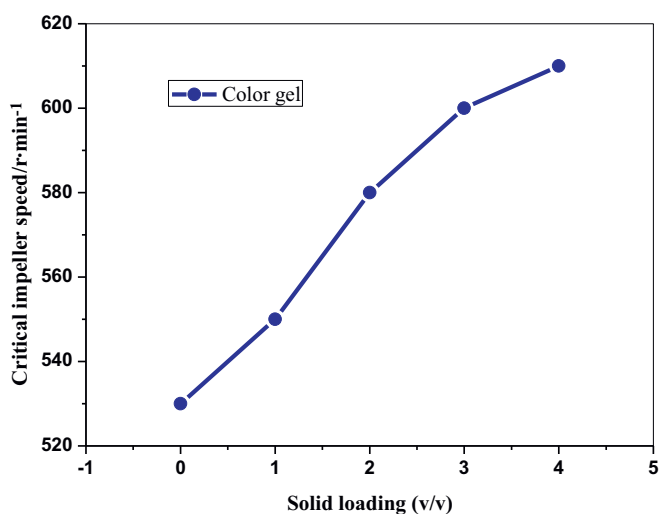


Fig. 7. Critical impeller speeds for silica gel.

The diameter of the desalting resin was about 680 μm , which was much larger than that of the hollow glass beads. At the same time, the density of the desalting resin was a little less than that of the hollow glass bead. The critical impeller speeds were also measured for this material in the volume contents ranging from 0 to 19.0% (v/v). The results were shown in Fig. 6. The critical impeller speed increased with the loading of the solid in the range of low concentrations. It reached the maximum value near 5.0% (v/v) solid loading and then began to decline until the solid loading was 16.0% (v/v). The trend of the curve in Fig. 7 was similar to those of Fig. 6, except that the abscissas corresponding to the turning point were different. The reason might be that the density of the desalting resin was much less than that of hollow glass beads.

The results for silica gel are shown in Fig. 7. This material was the largest and the heaviest used in this work, with about 3-mm diameter and a density about 2600 $\text{kg} \cdot \text{m}^{-3}$. The added silica gel had a strong effect on the critical impeller speed. The critical impeller speed increased rapidly with addition of the gel. Due to the high density and diameter, silica gel is very difficult to suspend. In the experimental impeller speeds, only part of silica gel particles detached the bottom of the tank and circulated in the lower recirculation zone. The increasing of the density might be the major reason for the rapid increase of N_C .

4.2. Solid suspension

To determine if the particles are completely suspended, turn off the power of the motor and wait for the particles to settle down, then observe the distribution of particles on the bottom of the tank. If the particles are completely floated, the particles will be evenly spread at the bottom of the tank (Fig. 8(a)). Otherwise, the particles will be sucked into the center zone under the turbine (Fig. 8(b)). Silica gel is difficult to totally suspend because of its large density.

Gas induction was beneficial to the suspension of the solid. Fig. 9 showed a case for hollow glass bead (100 μm) with 1.1% (v/v) loading. The critical impeller speeds was 550 $\text{r} \cdot \text{min}^{-1}$. When the impeller speed was a little less than 550 $\text{r} \cdot \text{min}^{-1}$, there was no gas induction (Fig. 9(a)). There was large amount of solid particles stayed on the bottom. Once the impeller speed attained 550 $\text{r} \cdot \text{min}^{-1}$, the gas was induced into the tank through the orifices on the impeller blades. It was observed that much more solid particles were carried into the flow circulation (Fig. 9(b)).

4.3. Discussion

Hollow glass beads, silica gel and desalting resin were used to study the critical gas-inducing impeller speeds in a baffled tank. Different results were got when comparing to the previous work of Murthy *et al.* [1], which showed that the critical gas-inducing impeller speeds always increased with increasing of solid loading and the particle size. In most cases of our experiment except those with color gel, when the solid loading reached a certain amount, the critical impeller speed would decline until it levels off. The difference of impeller type and suspension state of particles might be the reasons for the different conclusions.

Adding particles in the water increased the apparent density of the liquid phase. At the same time, the liquid velocity upstream of the orifice relative to the orifice velocity might be increased, too. But the influence of particles on the pressure drop is uncertain. So, the influence of solid loading on N_C was not quite certain.

5. Conclusions

- 1) The critical impeller speed was influenced by solid properties. The decrease of the solid particle size would lead to the increase of the critical impeller speed. The critical impeller speeds

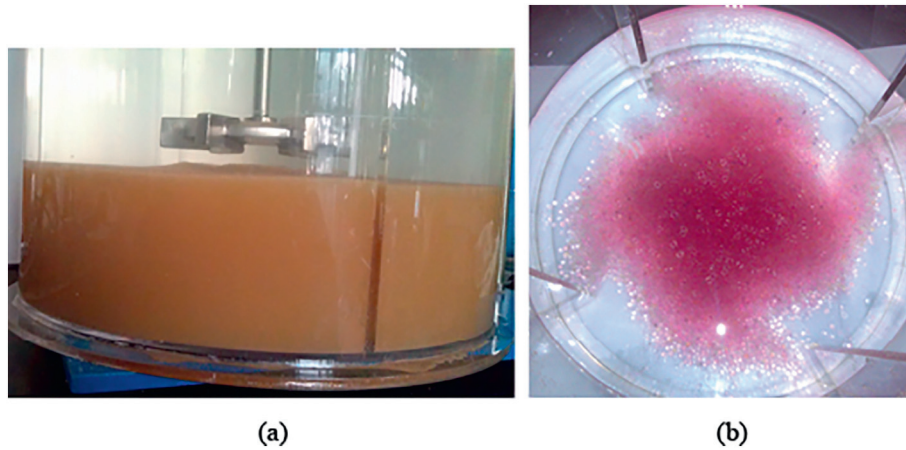


Fig. 8. Spread of the particles after the stop of the motor ($N = 550 \text{ r} \cdot \text{min}^{-1}$) (a) Desalting resin totally suspension; (b) Silica gel partially suspension.

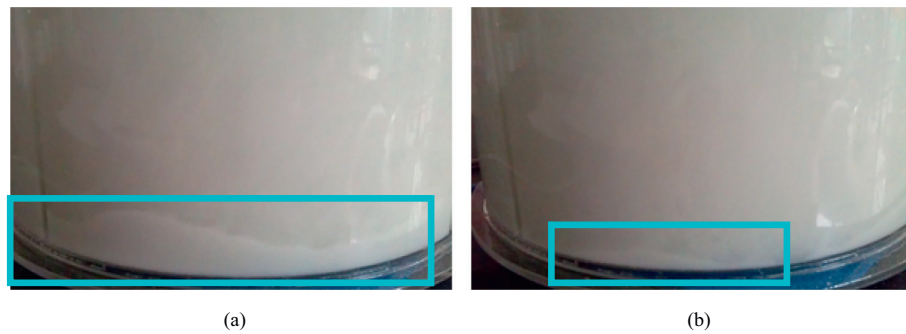


Fig. 9. Suspension of the solid of glass bead (1.1% (v/v), $N = 550 \text{ r} \cdot \text{min}^{-1}$, $d_s = 100 \mu\text{m}$). (a) no gas induction; (b) with gas induction.

increased with the adding of a small amount of particles, then, might drop with more solid loading, and finally, it would keep unchanged when the concentration of the solid reached a certain value. In some cases, the critical gas-inducing impeller speeds for solid loaded systems were even less than that without solids added in the tank.

- 2) Gas induction would improve the suspension of the solid phase. As a result, the energy consumption will be reduced by using of the gas induction impeller.

Nomenclature

C_1, C_2, C_μ	coefficient
C_p	orifice pressure coefficient
C_s	volume concentration of particles
D	impeller diameter, m
d_s	particle diameter, m
G	turbulence generation rate
g	gravity acceleration, $\text{m} \cdot \text{s}^{-2}$
h	gas outlet orifices submersion depth, m
K	blade slip factor
k	turbulence kinetic energy, $\text{m}^2 \cdot \text{s}^{-2}$
N_C	critical impeller speed, $\text{r} \cdot \text{min}^{-1}$
N_{js}	just suspended speed, $\text{r} \cdot \text{min}^{-1}$
p	pressure, $\text{Pa} \cdot \text{m}^3 \cdot \text{kg}^{-1}$
P_o	pressure at the outlet orifice on the blade surface, $\text{Pa} \cdot \text{m}^3 \cdot \text{kg}^{-1}$
P_s	pressure at the front stagnation point on the blade surface, $\text{Pa} \cdot \text{m}^3 \cdot \text{kg}^{-1}$
R_o	the orifice radial distance from the impeller axis, m
U	liquid velocity upstream of the orifice relative to the orifice velocity, $\text{m} \cdot \text{s}^{-1}$
u	velocity, $\text{m} \cdot \text{s}^{-1}$

δ_{ij}	distribution function
ε	turbulence dissipation rate, $\text{m}^2 \cdot \text{s}^{-3}$
μ	viscosity of the liquid, $\text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$
μ_t	turbulent viscosity, $\text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$
ρ_l	density of the liquid phase, $\text{kg} \cdot \text{m}^{-3}$
ρ_s	density of the solid particle, $\text{kg} \cdot \text{m}^{-3}$
$\sigma_k, \sigma_\varepsilon$	coefficient

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