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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 kLa coefficient value (Kiełbus-Rąpała 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 (Kiełbus-Rąpała and Karcz (2010)), conditions of solid and gas bubbles dispersion in the vessel with two impellers (Kiełbus-Rąpała 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 at 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.

* 1. 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 *β* = 45°, generating mixed flow: radially-axial with the predominant axial component, pumping the fluid towards the free surface (PBT↑, Figure 1c). Geometrical parameters of the impellers are collected in Table 1.

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| a) ***mieszalnik1*** | |  |  | | --- | --- | | Geometrical parameter | Value of parameter | | Inner vessel diameter | *D* = 0.288 m | | Liquid height in vessel | *H* = *D* | | Number of baffles | *J* = 4 | | Width of the baffle | *B* = 0.1*D* | | Number of agitators | *i* = 2 | | Agitators diameter | *d* = 0.33*D* | | Lower agitator off-bottom clearance | *h*1 = 0.33*D* | | Upper agitator off-bottom clearance | *h*2 = 0.67*D* | | Number of blades | *Z* = 6 | | Gas sparger diameter | *d*d = 0.7*d* | | Gas sparger off-bottom clearance | *e* = 0.5 *h*1 | | b) |  |
| c) |  |

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↑

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

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| No. | Impeller | *d/D* | *a*/*d* | *b*/*d* | *Z* | ** |
| 1. | Rushton turbine RT | 0.33 | 0.25 | 0.2 | 6 |  |
| 2. | Pitched blade turbine PBT↑ | 0.33 |  | 0.2 | 6 | 45º |

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

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| --- | --- | --- | --- |
| Phase |  | Density at 21ºC | Comments |
| Liquid phase | Distilled water | *ρ* = 998 kg/m3 | in coalescing system |
| Solid phase | Aqueous solution of sodium chloride  with concentration *C* = 0.4 kmol/m3  Aqueous solution of sodium chloride  with concentration C = 0.8 kmol/m3  Polyethylene particles | *ρ* = 1013.7 kg/m3  *ρ* = 1030 kg/m3  *ρ*p = 955 kg/m3 | in non coalescing system  in non coalescing system  *d*p = 3.025 mm |

Table 3: Operating conditions used in the studies

|  |  |  |  |
| --- | --- | --- | --- |
|  | Parameter | Range of the values | Comments |
|  | Gas flow rates, *Vg* | 0 - 4.44x104 m3/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 ** was determined from the following definition

(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 ** 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 ± 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 ± 1.98 was obtained for the system with water as continuous phase, at *n*JDG = 8.53 1/s, *V*g = 2.78x10-4 m3/s, and *X* = 0.5 mass %. The highest value of the confidence interval, ascribed to *h*g = 22.3 ± 4.4 was also obtained for the system with water, at *n*JDG = 10.6 1/s, *V*g = 3.89x10-4 m3/s, and *X* = 5 % by wt.

* 1. 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 > higher value of *n*JD and *n*CD.

Chosen data of nJD, nL, nCD, obtained in the system with three different particles mass fraction X are presented graphically as a function n = f(Vg) 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 nJD, nL and nCD values define the boundaries of characteristic flow models areas. The zone below the nL (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 nL and nCD values (triangle points) is the loading zone, where dispersion of gas without recirculation is observed. Above the nJD values (square points) the good drown 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 nCD (triangles) or nJD (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 nJD (squares) than evenly dispersion of gas bubbles nCD (triangles). In this system there is strong effect of solids fraction X on the just drown down agitator speed, nJD values increased with an increase of X. In the system with the highest particles fraction (X = 5 mass %, Figure 2c) nJD values were significantly higher in the whole range of gas flow rate Vg. 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 nJD, nL, nCD values increased with an increase of gas quantity.

In the system with the electrolyte, at the lowest particles fraction (Figure 2d), achieving just drown down flow pattern required a slightly greater nJD values comparing with coalescing system. For higher X the nJD 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 nCD were higher than nJD at every X, but the differences decreased with the increase of solid fraction.

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| --- | --- |
| d)  a) |  |
| e)  b) |  |
| f)  c) |  |

Figure 2: Comparison of the dependence nJD, nL, nCD = f(Vg) 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/m3; 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 nJDG values corresponded to non-coalescing system. That means, that to create three phase system lower agitator speed are required in non-coalescing system

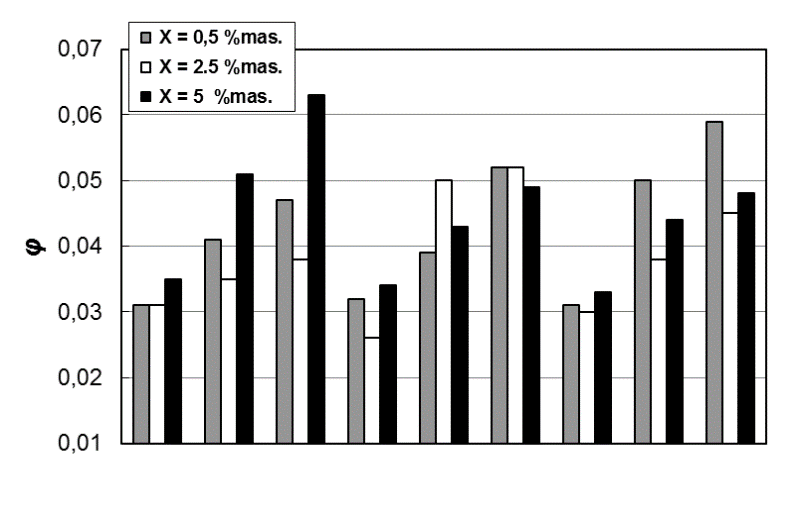
The effect of gas flow rate Vg on the nJD, nL and nCD values is shown in Figure 3. In this Figure the impeller speeds for two different values of Vg in the system with distilled water (Figure 3a) and aqueous solution of 0,4 kmol/m3 NaCl (Figure 3b), obtained for five different mass fraction of floating particles, are compared. The change in the gas flow rates values influenced the most nCD agitator speed. In each of analysed system, at the constant value of X, increasing of gas flow rate resulted in nCD 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 Vg value, slightly greater nCD values were obtained for lower particles fraction X in coalescing system for all gas flow rates and in non-coalescing system for higher Vg values. The just drown down agitator speed nJD is also influenced by gas flow rate Vg. The strongest increase of nJD value with the increase of Vg at X = const was observed in coalescing systems with higher particles mass fraction. Concerning nL 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 nL for the same particles fraction and different Vg.

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 Vg. The biggest increase characterised nJD in the coalescing system.

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| --- | --- |
| a) | b) |
| ***V*g = 3.89**  ***V*g = 1.67**  0.5 1 2.5 4 5 0.5 1 2.5 4 5  ***X*, % mass.** | ***V*g = 3.89**  ***V*g = 1.67**  0.5 1 2.5 4 5 0.5 1 2.5 4 5  ***X*, % mass.** |

Figure 3: The effects of the floating particles concentration X and gas flow rate Vg on the minimum impeller speeds nJD, nL, nCD; a) liquid phase: distilled water; b) liquid phase: aqueous solution of NaCl with concentration 0.4 kmol/m3; different values of gas flow rate Vg = 1.67 x 10-4m3/s or 3.89 x 10-4m3/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 nJDG, determined for each analysed system. Both: floating particles fraction X and gas flow rate Vg 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 Vg 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 nJDG, comparing to non-coalescing system.



**0.8 NaCl**

**0.4 NaCl**

1.11 2.22 3.33 1.11 2.22 3.33 1.11 2.22 3.33

***V*g x104 m3/s**

**water**

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

* 1. 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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