

Experimental Analysis of Conditions of Gas-Liquid-Floating Particles System Production in an Agitated Vessel Equipped with Two Impellers

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The characteristic flow patterns of the three-phase gas-floating particles-liquid system produced in a baffled agitated vessel with two high-speed impellers on the common shaft were experimentally determined. The minimum impeller speeds adequate to obtain loading, complete dispersion and just drawdown (of floating particles) flow patterns for such multiphase system were identified. The results confirmed that there is influence of gas flow rate V_g and particles concentration X on the value of minimum impeller speeds for each flow model (n_{JD} , n_L , n_{CD} , n_{JDG}) and gas hold-up ϕ in analyzed systems.

1. Introduction

Mechanically agitated multiphase systems are used in many industries, including chemical, petrochemical, polymerization, food or fermentation. In every multiphase system it is necessary to ensure the greatest possible contact between dispersed and continuous phases.

In literature, different aspects of the hydrodynamics and mass transfer are analysed for the solid-liquid, gas-liquid and gas-solid-liquid systems. Investigations of gas-liquid systems were performed for: different types of impeller (Nienow and Lilly (1996)); different multi-impeller configurations (Moucha et al. (2003)); mixture flow and bubbles distribution (Montante et al. (2006)); experimental PIV analysis and CFD modelling of gas-liquid flow (Montante et al. (2007)); effect of liquid phase properties on $k_L a$ coefficient value (Kielbus-Rapala et al. (2011)); aspects of hydrodynamics and mass transfer in fermenters (Petříček et al. (2018)). Studies of gas-solid-liquid system hydrodynamics were carried out for: critical impeller speeds (Zhu and Wu (2002)); critical impeller speed, power consumption and gas hold up (Kielbus-Rapala and Karcz (2010)), conditions of solid and gas bubbles dispersion in the vessel with two impellers (Kielbus-Rapala and Karcz (2012)).

Density of the particles used as dispersed phase can be greater (conventional suspension) or lesser (floating particles) than density of the continuous phase. In the floating particles-liquid systems, contrary to the conventional suspension, where the particles should be suspended from the bottom of the vessel, the formation of the suspension involves drawing floating particles under the surface of the liquid and distributing them in its volume. The conditions of such systems production are affected by many factors (Etchells, 2001), for example: geometrical parameters of the vessel (Ozcan-Taskin (2006); Khazam and Kresta (2009); baffles configuration (Karcz and Mackiewicz (2009)); Atibeni et al. (2013)), agitator type (Ozcan-Taskin and Wei (2003); Karcz and Mackiewicz (2006)); agitators number, their size and location (Wójtowicz (2014)), as well as solids properties: its wettability (Karcz and Mackiewicz (2007)) or size and concentration of particles (Wood et al. (2018)). Mechanically agitated multiphase systems with the floating particles are studied experimentally and numerically (Liu et al. (2017)).

The presence of the gas phase in the floating particles-liquid system is the additional factor which affects the impeller speed at which floating particles are drawing under the liquid surface and dispersed into the liquid volume. Compared to the two phase floating particles-liquid systems, only several research works are devoted to three phase systems with such particles (Bakker and Frijlink (1989); Xu et al. (2001), Bao et al. (2005)).

The aim of this research work was to analyse the conditions of the production of gas-floating particles-liquid system in the agitated vessel of inner diameter $D = 0.288$ m with two impellers. The effect of gas flow rate V_g , the particles diameter d_p and concentration X on the critical agitation speeds n_{JDG} necessary to create gas-floating particles-liquid system, and the gas hold-up ϕ in this system was studied.

2. Experimental

The measurements were conducted in the transparent, cylindrical, baffled vessel of inner diameter $D = 0.288$ m and working liquid volume $V_L = 0.02$ m³ (Figure 1a). The set of two high-speed agitators located on the common shaft were used for agitation. Rushton turbine (Figure 1b) was used as the lower agitator. Its role was breaking gas bubbles to smallest and distribution them into the volume of liquid. The upper agitator, whose main task was drawing down floating particles under the surface of the liquid, was pitched blade turbine with six blades inclined at an angle $\beta = 45^\circ$, generating mixed flow: radially-axial with the predominant axial component, pumping the fluid towards the free surface (PBT $\hat{\uparrow}$, Figure 1c). Geometrical parameters of the impellers are collected in Table 1.

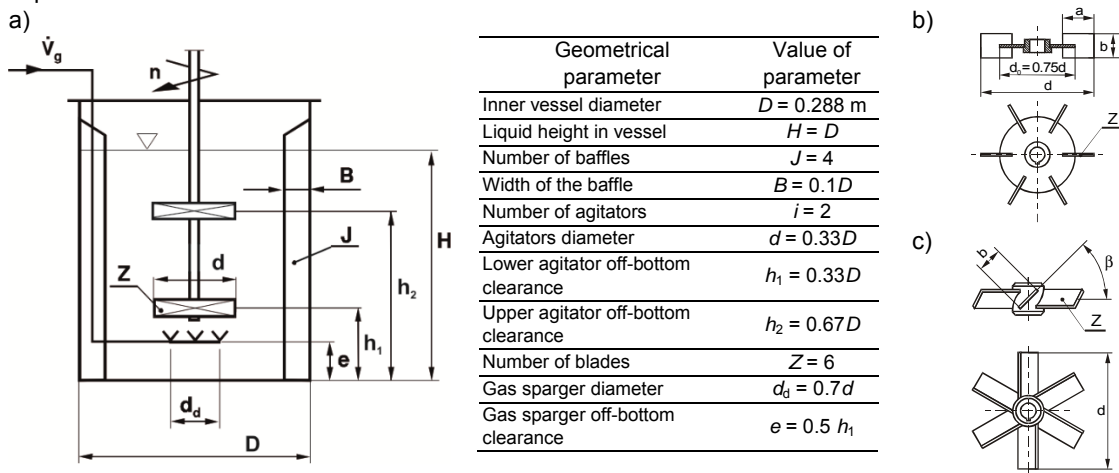


Figure 1: Agitated vessel and impellers used in the study; a) geometrical parameters of the vessel; b) Rushton turbine RT, c) pitched blade turbine PBT $\hat{\uparrow}$

Table 1: Geometrical parameters of the impellers use in the study

No.	Impeller	d/D	a/d	b/d	Z	β
1.	Rushton turbine RT	0.33	0.25	0.2	6	
2.	Pitched blade turbine PBT $\hat{\uparrow}$	0.33		0.2	6	45°

The measurements were carried out in coalescing and non-coalescing systems. The details of the liquid and solid phases are presented in the Table 2. Gas phase was air. All the experiments were conducted within the turbulent regime of the fluid flow in the agitated vessel. Operating conditions are shown in Table 3.

Table 2: Phase properties

Phase		Density at 21°C	Comments
Liquid phase	Distilled water	$\rho = 998$ kg/m ³	in coalescing system
	Aqueous solution of sodium chloride with concentration $C = 0.4$ kmol/m ³	$\rho = 1013.7$ kg/m ³	in non coalescing system
	Aqueous solution of sodium chloride with concentration $C = 0.8$ kmol/m ³	$\rho = 1030$ kg/m ³	in non coalescing system
Solid phase	Polyethylene particles	$\rho_p = 955$ kg/m ³	$d_p = 3.025$ mm

Table 3: Operating conditions used in the studies

Parameter	Range of the values	Comments
Gas flow rates, V_g	0 - 4.44×10^4 m ³ /s	6 different values
Solid concentration, X	0 - 5 % by wt.	5 different values

The minimum agitator speeds n_L , n_{CD} and n_{JD} , at which the characteristic flow patterns of multiphase mixture were obtained, were determined visually, observing for each solid concentration X and each gas stream V_g the behaviour of the dispersed phases. n_L is the minimum impeller speed at which *loading model* of mixture flow is observed, n_{CD} is the minimum agitator speed at which *complete dispersion* of gas bubbles is obtained, whilst n_{JD} is the minimum impeller speed at which the floating particles are *just drawing down* into the liquid. n_{JD} is analogous quantity to the minimum impeller speed n_{JS} for conventional suspension, at which the particles are just suspended in the liquid volume (according to Zwietering criterion (Zwietering (1958))).

In addition, for the n_{JDG} speed, at which complete gas dispersion occurred simultaneously with the particles suspension (a three-phase system was created), gas hold-up value φ was determined. The gas hold-up φ was determined from the following definition

$$\varphi = \frac{V_g}{V_g + V_L} = \frac{h_g}{h_g + H} \quad (1)$$

where V_g denotes the volume of gas phase, V_L – volume of the liquid phase; h_g – difference between heights of multiphase and liquid phase systems; H – liquid height in the agitated vessel. The averaged value of the gas hold-up φ was determined from 10 readings of the multiphase mixture height h_g on the scale located on the wall of the agitated vessel. For each series of 10 readings confidence intervals were estimated (according to definition $h_g = h_m \pm s(h_g)t$, in which: h_m is a mean value of mixture height, $s(h_g)$ is a standard deviation, whilst $t = 2.2622$ is value of Student test). The lowest value of the confidence interval, ascribed to $h_g = 13.1 \pm 1.98$ was obtained for the system with water as continuous phase, at $n_{JDG} = 8.53$ 1/s, $V_g = 2.78 \times 10^{-4}$ m³/s, and $X = 0.5$ mass %. The highest value of the confidence interval, ascribed to $h_g = 22.3 \pm 4.4$ was also obtained for the system with water, at $n_{JDG} = 10.6$ 1/s, $V_g = 3.89 \times 10^{-4}$ m³/s, and $X = 5$ % by wt.

3. Results and discussion

On the basis of the experimental studies the characteristic flow patterns of the three-phase gas-floating particles-liquid system produced in the agitated vessel equipped with two impellers on the common shaft were identified. The following flow models and corresponding to them minimum impeller speeds n were evaluated:

- for floating particles-liquid system: a) the floating particles are just drawing down into the liquid volume at minimum impeller speed n_{JD} ;
- for gas-liquid system: b) flooding (gas flows axially towards the liquid surface), c) loading (dispersion of gas bubbles only in the zone from lower impeller to the liquid surface, the minimum impeller speed for it is n_L); d) complete dispersion (dispersion of gas with recirculation under the lower impeller, bubbles are dispersed in a whole liquid volume, the minimum impeller speed for it is n_{CD}).
- for gas-floating particles-liquid system: e) both floating particles and gas bubbles are dispersed with recirculation in the liquid phase. Minimum impeller speeds for that pattern flow n_{JDG} were estimated by comparing, independently found, both values n_{JD} and n_{CD} and assuming that higher value from n_{JD} and n_{CD} corresponds to minimum impeller speed n_{JDG} , i.e. $n_{JDG} \geq$ higher value of n_{JD} and n_{CD} .

Chosen data of n_{JD} , n_L , n_{CD} , obtained in the system with three different particles mass fraction X are presented graphically as a function $n = f(V_g)$ in Figure 2. In this Figure on the left hand side the values of n for distilled water as a liquid phase (Figure 2a-c), whilst on the right – for aqueous solution of electrolyte with concentration 0,4 kmol/m³ (Figure 2d-f) are shown. The n_{JD} , n_L and n_{CD} values define the boundaries of characteristic flow models areas. The zone below the n_L (below the circle points in Figure 2) is the *flooding zone*, in which the capacity of impeller pumping is too low to disperse gas phase. The area between n_L and n_{CD} values (triangle points) is the *loading zone*, where dispersion of gas without recirculation is observed. Above the n_{JD} values (square points) the good drawn down behaviour of particles was obtained. The zone, in which good gas dispersion in the whole liquid volume simultaneously with drawing down of floating particles under the surface is observed (three phase system is created), is obtained above the greater values from n_{CD} (triangles) or n_{JD} (squares).

In the coalescing system (Figure 2a) at the lower mass fraction X of floating particles ($X = 0.5$ %) the drawing down of particles under the liquid surface demanded lower agitator speed values n_{JD} (squares) than even dispersion of gas bubbles n_{CD} (triangles). In this system there is strong effect of solids fraction X on the just drawn down agitator speed, n_{JD} values increased with an increase of X . In the system with the highest particles fraction ($X = 5$ mass %, Figure 2c) n_{JD} values were significantly higher in the whole range of gas flow rate V_g . It can be stated that at greater mass fraction of particles there is much easier to disperse gas bubbles than drawing down of solids. Generally, all n_{JD} , n_L , n_{CD} values increased with an increase of gas quantity.

In the system with the electrolyte, at the lowest particles fraction (Figure 2d), achieving just down down flow pattern required a slightly greater n_{JD} values comparing with coalescing system. For higher X the n_{JD} values were significantly lower comparing with the data for coalescing system. Generally, in the non-coalescing system in the whole range of particles fraction X , it was easier to immerse floating particles, than obtain complete gas dispersion. The values n_{CD} were higher than n_{JD} at every X , but the differences decreased with the increase of solid fraction.

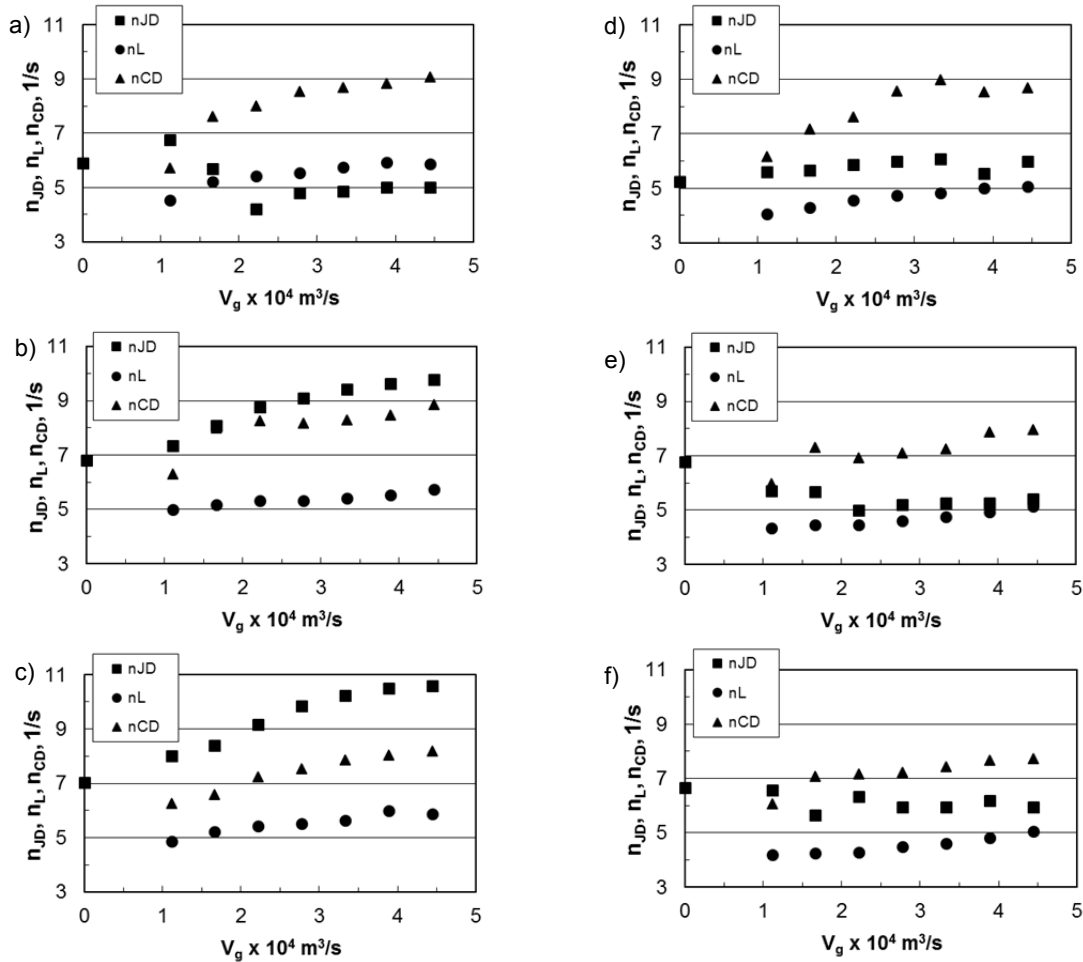


Figure 2: Comparison of the dependence n_{JD} , n_L , $n_{CD} = f(V_g)$ for the physical systems with different capability to gas bubbles coalesce; (a – c) liquid phase: distilled water; (d – f) liquid phase: aqueous solution of NaCl with concentration 0.4 kmol/m^3 ; different mass fractions X of particles; (a – d) 0.5 %; (b – e) 2.5 %; (c – f) 5 %

Comparing data for both systems: with distilled water and electrolyte it can be observed that, excluding small solid fraction ($X = 0.5\%$), significantly lower n_{JDG} values corresponded to non-coalescing system. That means, that to create three phase system lower agitator speed are required in non-coalescing system

The effect of gas flow rate V_g on the n_{JD} , n_L and n_{CD} values is shown in Figure 3. In this Figure the impeller speeds for two different values of V_g in the system with distilled water (Figure 3a) and aqueous solution of 0.4 kmol/m^3 NaCl (Figure 3b), obtained for five different mass fraction of floating particles, are compared. The change in the gas flow rates values influenced the most n_{CD} agitator speed. In each of analysed system, at the constant value of X , increasing of gas flow rate resulted in n_{CD} increase, independently of kind of continuous phase in the system. So it can be stated, that for the greater quantity of gas in the liquid, higher impeller speed are required to achieve complete dispersion of gas bubbles in the gas-floating particles-liquid system. For constant V_g value, slightly greater n_{CD} values were obtained for lower particles fraction X in coalescing system for all gas flow rates and in non-coalescing system for higher V_g values. The just down down agitator speed n_{JD} is also influenced by gas flow rate V_g . The strongest increase of n_{JD} value with the increase of V_g at $X = \text{const}$ was observed in coalescing systems with higher particles mass fraction. Concerning n_L agitator

speed a slightly greater values were achieved when gas flow rate was increased in all systems. It could be seen when comparing the values of n_L for the same particles fraction and different V_g . Analysing of the data presented in Figure 3 one can also observe how the values of characteristic agitator speeds changed with the increase of solid phase fraction X at a constant stream of gas V_g . The biggest increase characterised n_{JD} in the coalescing system.

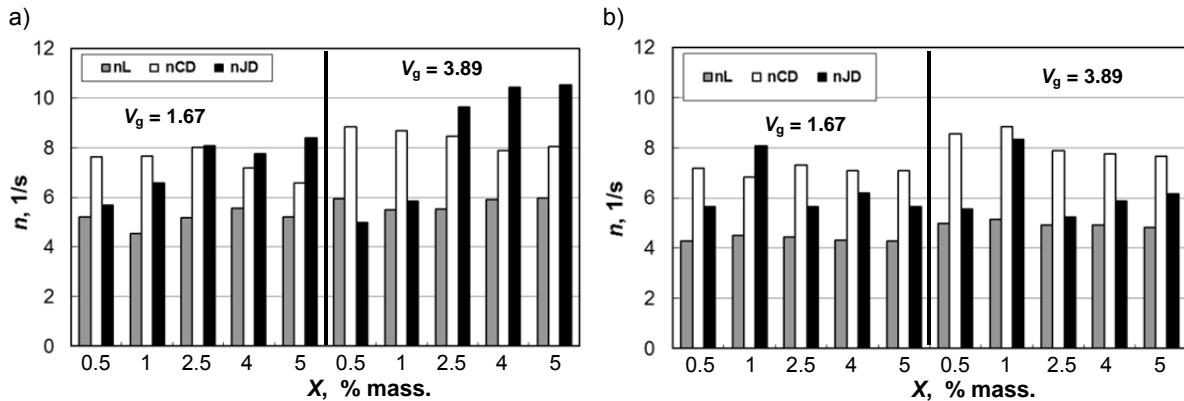


Figure 3: The effects of the floating particles concentration X and gas flow rate V_g on the minimum impeller speeds n_{JD} , n_L , n_{CD} ; a) liquid phase: distilled water; b) liquid phase: aqueous solution of NaCl with concentration 0.4 kmol/m^3 ; different values of gas flow rate $V_g = 1.67 \times 10^{-4} \text{ m}^3/\text{s}$ or $3.89 \times 10^{-4} \text{ m}^3/\text{s}$

In Figure 4 the comparison of the gas hold-up values for each analysed system, obtained at three chosen gas flow rates values, is presented. The ϕ values were measured for the agitator speed n_{JDG} , determined for each analysed system. Both: floating particles fraction X and gas flow rate V_g influenced gas hold-up ϕ . In the analysed gas-floating particles-liquid systems, gas hold-up values strongly increased with the increase of gas flow rate V_g for all particles fraction, independently of capability of the system to gas bubbles coalesce. The highest ϕ values were achieved in coalescing systems with higher particles fractions, but it should be noticed, that it correspond with significantly higher n_{JDG} , comparing to non-coalescing system.

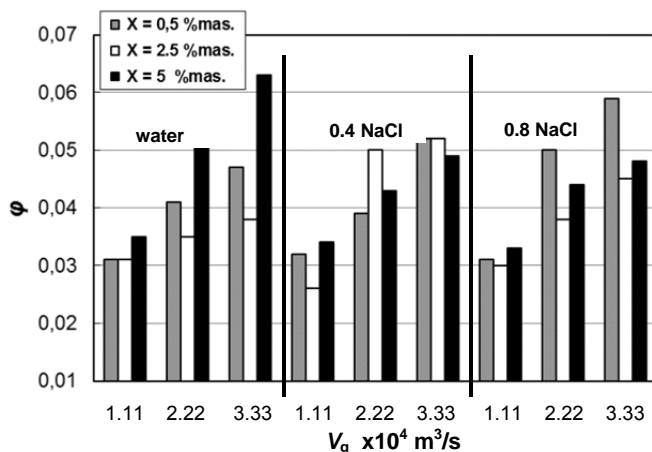


Figure 4: The effects of solids concentration X and gas flow rate V_g on the gas hold-up ϕ in gas-floating particles-liquid system

4. Conclusions

On the basis of the experimental analysis, the values of the critical impeller speeds n_{JD} , n_L and n_{CD} were determined and they were used to identify characteristic regions of the fluid flow of aerated suspension with floating particles produced in a baffled agitated vessel equipped with two high-speed impellers.

The results of the study show that within the range of the performed experiments:

1. The values of the just draw down impeller speed n_{JD} increased with the increase of both concentration X of the floating particles and gas flow rate V_g for the coalescing three-phase systems.
2. Lower n_{JD} values were obtained in non-coalescing system, especially for higher particles concentration.

3. Lower values of n_{JDG} were obtained in the system with electrolyte as a continuous phase therefore gas-floating particles mixture was easier to create in non-coalescing system.
4. Gas hold-up ϕ increased with the increase of the gas flow rate V_G , but the values of the ϕ depended on the floating particles concentration X and physical properties of the liquid phase.

Obtained results can be useful to project of mechanically agitated multiphase systems with floating particles of similar properties as studied in this paper.

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