

Article

Gas dispersion and solid suspension in a three-phase stirred tank with triple impellers

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ABSTRACT

The hydrodynamics is still not fully understood in the three-phase stirred tank equipped with multi-impeller due to the intensive interaction between phases. In this work, the solid critical suspension speed (N_{JSC}), relative power demand (RPD) and overall gas holdup (ε_G) were measured in an air–water–glass beads stirred tank equipped with multi-impeller, which consists of a parabolic blade disk turbine below two down-pumping hydrofoils. Results show that either the N_{JSC} or the specific power consumption increases when increasing the volumetric solid concentration or superficial gas velocity. RPD changes less than 10% when solid volumetric concentration ranges from 0 to 15%. ε_G decreases with the increase of solid concentration, and increases with the increase of both superficial gas velocity and the total specific power consumption. The quantitative correlations of N_{JSC} , RPD and ε_G were regressed as the function of superficial gas velocity, specific power consumption, Froude number and gas flow number, in order to provide the reference in the design of such three-phase stirred tank with similar multi-impellers.

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1. Introduction

Three-phase, gas–liquid–solid, mechanically stirred tanks are widely applied in industrial multiphase processes, including the hydrogenation, fermentation, and polymerization, due to the convenient operation and high economic benefits [1,2]. The prediction of parameters such as solid critical suspension speed, relative power demand and overall gas holdup in a three-phase stirred tank is often essential to design and scale up the industrial scale stirred tanks [3–5]. In the past decades, many researchers have focused on the influence of solid on the hydrodynamic parameters in the multiple-impeller, three-phase system, in order to design more efficiency, safety and reasonable reactors [6–8]. However, most available researches were limited to the discussion of the hydrodynamics in the stirred tank with several Rushton turbines or pitched-blade turbines, known as the radial or axial flow impeller combination, while relatively few studies have been involved in the combined flow impeller combination. Generally, the combined flow impeller combination contains a radial flow impeller often used as the bottom impeller to disperse the gas and suspend the solid, and several axial flow impellers mounted above the radial impeller to provide effective homogenization, like PDT + 2CBY in this study. The combined flow impeller combination usually performs better in the mixing and the mass transfer than the two traditional combinations under the same power consumption [9,10]. Hence, further research is

needed to investigate the performance of agitators using combined impellers to provide reference and data support for the design and optimizations of stirred tanks.

In the industrial application, the parabolic blade disk turbine (PDT) and narrow blade axial flow impeller (CBY) are the two most widely used agitators, such as in the fermentation and mineral processing. However, the hydrodynamics performance of impeller with different diameters is different especially when the ratio between liquid level and tank diameter is large [11–14]. The ratio between impeller diameter and tank diameter can be varied with the operations and agitation purposes, and the agitators with different D/T often exhibit different hydrodynamic performance. In addition, the cost of impeller manufacture is also related to the diameter of impellers. For example, a smaller impeller requires less material cost and lower power consumption under the same power input operation compared with a larger impeller, which could be a vital factor in the design and manufacture of a stirred fermenter as large as 800 m³. Therefore, it is meaningful to reveal the relationship between gas dispersion properties and the agitator geometrical parameters in the optimization and design of the industrial gas–liquid or gas–liquid–solid stirred tank reactors. In the work of Bao *et al.* [15], the influence of impeller diameter on gas dispersion was investigated by both experimental and CFD simulation methods, and the results show an optimum impeller size ($D/T = 0.33$) for gas dispersion in a gas–liquid system.

Our previous researches [16–18] have focused in the gas dispersion and solid suspension in a multi-impeller three-phase system with impeller combination HEDT + 2WH_U, composing a deep hollow blade

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(semi-ellipse) disk turbine (HEDT) below two up-pumping four-wide-blade hydrofoil impellers (WH_U). However, compared with this combination, whose power number is as high as 4.2, the power number of the combination PDT + 2CBY is only half of it, resulting in a higher rotational speed and lower torque under the same power input [19–21]. Therefore, the combination PDT + 2CBY is usually used in the mixing requiring intensive shear and high circulation. However, the quantitative analysis of solid critical suspension speed, relative power demand and overall gas holdup in a three-phase stirred tank with such combined impellers are not available in the previous literature. In this work, we firstly set the experimental D/T to 0.33, based on the results of Bao *et al.* on optimizing D/T of gas–liquid stirred tank [15], and then investigate the effects of solid concentration C_V , gas flow number (Fl_G), Froude number (Fr) on the macroscopic gas–dispersion and solid-suspension properties. Finally, correlations related to the above parameters are proposed for the design of three phase stirred tank with similar impeller configuration.

2. Apparatus and Conditions

The experimental stirred tank is a dished-bottom cylindrical tank with an inner diameter T of 0.48 m and a filling liquid aspect ratio $H_0/T = 1.66$, as shown in Fig. 1. Four baffles 0.045 m in width are equally mounted with the clearance 0.005 m from the wall. The impeller combination consists of a PDT impeller and two CBY impellers, as shown in Fig. 2. The diameter of the impellers D is 0.33 T . The distance between two adjacent impellers is fixed at 0.48 T . The clearance of the impeller disc from the tank bottom is 0.33 T .

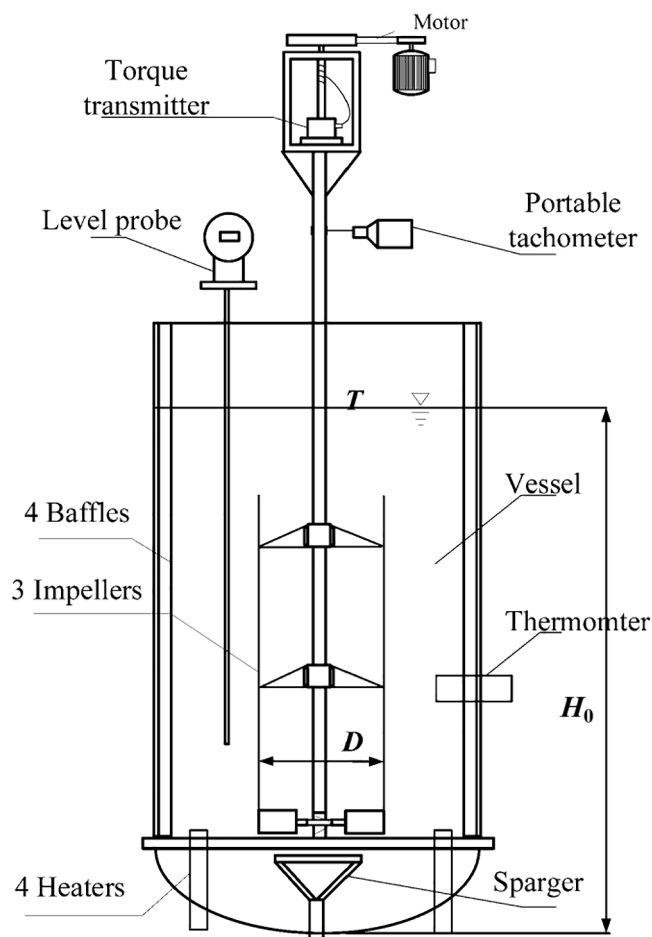


Fig. 1. Schematic of the experimental apparatus.

Air, as the experimental gas phase, is sparged into the tank filled with deionized water after passing through filters to increase gas purity. The ring sparger with diameter $0.8D$ locates $0.25 T$ above the tank bottom, and the liquid bulk temperature is kept at $24\text{ }^{\circ}\text{C}$.

In the operation of gas–liquid–solid three phase stirred tank, the solid phase is glass beads with average diameter of $100\text{ }\mu\text{m}$ and density $2500\text{ kg}\cdot\text{m}^{-3}$. The volumetric solid concentrations C_V are 3%, 6%, 10%, and 15%, while the gas rates range from 5 to $25\text{ m}^3\cdot\text{h}^{-1}$, and the corresponding superficial gas velocity V_S are from 0.0074 to $0.039\text{ m}\cdot\text{s}^{-1}$.

The power consumption is calculated from the torque acting on the shaft and the impeller speed based on a torque transmitter and a portable tachometer.

The critical minimum impeller speed for just suspending particles is determined visually by observing from the transparent base of the tank, especially the region around the center of the tank where the particles often settled. Following the Zwietering (1958) criterion [21] for the just-suspended condition of settling particles, the just-suspension speed, N_{JS} , could be consistently judged within an accuracy of about 5% in the experiments. Each value of N_{JS} is the mean of at least three observations with the deviation between individual results less than 10%. The critical agitation speed in a three-phase system is identified as N_{JSG} with the corresponding power consumption P_{JSG} .

The gas holdup is measured by a calibrated radar probe (Krohne Reflex-Radar BM100A, Germany), as shown in Fig. 3. The overall gas holdup is defined as

$$\varepsilon_G = \frac{H_G - H_0}{H_G - H'} \quad (1)$$

H_G , H_0 and H' are respectively the liquid level with gas, in original condition and the dished-bottom correction factor, which takes 0.04 m by experience.

3. Results and Discussion

In a gas–liquid–solid three-phase stirred tank, both solid suspension and gas–liquid dispersion performance are very important. The previous research [15,23] involves the effect of impeller diameter ranging from $0.30 T$ to $0.40 T$ on the gas dispersion in a gas–liquid stirred tank. The results show that the agitation system with $D/T = 0.33$ has a good balance between the gas recirculation and liquid shearing rate, resulting in the highest gas holdup among four different D/T . Therefore, in this work we set $D/T = 0.33$ and then investigate the effect of solid on the hydrodynamics in a three-phase stirred tank.

3.1. Critical suspension speed N_{JSG} and power demand P_{JSG}

3.1.1. Effect of volumetric solid concentration C_V

The critical suspension speed in solid–liquid system and gas–liquid–solid system are expressed as N_{JS} and N_{JSG} , respectively. Their corresponding power demands are defined as P_{mJS} and P_{mJSG} . The effect of volumetric solid concentration C_V on N_{JSG} and P_{mJSG} at different V_S is shown in Fig. 4. Both N_{JSG} and P_{mJSG} increase with the increasing C_V .

In order to quantitatively analyze and compare the results with previous research, especially Zwietering's classical equation, the effect of solid mass concentration, X , on N_{JSG} and P_{mJSG} is correlated by Eqs. (2) and (3), and the results are shown in Tables 1 and 2.

$$N_{JS} \text{ or } N_{JSG} = A_1 X^{B_1} \quad (2)$$

$$P_{mJS} \text{ or } P_{mJSG} = A_2 X^{B_2} \quad (3)$$

The solid mass concentrations X ranges from 7% to 30%. The first row in both Tables 1 and 2 refers to the solid–liquid system. The exponent of X on N_{JSG} obtained in this work is 0.071 , smaller than 0.13 in Zwietering's equation [21]. First, Zwietering's equation was obtained

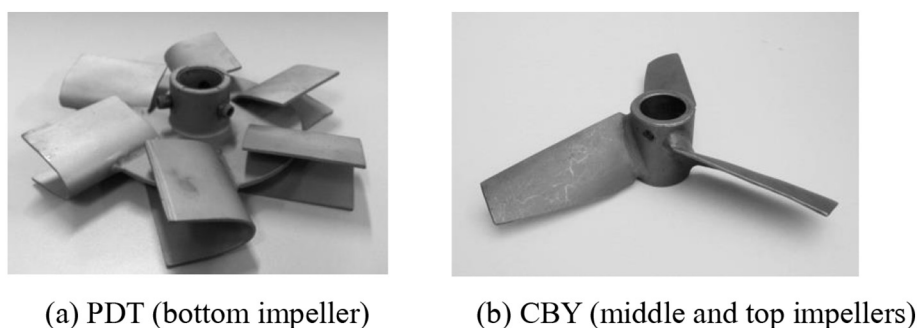


Fig. 2. Impellers used in the experiments.

in a stirred tank with single impeller while the triple-impeller combination is used in the work. Second, our previous research [23] indicated that the exponent B_1 is smaller for a radial flow type impeller than that for an axial flow impeller. In this work, the radial flow PDT is used as the bottom impeller that plays an important role in both solid suspension and gas dispersion.

Bao [23] proposed the exponent B_1 of 0.081 with similar impeller combination HEDT + 2WH_D, which is also smaller than the value 0.13 in the classical Zwietering's equation. Once gas is introduced into the solid–liquid systems, B_1 becomes smaller, implying that N_{JSG} becomes less sensitive with X in a three-phase stirred tank. Quantitative comparison of B_1 in Table 1 shows that B_1 reduces from 0.071 to 0.042 when V_s increases from 0 to $0.039 \text{ m} \cdot \text{s}^{-1}$, with a reduction of 40.8%. The same comparison based on Bao's data [23] reveals almost the same reduction of 40.7% with a decreasing B_1 from 0.081 to 0.048 as shown in Table 1.

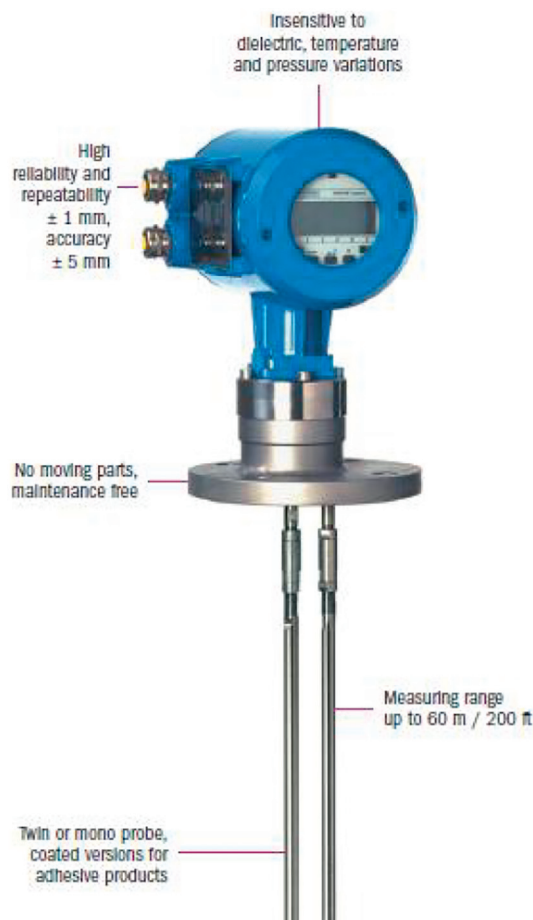


Fig. 3. Radar probe for liquid level measurement.

Table 2 shows the quantitative influence of X on P_{mJSG} , and the exponent B_2 decreases from 0.30 to 0.079. Since the power consumption is proportional to the third power of the agitation speed, it is understandable that B_2 is approximately 3 times of B_1 .

3.1.2. Effect of gas flow at different C_v

Fig. 5 shows the relationship between N_{JSG} or P_{mJSG} and V_s when C_v ranges from 3% to 15%. Both N_{JSG} and P_{mJSG} increase with the increase of V_s at different C_v . Firstly, the decreased relative power demand caused by the existence of gas leads to the reduction of the pumping capacity and the circulation flow of impellers. Higher agitation speed and more power consumption are required to suspend the solids and disperse the gas when more gas is introduced. Secondly, the density difference between the gas–liquid mixture and solids becomes higher than the density difference between liquid and solid. When more gas is introduced, the net gravity on solid particles is larger and the drag force is smaller since the density difference between gas–liquid fluid and solids increases. As a result, the drag force is hard to overcome the solid net gravity in the suspending. Therefore the N_{JSG} or P_{mJSG} should be increased for increasing drag force.

Previous works [1,25–27] dealing with the performance of gassed reactors specify gas flow rates in vvm (volume of gas per volume of unaerated liquid per minute), and this is particularly useful in the fermenter and other bioreactors. In our equipment, the conversion from vvm to the superficial velocity is $1.0V_s \text{ (in } \text{m} \cdot \text{s}^{-1}) = 0.012Q_G \text{ (in vvm)}$.

When gas is introduced into the solid–liquid system, the suspended solids might back into settling state. In those cases an increase of agitation speed is required to maintain the suspension. The increasing extent, ΔN_{JSG} and ΔP_{mJSG} , are respectively defined as $\Delta N_{JSG} = N_{JSG} - N_{JS}$ and $\Delta P_{mJSG} = P_{mJSG} - P_{mJS}$. Fig. 6 shows that both ΔN_{JSG} and ΔP_{mJSG} increase with the increasing Q_G , showing an approximate linear relation, and the curves of both ΔN_{JSG} and ΔP_{mJSG} for C_v are almost coincident. This trend can be fit by a simple linear regression using Eqs. (4) and (5).

$$\Delta N_{JS} = N_{JSG} - N_{JS} = mQ_G \quad (4)$$

$$\Delta P_{mJS} = P_{mJSG} - P_{mJS} = nQ_G \quad (5)$$

where Q_G is volume of gas per volume of unaerated liquid per minute, vvm.

The average values of coefficients m and n are 0.66 and 0.053 for C_v from 3% to 15%.

$$\Delta N_{JS} = N_{JSG} - N_{JS} = 0.66Q_G \quad (6)$$

$$\Delta P_{mJS} = P_{mJSG} - P_{mJS} = 0.053Q_G \quad (7)$$

Fig. 7 shows the comparison of P_{mJSG} between different tripe-impeller combinations and that under $C_v = 3\%$ obtained by Chen [24] with HEDT + 2WH_U and Bao [23] with HEDT + 2WH_D. It can be found that the combination of PDT + 2CBY has the lowest P_{mJSG} . We

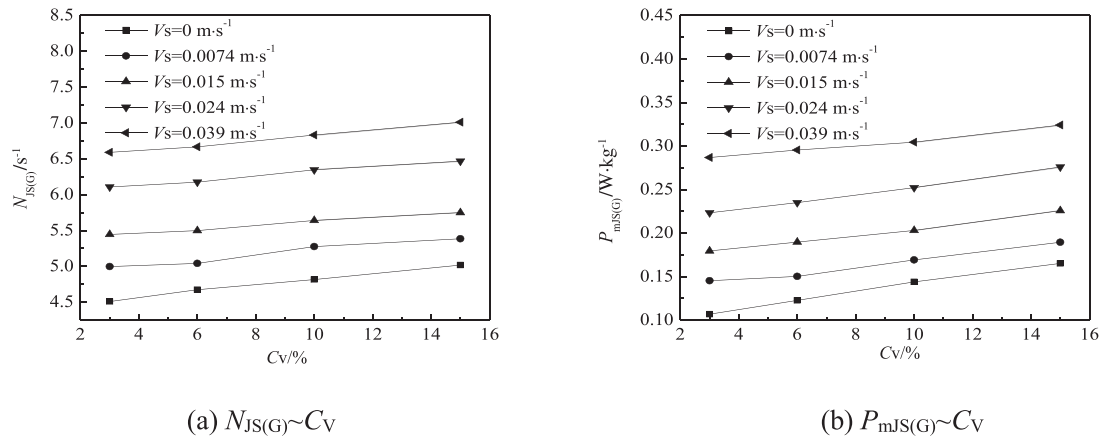


Fig. 4. Relationship between N_{JSG} and P_{mJSG} and C_V at different V_S .

use Eq. (5) to correlate the relationship between P_{mJSG} and Q_G for three impeller combinations under given $C_V = 3\%$ as follows, $P_{mJSG} = 0.416 + 0.129Q_G$ for HEDT + 2WH_U, $P_{mJSG} = 0.285 + 0.089Q_G$ for HEDT + 2WH_D, and $P_{mJSG} = 0.107 + 0.056Q_G$ for PDT + 2CBY, respectively. The intercepts of these three equations reflect the value of P_{mJS} in the solid–liquid systems without gas, and the slopes reflect the increment of ΔP_{mJSG} with the increase of Q_G (vvm). The lowest intercept and slope appear in the combination of PDT + 2CBY, which means PDT + 2CBY can not only suspend solids in solid–liquid system with high efficiency, but also with the lowest increment of P_m in suspending the solids in an aerated three phase stirred tank.

Zhu and Wu [25], working with the single RT impeller in two stirred tanks with the diameters of 0.39 m and 1.07 m, respectively, studied the relationship between ΔN_{JSG} and Q_G in the gas–liquid–solid three-phase systems when X ranges from 5% to 63% and Q_G is less than 2.0 vvm. They found that ΔN_{JSG} increases with the increasing Q_G , but not following a simple linear relationship. So they proposed a correlation to describe the relation between N_{JSG}/N_{JS} and the operational conditions, $\frac{N_{JSG}}{N_{JS}} = 1 + 2.6 \left(\frac{Q}{N_{JS} D^3} \right)^{0.7}$. The relationship between N_{JSG}/N_{JS} or P_{mJSG}/P_{mJS} and Fl_G under different C_V is shown in Fig. 8, and all the data can be regressed in the same form proposed by Zhu and Wu, as shown in Eqs. (8) and (9),

$$\frac{N_{JSG}}{N_{JS}} = 1 + 0.77 \left(\frac{Q}{N_{JS} D^3} \right)^{0.89} \quad R^2 = 0.978 \quad (8)$$

$$\frac{P_{mJSG}}{P_{mJS}} = 1 + 2.55 \left(\frac{Q}{N_{JS} D^3} \right)^{1.03} \quad R^2 = 0.925 \quad (9)$$

Fig. 8 shows that the effect of C_V on the relationship of N_{JSG}/N_{JS} and Fl_G is weak, but strong on the relationship between P_{mJSG}/P_{mJS} and Fl_G ,

Table 1
Regression results of N_{JSG} at different V_S and the comparison with literature

This work, PDT + 2CBY ($D/T = 0.33$)			Bao et al. [23], HEDT + 2WH _D ($D/T = 0.40$)		
$V_S/\text{m}\cdot\text{s}^{-1}$	A_1	B_1	R^2	A_1	B_1
0	5.42	0.071	0.969	4.9	0.081
0.0074	5.72	0.054	0.895	5.6	0.079
0.015	5.99	0.038	0.926	5.7	0.075
0.024	6.75	0.040	0.931	5.7	0.060
0.039	7.32	0.042	0.915	5.9	0.048

and the correlation coefficient 0.925 in Eq. (9) reflects that it is inappropriate to neglect the effect of C_V .

Therefore, in order to quantify the effect of aeration on the solid suspension, we use $\Delta N_{JSG}/N_{JS}$ and $\Delta P_{mJSG}/P_{mJS}$ instead of N_{JSG}/N_{JS} and P_{mJSG}/P_{mJS} , and include the effect of C_V , in Eqs. (10) and (11).

$$\frac{\Delta N_{JSG}}{N_{JS}} = 1.36 Fl_G^{0.065} (1 + C_V)^{-1.00} \quad R^2 = 0.959 \quad (10)$$

$$\frac{\Delta P_{mJSG}}{P_{mJS}} = 6.04 Fl_G^{1.20} (1 + C_V)^{-4.68} \quad R^2 = 0.986 \quad (11)$$

Eqs. (10) and (11) show that the exponents of solid concentration for $\Delta N_{JSG}/N_{JS}$ and $\Delta P_{mJSG}/P_{mJS}$ are -1.00 and -4.68 , respectively, implying that both $\Delta N_{JSG}/N_{JS}$ and $\Delta P_{mJSG}/P_{mJS}$ decrease with the increase of C_V .

3.2. Relative power demand

Fig. 9 shows the relationship between RPD and gas flow number (Fl_G) when C_V varies from 0 to 15%, in which Fig. 9(a) and (b) show that RPD decreases with the increase of Fl_G and agitation speed, the same as in gas–liquid system. When C_V is less than 15%, the change of RPD is within 10% of that without solids. Similar results can also be found in the work of Chen [28] with impeller combination HEDT + 2WH_U.

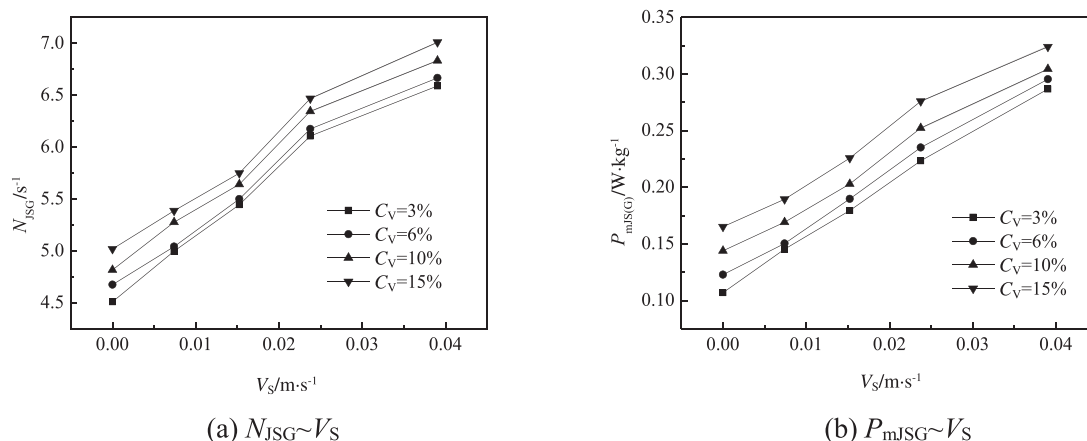
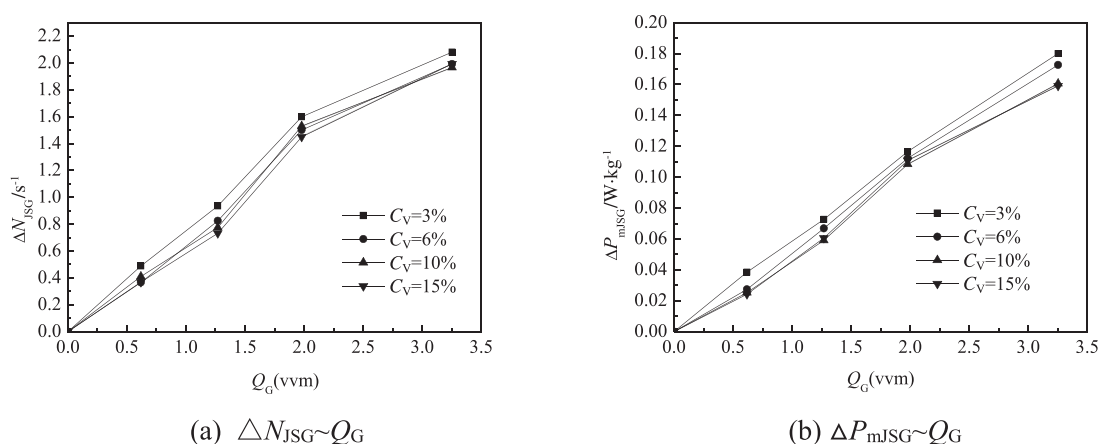
Because the gassed power consumption is related to Fl_G and Fr , we use Eq. (12) to regress the experimental data under different C_V as shown in Table 3.

$$RPD = a_2 Fl_G^{b_2} Fr^{c_2} \quad (12)$$

Table 3 shows that the exponents of Fr and Fl_G are both negative and the absolute value of factor b_2 is almost unchanged while c_2 decreases with the increase of C_V , which means that the influence of Fr on RPD is reduced. In addition, Fig. 10 shows that the effect of N on RPD in gas–liquid system is more obvious than that in gas–liquid–solid system with C_V

Table 2
Regression results of P_{mJSG} at different V_S

$V_S/\text{m}\cdot\text{s}^{-1}$	A_2	B_2	R^2
0	0.23	0.30	0.982
0.0074	0.23	0.19	0.894
0.015	0.27	0.16	0.923
0.024	0.31	0.15	0.939
0.039	0.35	0.079	0.883

Fig. 5. Relationship between N_{JSG} or P_{mJSG} and V_S at different C_V .Fig. 6. Relationship between ΔN_{JSG} or ΔP_{mJSG} and Q_G at different C_V .

of 15%. The exponent c_2 is only about half of that when C_V is 15% as shown in Table 3.

We use Eq. (13) to correlate C_V , Fr and Fl_G with RPD and obtain Eq. (14), where $0 \leq C_V \leq 15.0\%$, $0 \leq Fl_G \leq 0.31$ and $1.02 \leq Fr \leq 1.94$.

$$RPD = a_3 Fl_G^{b_3} Fr^{c_3} (1 + C_V)^{d_3} \quad (13)$$

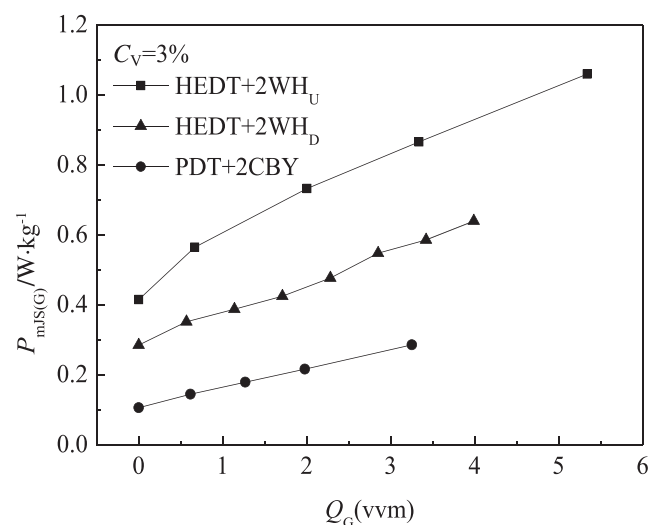
$$RPD = 0.58 Fl_G^{-0.14} Fr^{-0.17} (1 + C_V)^{-0.081} \quad R^2 = 0.944 \quad (14)$$

3.3. Overall gas holdup

Fig. 11 shows the relationship between the overall gas holdup ε_G and the total specific energy P_{Tm} under different C_V and V_S . P_{Tm} includes both the agitator shaft power and the potential energy of the liquid displaced by the sparged gas as reported in the literature [6]. The overall gas holdup increases when P_{Tm} increases under given C_V and V_S . With a higher power input, bubbles are easily broken, and dispersed in the stirred tank. This may elongate the residence time of bubble in the tank, which is beneficial to the gas hold-up. It also can be found in Fig. 11 that ε_G increases with the increase of V_S when P_{Tm} and C_V are the same. This is because the increase of V_S leads to a larger total volume fraction of gas in the system.

Moreover, Fig. 11 shows that ε_G decreases with the increase of C_V under the same V_S and P_{Tm} . The reason is that in a gas–liquid–solid system the power input is not only consumed for the gas dispersion and

liquid circulation but also the solid suspension. Therefore, the uniformity of gas dispersion in the gas–liquid–solid system is not as well as that in the gas–liquid system under a given P_{Tm} . Moreover, bubbles usually break up in the discharge area of impellers and then coalesce in the circulation area with lower shear rate. The existence of solids may

Fig. 7. Comparison of P_{mJSG} for different tripe-impeller combinations.

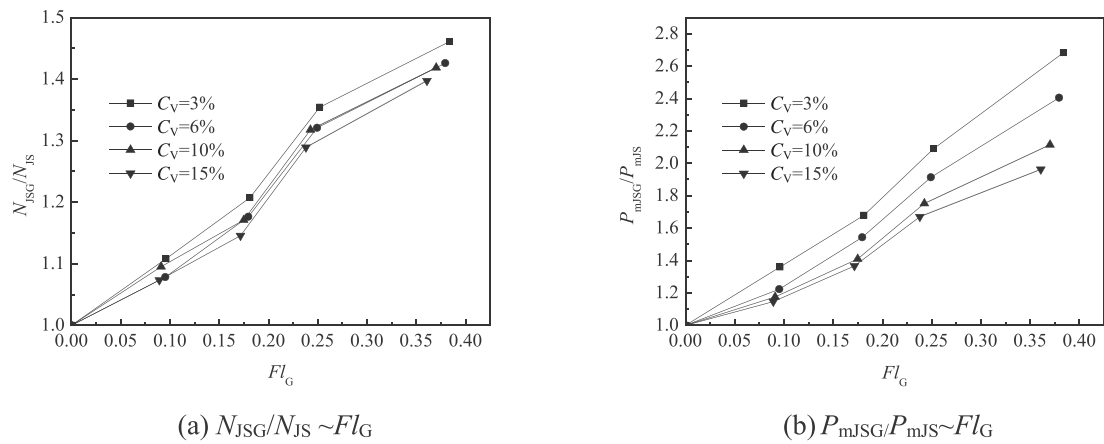


Fig. 8. Relationship between N_{JSG}/N_{JS} or P_{mJSG}/P_{mJS} and Fl_G under different C_V .

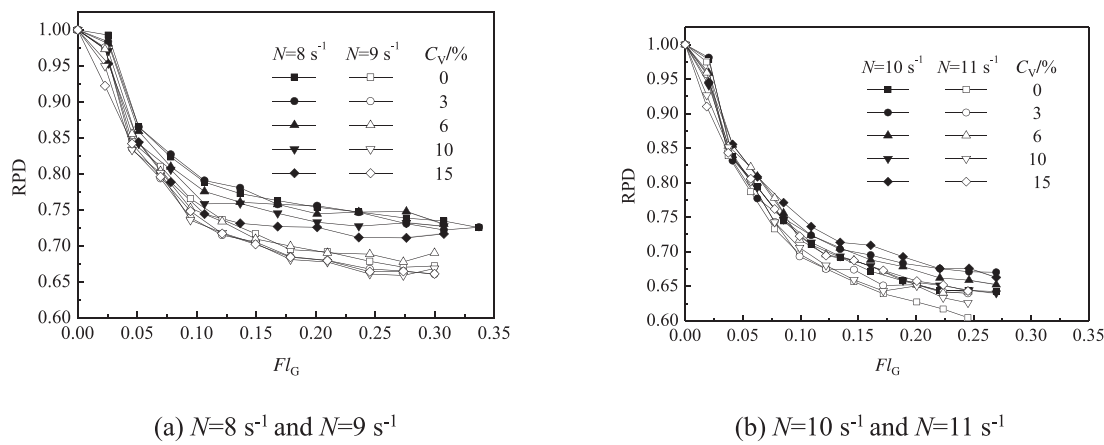


Fig. 9. Relationship between RPD and Fl_G under various C_V .

decrease the turbulence intensity in that region and weaken the bubble breakup, as a result, ε_G in gas–liquid–solid system with C_V of 15% decreases about 10% to 13% compared with those in two phase systems.

Chen [28], working on the HEDT + 2WH_U impellers under the experimental conditions ($T = 24\text{ }^{\circ}\text{C}$, $V_S = 0.0237\text{ m}\cdot\text{s}^{-1}$, $C_V = 0, 6\%, 15\%$), measured the gas holdup and obtained the similar results that the gas holdup decreases with the increase of C_V . When C_V is 15%, the gas holdup decreases about 10% to 25% compared with that in the gas–liquid systems. Fig. 12 compared the gas holdups for PDT + 2CBY and HEDT + 2WH_U and showed that gas holdups for HEDT + 2WH_U is 9% and 4% higher than those for PDT + 2CBY at given P_{Tm} of $1.0\text{ W}\cdot\text{kg}^{-1}$, corresponding to C_V of 0% and 6%, respectively. However, when C_V is 15%, the gas holdup for PDT + 2CBY is about 7% higher than that for HEDT + 2WH_U. It should be noted that the power numbers for PDT + 2CBY and HEDT + 2WH_U are 2.2 and 4.2, respectively, so PDT + 2CBY is usually used at lower P_{Tm} , while HEDT + 2WH_U is suggested in the case of higher P_{Tm} .

Table 3
Regression results of RPD under different C_V

$C_V/\%$	a_2	b_2	c_2	R^2
0.0	0.58	−0.15	−0.23	0.954
3.0	0.58	−0.14	−0.19	0.941
6.0	0.58	−0.14	−0.15	0.955
10.0	0.57	−0.15	−0.17	0.957
15.0	0.57	−0.14	−0.10	0.965

We use Eq. (15) to quantify the effect of V_S and P_{Tm} on ε_G under different C_V , and the results are shown in Table 4.

$$\varepsilon_G = \alpha_2 P_{Tm}^{b_2} V_S^{c_2} \quad (15)$$

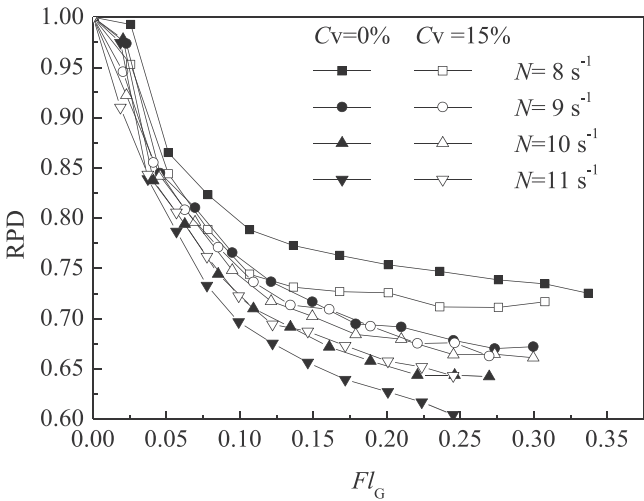


Fig. 10. Relationship between RPD and Fl_G under various N .

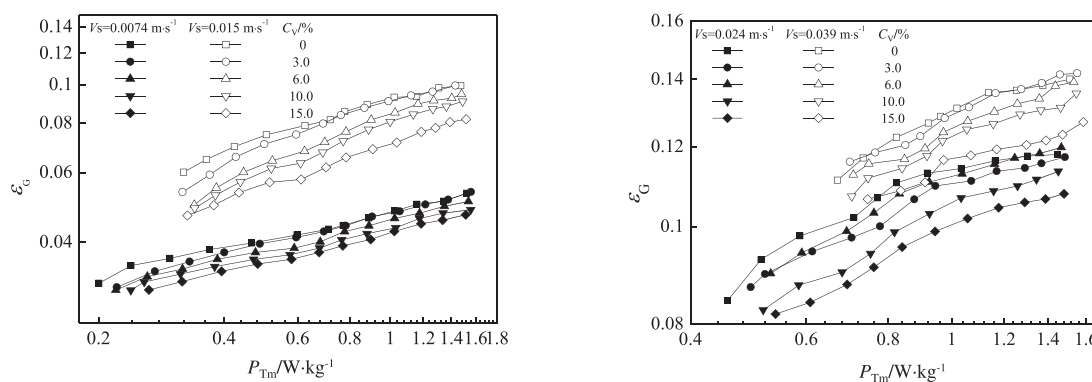


Fig. 11. Relationship between overall gas holdup and C_V at different V_S .

In Table 4, the exponents of V_S are about twice of those of P_{Tm} , implying that it's more efficient to increase ε_G by introducing more gas than by inputting more power.

Considering the influence of P_{Tm} , V_S and C_V on the overall gas holdup, we use Eq. (16) to correlate the experimental data as follow, and the regressed result is shown as Eq. 17.

$$\varepsilon_G = \alpha_3 P_{Tm}^{\beta_3} V_S^{\gamma_3} (1 + C_V)^{\eta} \quad (16)$$

$$\varepsilon_G = 0.73 P_{Tm}^{0.29} V_S^{0.52} (1 + C_V)^{-1.01} \quad R^2 = 0.965 \quad (17)$$

The exponent of $(1 + C_V)$ is negative, which means that ε_G decreases with the increase of C_V . It should be considered that Eq. (17) is suitable for this case of PDT + 2CBY combination operating under $0 \leq C_V \leq 15.0\%$, $0.22 \leq P_{Tm} \leq 1.59 \text{ W} \cdot \text{kg}^{-1}$ and $0.0074 \leq V_S \leq 0.039 \text{ m} \cdot \text{s}^{-1}$.

Chen [28] proposed a similar equation $\varepsilon_G = 0.89 P_{Tm}^{0.16} V_S^{0.55} (1 + C_V)^{-1.78}$ for HEDT + 2WH_U. Compared with Eq. (17), we found that the exponent of P_{Tm} with HEDT + 2WH_U is obviously smaller than that for PDT + 2CBY because of the different power consumption ranges as shown in Fig. 12. Specifically, P_{Tm} for HEDT + 2WH_U ranges from 0.90 to $5.00 \text{ W} \cdot \text{kg}^{-1}$ but P_{Tm} for PDT + 2CBY ranges from 0.22 to $1.59 \text{ W} \cdot \text{kg}^{-1}$, much lower than that for HEDT + 2WH_U. As an instructive direction for the industrial design, it is not always effective to improve the gas dispersion performance by increasing power consumption as we expected, especially when P_{Tm} is already pretty high. In addition, the absolute value of the exponent of $(1 + C_V)$ in the case of HEDT + 2WH_U is larger than that of PDT + 2CBY,

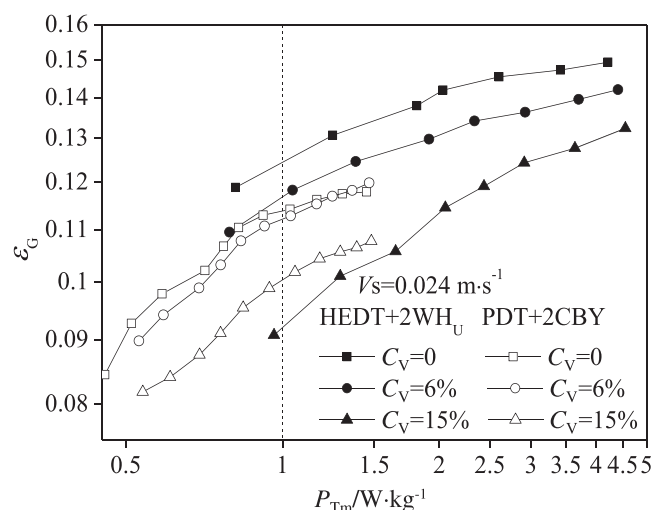


Fig. 12. Overall gas holdups for different tripe impeller combinations.

which means C_V has a larger influence on the overall gas holdup in the stirred tank agitated by HEDT + 2WH_U.

4. Conclusions

The hydrodynamics of triple impeller PDT + 2CBY is experimentally investigated in gas–liquid–solid systems. In the gas–liquid system [15], the optimized value of D to that of tank D/T is 0.33 for gas dispersion under high gas superficial velocity, with a favorable balance between the gas recirculation and shear rate level. With this D/T , in order to research the influence of solid on the hydrodynamics in a three-phase stirred tank, the solid suspension and gas dispersion properties in air–water–glass beads system were studied in this work.

In the gas–liquid–solid system, the solid critical suspension speed, relative power demand and overall gas holdup were measured. Both N_{JSG} and the corresponding critical specific power consumption P_{mJSG} increase with the increasing solid concentration C_V , with a power exponent smaller than that in the Zwietering's equation. With the introduction of gas into the solid suspension system, both N_{JSG} and P_{mJSG} increase with the increasing V_S , which is approximately following the linear regression.

RPD in the gas–liquid–solid system decreases with the increase of the flow number Fl_G and Froude number Fr , but changes little with the increasing C_V . RPD could be expressed as the function of Fl_G , Fr and C_V , $RPD = 0.58 Fl_G^{-0.14} Fr^{-0.17} (1 + C_V)^{-0.081}$. The overall gas holdup in the gas–liquid–solid system increases with the increase of P_{Tm} and V_S and decreases obviously with the increasing C_V . The gas holdup could be expressed as the function of P_{Tm} , V_S and the solid volumetric concentration $\varepsilon_G = 0.73 P_{Tm}^{0.29} V_S^{0.52} (1 + C_V)^{-1.01}$. Compared with another typical triple impeller combination HEDT + 2WH_U, PDT + 2CBY is suggested used in the operation of relative high shear rate and low power consumption, considering the overall gas hold-up. Meanwhile, the addition of solids into the stirred tank will affect the overall gas hold-up, but the influence on the low power number of narrow-blade combination PDT + 2CBY is weaker than the wide-blade combination HEDT + 2WH_U. The quantitative regression of N_{JSG} , RPD and gas holdup could be regarded as the references for the design of three phase stirred tank with similar impeller combination.

Table 4
Regression results of overall gas holdup under different C_V

$C_V/\%$	α_2	β_2	γ_2	R^2
0.0	0.68	0.26	0.50	0.956
3.0	0.68	0.28	0.51	0.968
6.0	0.69	0.31	0.51	0.960
10.0	0.68	0.31	0.53	0.973
15.0	0.71	0.29	0.55	0.976

Nomenclature

C	clearance of impeller off the tank bottom, mm
C_V	volumetric solid concentration, $\text{m}^3 \cdot (\text{m}^3 \text{ suspension})^{-1}$
D	diameter of impeller, mm
Fl_G	gas flow number; $Fl_G = Q/ND^3$
Fr	Froude number; $Fr = N^2 D/g$
g	gravity acceleration, $\text{m} \cdot \text{s}^{-2}$
H	dished-bottom correction factor, mm
H_G	height of liquid with gas, mm
H_0	height of liquid in an ungassed stirred tank, mm
N	impeller speed, s^{-1}
N_{JS}	just-suspension speed in the solid–liquid system, s^{-1}
N_{JSG}	just-suspension speed in the gas–solid–liquid system, s^{-1}
P_{mJS}	specific just-suspension power input in the solid–liquid system, $\text{W} \cdot \text{kg}^{-1}$
P_{mJSG}	specific just-suspension power input in the gas–solid–liquid system, $\text{W} \cdot \text{kg}^{-1}$
P_m	specific power input, $\text{W} \cdot \text{kg}^{-1}$
P_{Tm}	total specific power input, $\text{W} \cdot \text{kg}^{-1}$
Q	gas flow rate, $\text{m}^3 \cdot \text{s}^{-1}$
Q_G	volume of gas per volume of unaerated liquid per minute, vvm
RPD	relative power demand, defined as the ratio of the gassed to un-gassed power input (P_G/P_U)
T	diameter of the stirred tank, mm
V_S	superficial gas velocity, $\text{m} \cdot \text{s}^{-1}$
X	solid mass concentration, $\text{kg solid} \cdot (\text{kg liquid and solid mixture})^{-1}$
ε_G	overall gas holdup

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