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Hydrodynamics of biophase-gas-liquid systems in a vessel equipped with vertical tubular baffles

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Abstract
The influence of the impeller type, impeller speed, volumetric gas flow rates, type of sugar and type of yeast on the hydrodynamics (gas hold-up and residence time of gas bubbles) in a vessel with 24 vertical tubular baffles has been presented in this paper. The measurement of hydrodynamics was conducted in the vessel with inner diameter $D = 0.288$ m and liquid height of $H = 0.288$ m. Three different agitators were used in the experimental study. Seven different series, three of which refer to the two-phase system and four to the three-phase system were mixed in the vessel. The influence of gas flow number, Weber number, the mass fraction of aqueous sugar solution c_i, and mass fraction of yeast suspension y_{ss} for two- and three-phase systems on the gas hold-up φ were described mathematically. These equations do not have equivalents in the literature.

Keywords
mixing, gas-liquid or biophase-gas-liquid, gas hold-up, residence time of gas bubbles, vertical tubular baffles

1. INTRODUCTION

Yeast is probably one of the earliest organisms used (Aouizerat et al., 2019; Kręgiel et al., 2008; Kunicka and Rajkowska, 2010; Legras et al., 2007; Robak et al., 2017). The most commonly used species in science and in industrial applications is the yeast *Saccharomyces cerevisiae*. In terms of industrial applications, the individual strains are used in various food fields (in bakery, brewing, distillery, etc.). From a scientific point of view, their use is beneficial not only because of their rapid growth, but also because of their relatively low and uncomplicated cultivation requirements. In the case of standard gas-liquid systems, detailed and long-term studies are needed to determine the appropriate conditions for such systems (Amiraftabi et al. 2020; Jamshidzadeh et al., 2020; Jamshed et al., 2018; Montante and Paglianti, 2015; Mueller and Dudukovic, 2010). The addition of the third phase, the solid, prolongs this process even further (Major-Godlewska and Karcz, 2012). On the other hand, the most complicated and problematic situation occurs when the solid is replaced by microorganisms (biological phase) (Cudak and Rakoczy, 2022; Gelves et al., 2014; Khalili et al., 2018; Major-Godlewska and Cudak, 2024). In order to obtain appropriate hydrodynamics of systems with a biological phase, it is necessary to observe appropriate conditions that will allow for the proper conduct of tests and permit their repetition. These conditions include the appropriate selection of biological phase (microorganisms), liquid phase (nutrients, culture medium), environmental factors, and geometric, operational and physical parameters. Two of them, the nutrient and the conditions of the process, are related to the selection of the biological phase (microorganisms). The survival, growth rate and metabolic activity of microorganisms are determined by their structure and physiology and the influence of environmental factors. The effects of these interactions depend on their type and intensity and on the properties of the organisms they affect. The main factors influencing the growth of microorganisms are: temperature, pH in the environment, oxidation-reduction potential, water activity in the environment and hydrostatic pressure (Kowal, 2010; Szewczyk, 2003).

Obtaining the appropriate hydrodynamics (gas hold-up or residence time of gas bubbles) of three-phase systems with a biological phase depends on the appropriate selection of individual geometric, operational and physical parameters. There are many papers in the literature describing the influence of individual parameters on gas hold-up or time spent in liquid of gas bubbles. Both one and the other depend on the geometry of the system – the type of bioreactor (with or without compartments) and the mixture (type, number, location of the mixtures) (Bao et al., 2015; Busciglio et al., 2013; Liu et al., 2020; Major-Godlewska and Karcz, 2011; Saravanan et al., 2009; Wan et al., 2016; Xie et al., 2014; Yang et al., 2014). A properly selected impeller or impeller configuration allows for adequate dispersion of gas bubbles in the system (adequate aeration of the system) and uniform dispersion of the biophase (Cudak, 2014, 2020; Frankiewicz and Woziwodzki, 2023; Major-Godlewska and Radecki, 2018; Moucha et al., 2003; Newell and Grano, 2007; Petříček et al., 2018; Rahimzadeh et al., 2022; Saravanan et al., 2009; Wan et al., 2016; Xie et al., 2014). In the case of systems with a biological phase, the choice of the mixer is somewhat narrowed due to the stresses produced by the impeller blades (Bustamante et al., 2013; Campesi et al., 2009; Collignon et al., 2010; Cudak and Rakoczy, 2022; de Jesus et al., 2017; Major-Godlewska and Cudak, 2024; Newell and Grano, 2007;

Yang et al., 2014). Ensuring the appropriate conditions in the system also depends on the operating parameters, i.e. the impeller speed or the volumetric flow of the gas through the system. Both these parameters are closely related because the higher the gas flow rates in the system, the greater the impeller speed at which good dispersion of the gas in liquid is obtained (Barros et al., 2022; Busciglio et al., 2013; Cudak, 2014; 2016; Major-Godlewska and Radecki, 2018; Montante and Paglianti, 2015; Mueller and Dudukovic, 2010; Petříček et al., 2018).

The paper presents the results of research on the hydrodynamics of multiphase systems in a vessel with an impeller and vertical tubular baffles. The yeast used for sweet products in the study was compared with the yeast used for traditional products, discussed in detail in the by Major-Godlewska and Cudak (2024).

2. MATERIALS AND METHODS

The materials used in the studies of hydrodynamics of multiphase systems were: air as the gas phase, distilled water and aqueous solutions of glucose (c_g) and sucrose (c_s) as the liquid phase, and the yeast (y_s) *Saccharomyces cerevisiae* as the biophase. Due to their application, yeasts used for savory products (y_{st}) or sweet products (y_{ss}) can be distinguished.

The analysis of the hydrodynamics of multiphase systems in a vessel with vertical tubular baffles was performed for three gas-liquid systems: air–distilled water, air–aqueous solution of glucose with a mass fraction of $c_g = 0.06$ kg$_A$/kg, air–aqueous solution of sucrose with a mass fraction of $c_s = 0.06$ kg$_A$/kg and for four biophase-gas-liquid systems: air as a gas, aqueous solution of glucose or sucrose with a mass fraction of $c_i = 0.06$ kg$_A$/kg as liquid and the fresh pressed baker's yeast *Saccharomyces cerevisiae*, for traditional and sweet products, produced by Lesaffre Polska S.A. with mass fraction $y_{si} = 0.02$ kg$_A$/kg as biophase.

The properties of fluids such as dynamic viscosity coefficient η, density ρ and surface tension σ for Newtonian fluids, including distilled water and aqueous solutions of glucose (c_g) and sucrose (c_s) are presented in Major-Godlewska and Cudak (2024). The range of rheological parameters such as flow index m and consistency index K of non-Newtonian fluids (biofluids) and the values of density ρ and surface tension σ are presented in Table 1. Fluid properties measurements were performed at the temperature range of 22–25 °C, corresponding to the temperature of hydrodynamic measurements. Rheological parameters were determined using a system of two coaxial cylinders (DG 41) with a rheoviscometer of RT 10 manufactured by Haake. Rheological measurements were performed for the shear rate $\dot{\gamma} \leqslant 500$ 1/s. The values of apparent viscosity η_{BL} coefficient for non-Newtonian liquids were calculated from Equation (1):

$$\eta_{BL} = K \cdot \dot{\gamma}^{(m-1)} \tag{1}$$

The gas hold-up was conducted in a vessel with an internal diameter of $D = 0.288$ m filled with liquid to $H = 0.288$ m. An interesting solution was to replace standard vertical flat baffles with vertical tubular baffles (Major-Godlewska and Cudak, 2022; 2024; Major-Godlewska and Radecki, 2018). A geometric system of vertical tubular baffles – high speed impeller is characterized by a lower value of the power number Ne in the case of liquids (single-phase system) (Major-Godlewska and Karcz, 2018). Additionally, vertical tubular baffles used as coils (Karcz and Major, 2001) can be used to maintain a constant process temperature, important from the point of view of bioprocess. The vertical tubular $J = 24$ baffles (diameter of a single baffle tube $B = 0.02D$), placed symmetrically around the circumference $D_B = 0.7D$ of the vessel were used for the hydrodynamics of the system tests. For mixing, impellers with a standard diameter $d = 0.33D$ were used, differing in type and number of Z blades. Two turbine type impellers: Rushton turbine (RT, $Z = 6$) and Smith turbine (CD6, $Z = 6$) and one A315 impeller ($Z = 4$) were used to mix the produced systems (Fig. 1). Rushton turbine impeller (RT) was used as a standard impeller and two impellers (CD6 and A315) that generate lower shear stresses, beneficial for biological systems, were selected for mixing. The gas was supplied to the liquid by a ring shaped gas distributor with a diameter $d_g = 0.7d$ placed halfway ($e = 0.5h$ and $h = 0.17H$, where h was the distance of the impeller from the bottom) between the impeller and the bottom of the vessel. The gas distributor had 6 holes placed symmetrically, each with a diameter of 2 mm. The air supplied from the compressor flowed through a vessel filled with distilled water to humidify it before being fed to the system.

The studies of hydrodynamics of the biophase-gas-liquid system with the use of yeast for sweet products were performed for turbulent fluid flow in the system $\mathrm{Re} = \langle 2.8{\cdot}10^4; 8.4{\cdot}10^4 \rangle$, assuming n_{cr} as the lowest values at which good gas dispersion in the liquid occurs. The standard criterion for assessing the proper dispersion of gas in a mixed liquid (good gas dispersion) is the condition in which gas bubbles circulate with the liquid in the entire volume (gas bubbles are located both above and below the impeller) (Kamieński, 2004). The values of $n_{cr} = f$ (biophase-gas-liquid system) for the three impellers used in the studies: Rushton turbine (RT), Smith turbine (CD6) and A315 and three volumetric gas flow rates $Q_{GV} = 0.89$; 1.33; 1.78 vvm (with the gas flow rates $\dot{V}_g = 2.78 \cdot 10^{-4}$; $4.17 \cdot 10^{-4}$; $5.56 \cdot 10^{-4}$ m^3/s) are presented in Fig. 2. The volumetric flow rate of gas fed to the system, presented as the volumetric gas flow rate Q_{GV} (the ratio of the volume flow rate of gas through the vessel in m^3/min to the volume of liquid in the vessel in m^3, vvm), enables the comparison of the results presented in this work with other results obtained in vessels of different scale. This is possible because the volumetric gas flow rate Q_{GV} is one of the four (along with the peripheral velocity of the end of the impeller blades, the specific energy consumption or the conventional linear gas velocity) scaling criteria (Tatterson, 1994).

Table 1. Ranges of rheological parameters m and K, density ρ and surface tension σ for the non-Newtonian liquid (biofluid).

Biophase-liquid system	Ranges m	Ranges K [Pa·s^m]	ρ [kg/m^3]	σ [N/m]
Aqueous solution of glucose $c_g = 0.06$ kg$_A$/kg and traditional yeast $y_{st} = 0.02$ kg$_A$/kg (Major-Godlewska and Cudak, 2024)	0.755–0.837	0.00725–0.00379	1021	0.0802
Aqueous solution of glucose $c_g = 0.06$ kg$_A$/kg and sweet yeast $y_{ss} = 0.02$ kg$_A$/kg	0.792–0.933	0.00559–0.00266	1022	0.0812
Aqueous solution of sucrose $c_s = 0.06$ kg$_A$/kg and traditional yeast $y_{st} = 0.02$ kg$_A$/kg (Major-Godlewska and Cudak, 2024)	0.821–0.847	0.00469–0.00418	1024	0.0812
Aqueous solution of sucrose $c_s = 0.06$ kg$_A$/kg and sweet yeast $y_{ss} = 0.02$ kg$_A$/kg	0.813–0.96	0.00521–0.00204	1024.5	0.0837

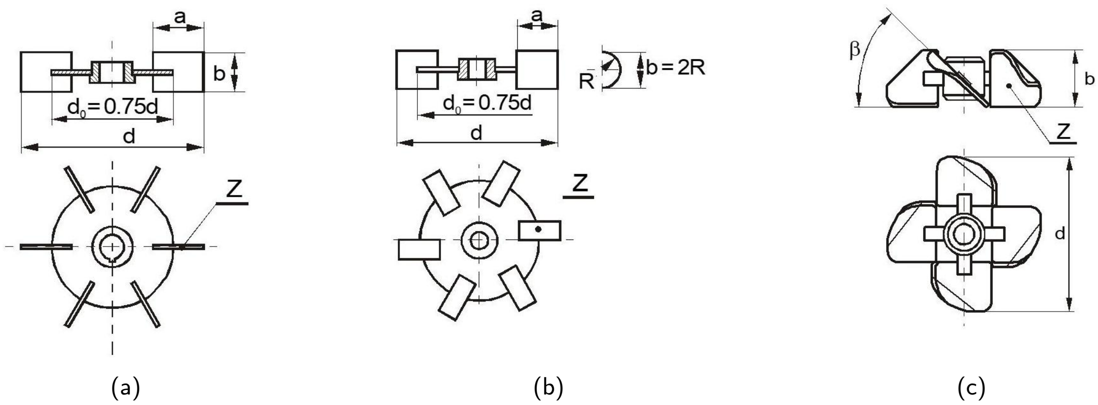


Figure 1. Impellers used in the research a) Rushton turbine impeller (RT); b) Smith turbine impeller (CD6); c) A 315 impeller.

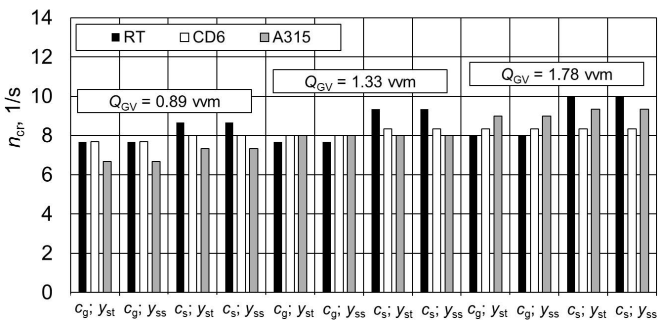


Figure 2. Dependence $n_{cr} = f$ (type of biophasa-gas-liquid).

The gas hold-up measurements were conducted for the range of good dispersion of gas bubbles in liquid and calculated from Equation (2):

$$\varphi = \frac{h_g}{h_g + H} \tag{2}$$

where values h_g – determined as height of a gas-liquid or biophase-gas-liquid mixture in the agitated vessel (which was calculated as the average with 10 values of h_g) and H – liquid height in the agitated vessel.

The residence time of gas bubbles in the system was calculated from Equation (3):

$$t_R = \frac{V_l \varphi}{\dot{V}_g (1 - \varphi)} \tag{3}$$

where: V_l – a volume of liquid (or biophase-liquid).

3. RESULTS AND DISCUSSION

The analysis of the hydrodynamics studies of two- and three-phase systems was carried out on the basis of seven different series, three of which refer to the two-phase system and four to the three-phase system.

The influence of the impeller speed n and the volumetric gas flow rate Q_{GV} for systems in which the gas phase was air and the liquid phase was distilled water, aqueous sugar solutions (c_g, c_s) and aqueous sugar solutions with yeast (y_{st}, y_{ss}), which in this case were the biophase, is shown in Figs. 3 and 4. Based on the data presented in Fig. 3, it was found that at the constant volumetric gas flow rate of $Q_{GV} = 1.33$ vvm,

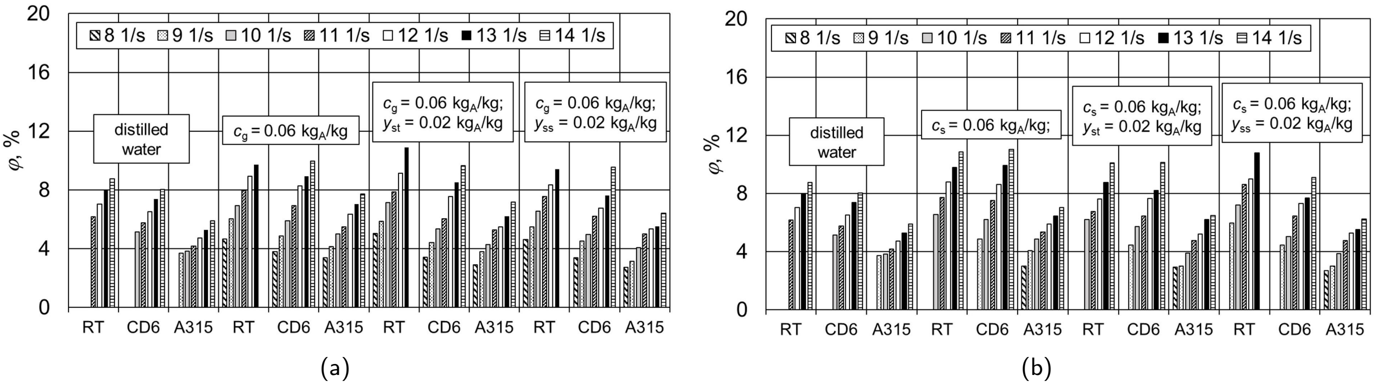


Figure 3. Dependence $\varphi = f$(type of impeller) for volumetric gas flow rate $Q_{GV} = 1.33$ vvm distilled water, aqueous solution of glucose (c_g), aqueous solution of glucose (c_g) with two types of baker's yeast (a) and distilled water, aqueous solution of sucrose (c_s), aqueous solution of sucrose (c_s) with two types of baker's yeast (b).

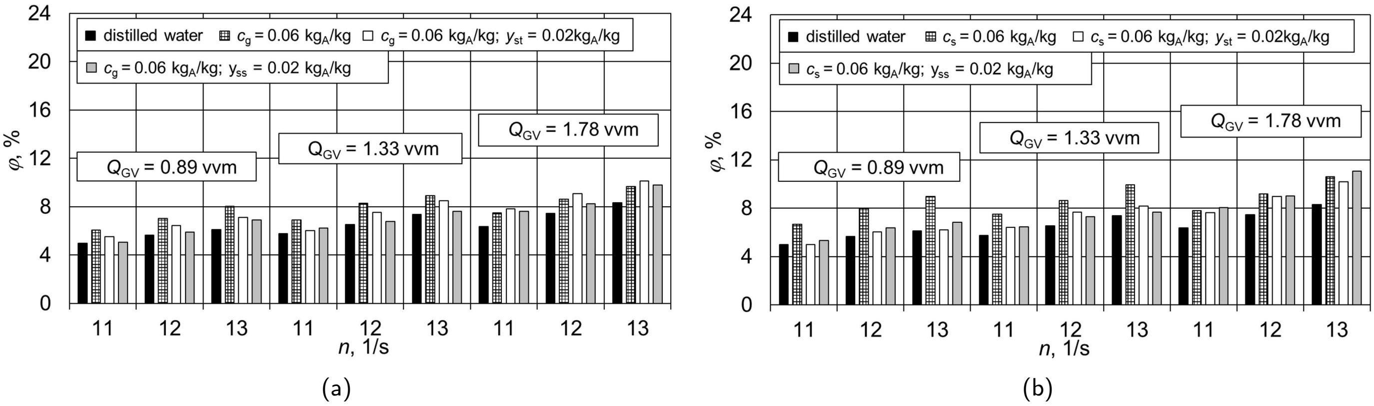


Figure 4. Dependence $\varphi = f(n)$ for Smith turbine impeller (CD6).

the φ values increased with the increase in the impeller speed $n = \langle 8 - 14 \rangle$ 1/s. It was also found that higher φ values, due to the nature of the circulation generated by these impellers, were obtained if Rushton or Smith turbine impellers were used for mixing compared to the A315 impeller.

The influence of the impeller speed n on the gas hold-up φ values is shown in Fig. 4, where the vessel used to mix two- and three-phase systems was a Smith turbine impeller. A similar trend as presented by Major-Godlewska and Cudak (2024) for the Rushton turbine impeller was observed when the Smith turbine impeller was used for mixing. Adding sugar to distilled water, with a mass fraction of 0.06 kg$_A$/kg, in the form of glucose (c_g) as a simple sugar or sucrose (c_s) as a disaccharide, increases the gas hold-up φ value in the analyzed case (Fig. 4) for three different volumetric gas flow rates $Q_{GV} = 0.89$; 1.33; 1.78 vvm and three impeller speed $n =$ 11, 12, 13 1/s. The values of φ differ from one another by about 20%, 27%, 21% for the impeller speed $n = 11, 12, 13$ 1/s and volumetric gas flow rates $Q_{GV} = 1.33$ vvm, comparing the two-phase system: air–distilled water with air–aqueous solution of glucose (c_g) (Fig. 4a) and 30%, 32%, 35% for the two-phase: air–distilled water with air–aqueous solution of sucrose (c_s) system for $n = \langle 11 - 13 \rangle$ 1/s and $Q_{GV} = 1.33$ vvm, respectively (Fig. 4b).

Adding the third phase in the form of yeast to the air–aqueous solution of glucose (c_g) system reduces the values φ for two volumetric gas flow rates $Q_{GV} = 0.89, 1.33$ vvm and three different speed impeller $n = 11, 12, 13$ 1/s (Fig. 4a) in comparison to the data presented for the air–aqueous solution of glucose (c_g) system. However, these values are higher than the φ values obtained for the air–distilled water system. In the case when the volumetric gas flow rate was $Q_{GV} = 1.78$ vvm (Fig. 4a), the values φ obtained for the three-phase system of air–aqueous solution of glucose (c_g)–yeast for traditional products (y_{st}) were higher by about 23%, 22%, 22% (for $n = 11, 12, 13$ 1/s, respectively) in comparison with the two-phase system of air–distilled water and by about 5% in comparison with the data obtained for the air–aqueous solution of glucose (c_g) system. In the case (Fig. 4b), when the third phase in the form of yeast (biophase) was added to the two-phase air–aqueous solution of sucrose (c_s) system, a decrease in the gas hold-up φ value was observed on average by about 29%, 28%, 38% in comparison to the values of φ obtained for the air–aqueous solution of sucrose (c_s) system for the volumetric gas flow rate $Q_{GV} = 0.89$ vvm, by about 17%, 15%, 25% for $Q_{GV} = 1.33$ vvm, respectively, for the Smith turbine impeller speed $n =$ 11, 12, 13 1/s.

The comparison of the obtained values gas hold-up φ for the biophase-gas-liquid system using an aqueous solution of glucose (c_g) or sucrose (c_s) and yeast y_{ss} for sweet products with the values φ obtained for the system in which yeast y_{st} for traditional products (Major-Godlewska and Cudak, 2024) was used as the biophase and three impellers (RT, CD6, A315) while maintaining a constant value $n = 12$ 1/s and for two different values $Q_{GV} = 0.89, 1.78$ vvm is presented in Fig. 5. Analyzing the data presented in Fig. 5, the influence of the yeast used (for sweet products y_{ss} and for traditional products y_{st}) on the value φ was observed. Analyzing the φ values obtained for the three-phase system of air–aqueous solution of glucose (c_g)–yeast (y_s), when a Rusthon turbine impeller was used for mixing and for a lower gas flow rate $Q_{GV} = 0.89$ vvm, it was found that the use of yeast for sweet products (y_{ss}) resulted in approximately 9% lower values of φ than for the same geometry and the system in which yeast for traditional products (y_{st}) was used. A similar trend was observed for the same biophase-gas-liquid system, when a Smith turbine impeller and an A315 impeller were used for mixing. The differences in the obtained values φ were 9% and 24%, respectively.

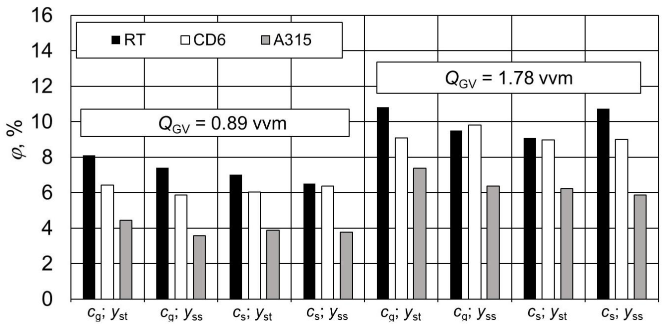


Figure 5. Dependence $\varphi = f$(types of baker's yeast), $n = 12$ 1/s.

When comparing the values of φ for the air–aqueous solution of sucrose (c_s)–yeast for sweet (y_{ss}) and traditional (y_{st}) product systems, it was observed that when the Rushton turbine impeller was used to agitate the three-phase system, values of φ higher by about 8% were obtained for the three-phase system in which the biophase was yeast for traditional products (y_{st}). In the case of the Smith turbine impeller, values higher by about 6% were obtained for the system with the biophase, which was yeast for sweet (y_{ss}) products, compared to the use of yeast for traditional products as the biophase. When using the A315 impeller for mixing the system, for $Q_{GV} = 0.89$ vvm, it was observed that changing the biophase from yeast for sweet products (y_{ss}) to yeast for traditional products (y_{st}) did not cause any differences in the values of φ.

Comparing the values of φ obtained for $Q_{GV} = 0.89$ vvm and three-phase systems differing in the aqueous sugar solution (air–aqueous glucose solution (c_g) or sucrose (c_s)–yeast for sweet products (y_{ss})) depending on the type of impeller used, the values of φ were by about 13% higher for the Rushton turbine impeller and the air–aqueous glucose solution (c_g)–yeast for sweet products (y_{ss}) system compared to the air–aqueous sucrose solution (c_s)–yeast for sweet product (y_{ss}) system. When the Smith turbine impeller or the A 315 impeller was used for mixing, higher values of φ by about 8% and 6%, respectively, were obtained for the air–aqueous solution of sucrose (c_s)–yeast for sweet product (y_{ss}) system compared to the air–aqueous solution of glucose (c_g)–yeast for sweet product (y_{ss}) system. The opposite trend was observed for a higher value of the volumetric gas flow rate $Q_{GV} = 1.78$ vvm. In this case, a higher value of φ by about 13% was obtained for the Rushton turbine impeller and the air–aqueous solution of sucrose (c_s)–yeast for sweet products (y_{ss}) system compared to the value φ where the aqueous solution of glucose (c_g) was used. When the Smith turbine impeller or the A 315 impeller was used for mixing, higher values of φ by about 9% and 8%, respectively, were obtained for the air–aqueous solution of glucose (c_g)–yeast for sweet products (y_{ss}) system in comparison to the air–aqueous solution of sucrose (c_s)–yeast for sweet product (y_{ss}) system.

The type of impeller used also influences the value φ. For example, the differences between the values φ obtained for the Rushton turbine impeller and the Smith turbine impeller or the Smith turbine impeller and the A315 impeller are 26% or 64%, respectively, for the air–aqueous solution of glucose (c_g)–yeast for sweet products (y_{ss}) system and the volumetric gas flow rate $Q_{GV} = 0.89$ vvm and 19% or 53%, respectively, for the air–aqueous solution of sucrose (c_s)–yeast for sweet products (y_{ss}) system and the volumetric gas flow rate $Q_{GV} = 1.78$ vvm. The values of φ are different in the case of the air–aqueous solution of sucrose (c_s)–yeast for sweet products (y_{ss}) system and the volumetric gas flow rate $Q_{GV} = 0.89$ vvm and the air–aqueous solution of glucose (c_g)–yeast for sweet products (y_{ss}) system and the volumetric gas flow rate $Q_{GV} = 1.78$ vvm, where the values φ are similar (the difference is not greater than 3%) when the Rushton or Smith turbine impeller is used for the vessel.

The dependence $\varphi = f$ (Kg) for three different types of impeller and four different biophase-gas-liquid systems for two different volumetric gas flow rates $Q_{GV} = 0.89$ and 1.78 vvm is presented in Fig. 6. Analyzing the presented data (Fig. 6), it was found that the gas hold-up φ values decrease with increasing the value of Kg for three impellers used for mixing three-phase systems and two volumetric gas flow rates Q_{GV}. The influence of Kg is smaller if the A 315 impeller is used for mixing three-phase systems compared to the Rushton turbine impeller and the Smith turbine impeller. It was observed (Fig. 6) that a constant gas hold-up φ value of about 4% for the air–aqueous solution of glucose (c_g)–yeast for sweet products (y_{ss}) system can be obtained at gas flow number values of Kg of about 0.039, 0.035 and 0.026 for the Rushton turbine impeller, Smith turbine impeller and A315 impeller, respectively, at the gas flow rate $Q_{GV} = 0.89$ vvm. Similarly, for the air–aqueous solution of sucrose (c_s)–yeast for sweet

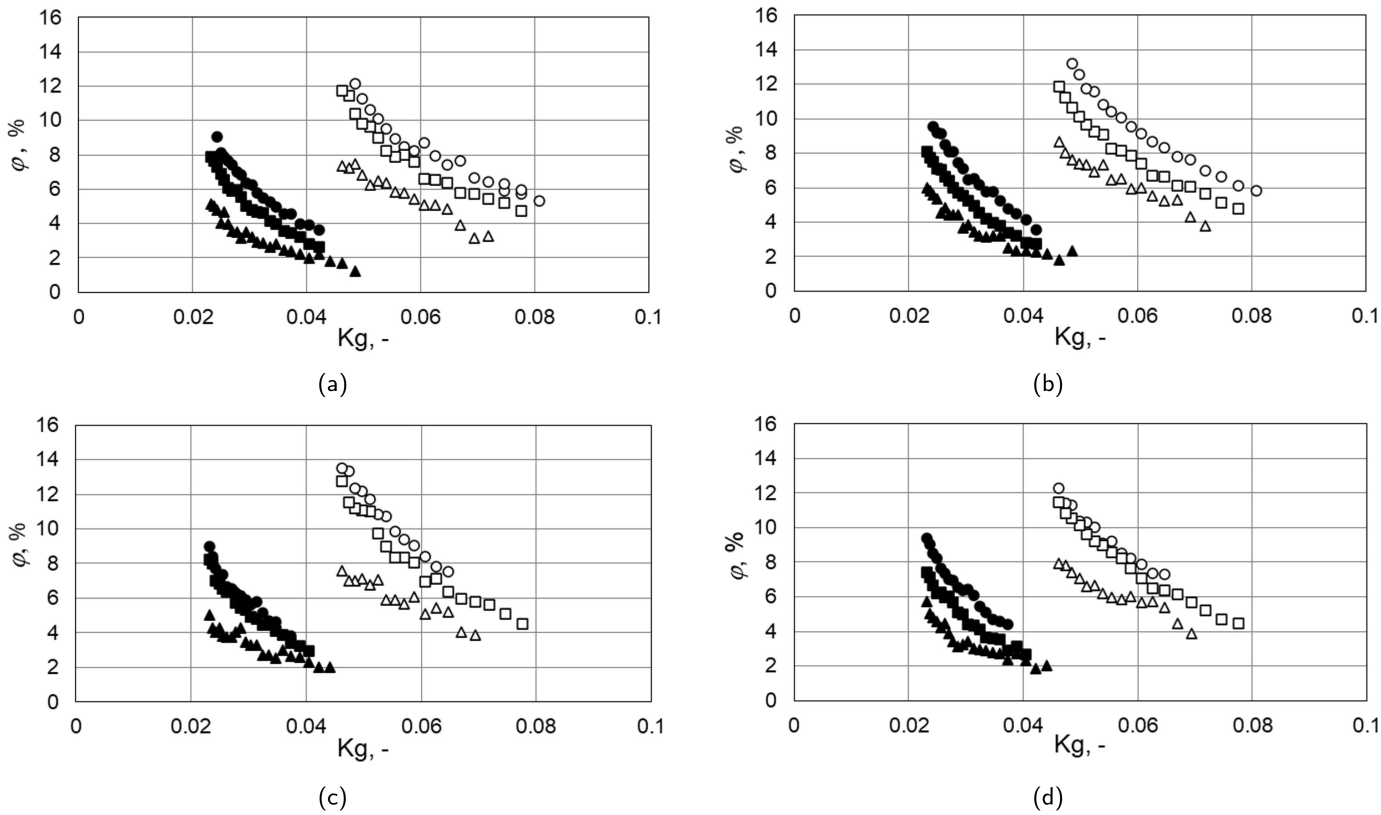


Figure 6. Dependence $\varphi = f$ (Kg) for three different types of impeller (●○ – RT, ■□ – CD6, ▲△ – A315) and four different systems: air–aqueous solution of glucose (c_g)–baker's yeast (y_{ss}) (a), air–aqueous solution of glucose (c_g)–baker's yeast (y_{st}) (b), air–aqueous solution of sucrose (c_s)–baker's yeast (y_{ss}) (c), air–aqueous solution of sucrose (c_g)–baker's yeast (y_{st}) (d) and for $Q_{GV} = 0.89$ vvm (●, ■, ▲) or $Q_{GV} = 1.78$ vvm (○, □, △).

product (y_{ss}) system, the values of Kg are about 0.036 for the Rushton and Smith turbine impellers and 0.024 for the A 315 impeller. If the yeast for sweet products (y_{ss}) is replaced with yeast for traditional products (y_{st}), where an aqueous glucose solution (c_g) is used as the liquid, then for values Kg of 0.039, 0.035 and 0.026 for the Rushton and Smith turbine impellers and the A315 impeller, respectively, the obtained values of φ are higher by about 12% or 20% for the Rushton turbine impeller or the A 315 impeller and comparable for the Smith turbine impeller.

The influence of the impeller type and volumetric gas flow rate Q_{GV} is also visible (Fig. 6). Assuming a constant value of Kg = 0.03 for $Q_{GV} = 0.89$ vvm, the highest value of φ was obtained for the Rushton turbine impeller and it is about 31% higher than the value of φ obtained for the Smith turbine impeller and almost twice as high as the value of φ obtained when the A 315 impeller was used to mix the air–aqueous solution of glucose (c_g)–yeast for sweet products (y_{ss}) system (Fig. 6a). A similar tendency is maintained when the air–aqueous solution of sucrose (c_s)–yeast for sweet products (y_{ss}) is a mixed system. In this case (Fig. 6c) the values of φ obtained for the Smith turbine impeller and the A315 impeller are lower by about 14% and 70% in comparison to the air–aqueous solution of sucrose (c_s)–yeast for sweet product (y_{ss}) system mixed with the Rushton turbine impeller. Comparing the gas hold-up φ values, presented in Fig. 6, obtained for three different impellers and four different biophase-gas-liquid systems, it was found that in order to maintain the value of φ at a similar level, increasing the volumetric gas flow rate from $Q_{GV} = 0.89$ vvm to $Q_{GV} = 1.78$ vvm causes an increase of the gas flow number Kg by about 2.5 times on average in the analyzed research range.

The obtained data allowed for a mathematical description of the influence gas flow number Kg, Weber number We, the mass fraction of aqueous solution (c_i) and mass fraction of yeast suspension (y_{ss}) have on the gas hold-up φ for a two- and three-phase systems:

$$\varphi = a_1 \cdot \mathrm{Kg}^{a_2} \cdot \mathrm{We}^{a_3} \cdot (1 + a_4 \cdot c_i) \cdot (1 + a_5 \cdot y_{ss}) \qquad (4)$$

The values of coefficients a_1, a_5 and exponents a_2, a_3 and a_4 in Eq. (4) for ranges of gas flow number Kg $\in \langle 0.023; 0.081\rangle$ and Weber number We $\in \langle 479; 2439\rangle$ are presented in Table 2.

The data of the residence time t_R of gas bubbles as a impeller speed n for three different types of impellers, two volumetric gas flow rates $Q_{GV} = 0.89$ vvm or 1.78 vvm and for a three-phase system differing in the medium used: aqueous glucose solution (c_g) or sucrose (c_s) are presented in Fig. 7. Based on

Table 2. Values of coefficients a_1, a_4, a_5 and exponents a_2, a_3 in Eq. (4), the average relative error and ranges of gas flow number Kg, Weber number We.

No	Agitator	a_1	a_2	a_3	a_4	a_5	$+\Delta$, %	c_i [kg$_A$/kg] y_{ss} [kg$_A$/kg]
1.	RT	$1.89 \cdot 10^{-4}$	0.37	0.95	4.20	5.69	6	distilled water and sucrose $c_s = 0; 0.06$; $y_{ss} = 0; 0.02$;
2.	CD6	$7.32 \cdot 10^{-5}$	0.38	1.08	5.16	0.766	6	
3.	A315	$2.61 \cdot 10^{-4}$	0.57	0.95	2.85	0.20	7	
4.	RT	$2.64 \cdot 10^{-4}$	0.31	0.88	5.59	0.164	4	distilled water and glucose $c_g = 0; 0.06$; $y_{ss} = 0; 0.02$;
5.	CD6	$1.05 \cdot 10^{-4}$	0.39	1.03	4.84	–2.201	4	
6.	A315	$1.56 \cdot 10^{-4}$	0.55	1.01	6.20	–8.107	7	

the data presented in Fig. 7, it was found that the residence time t_R of gas bubbles in the three-phase biophase-gas-liquid system was influenced by the impeller speed n, the volumetric gas flow rate Q_{GV} and the type of the impeller used. The values of t_R increase with the increase of the impeller speed n. For the three analyzed types of impellers and for different volumetric gas flow rates Q_{GV}, the increase in the value t_R with the increase in the impeller speed n is different. In the case when we use the Rushton turbine impeller for the volumetric gas flow rate of $Q_{GV} = 0.89$ vvm and two extreme cases of the impeller speed $n = 7.67$ 1/s and 13.33 1/s, the value t_R increases by about 2.6 times for the higher value of the impeller speed, while in the case of the A 315 impeller for the values $n = 7$ 1/s and 14 1/s by about 3 times (Fig. 7a). If the same values of the impeller speed $n = 7.67$ 1/s and 13.33 1/s are used for comparison, then in the case of the A315 impeller the values of t_R increase less than when the Rushton turbine impeller is used, only by about 2.2 times. Similarly, when analyzing the data for the air–aqueous solution of sucrose (c_s)–yeast for sweet products (y_{ss}) system (Fig. 7b), it was found that for the extreme values of $n = 8.67$ 1/s and 14 1/s and $n = 7.33$ 1/s and 14 1/s obtained for the Rushton turbine impeller and A315, respectively, the values of t_R increased by about 2.5 and 2.6 times for higher values of the impeller speed and intensity $Q_{GV} = 0.89$ vvm. The increase in the gas flow rate $Q_{GV} = 1.78$ vvm affects the increase in the impeller speed n, at which good gas dispersion occurs. Assuming the same values of the impeller speed $n = 10$ 1/s and 14 1/s for the Rushton turbine impeller and A315, the value of t_R increases approximately 1.9 and 1.5 times for higher impeller speed. In the case when the systems differed in the medium used and the Smith turbine impeller (CD6) was used for mixing for the same range of impeller speed $n = 8.33$ 1/s and 14 1/s, the value t_R increased by about 2.6 and 2.7 times for higher impeller speed n for $Q_{GV} = 0.89$ vvm and 1.78 vvm, respectively, when the medium used in the three-phase system was an aqueous glucose solution and by about 2.7 and 3.1 times for $Q_{GV} = 0.89$ vvm and 1.78 vvm and an aqueous sucrose solution, respectively (Fig. 7a and 7b).

Analyzing the data values (Fig. 8) of the residence time t_R of gas bubbles for different volumetric gas flow rates Q_{GV} ($Q_{GV} = 0.89$ vvm, $Q_{GV} = 1.78$ vvm), it was found that for a constant value of gas hold-up $\varphi =$ const, the residence time t_R of gas bubbles for the three impellers used in the tests (RT, CD6, A315) decreased with increasing volumetric gas flow

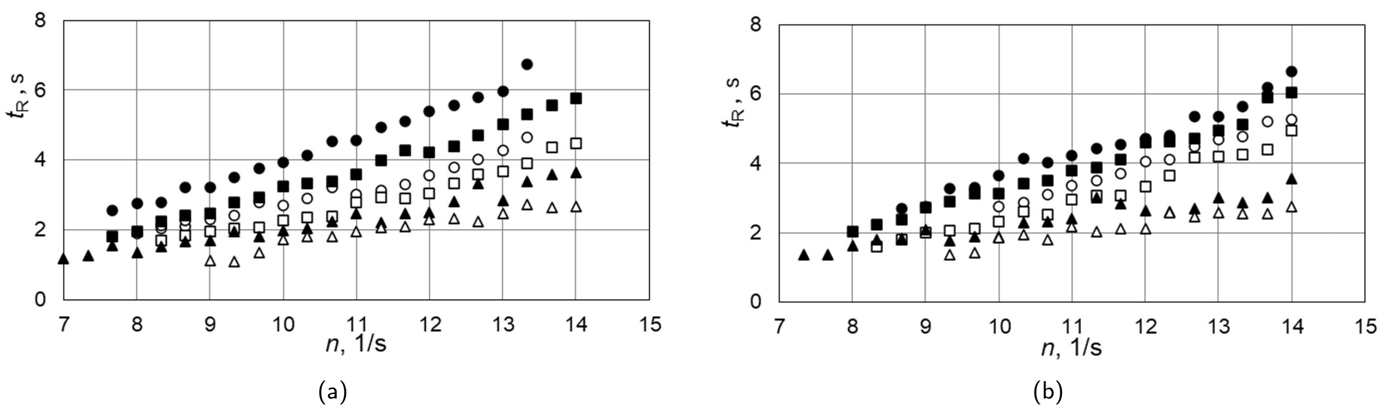
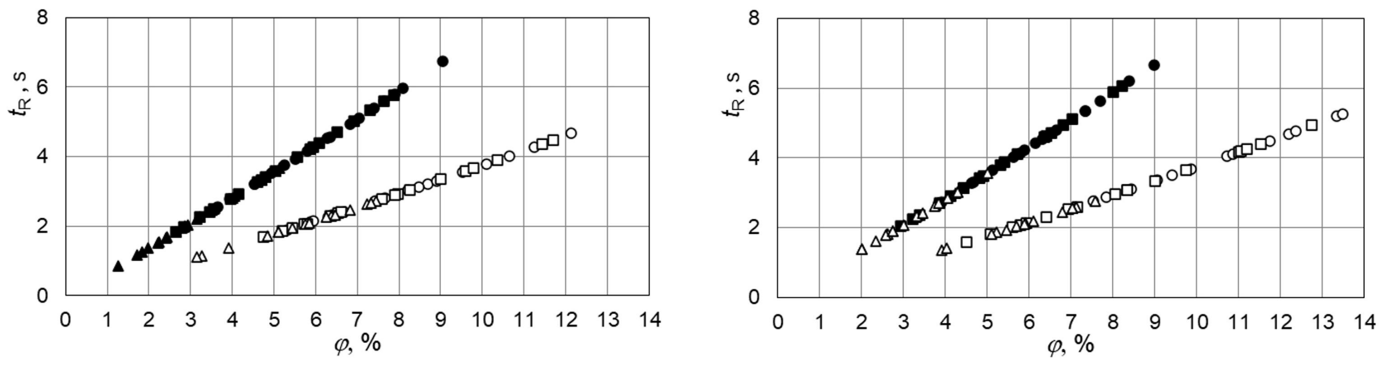


Figure 7. Dependence $t_R = f(n)$ for three different type of impeller (●○ – RT, ■□ – CD6, ▲△ – A315) and two different systems: air–aqueous solution of glucose (c_g)–baker's yeast (y_{ss}) (a), air–aqueous solution of sucrose (c_s)–baker's yeast (y_{ss}) (b), and for $Q_{GV} = 0.89$ vvm (●, ■, ▲) or $Q_{GV} = 1.78$ vvm (○, □, △).



(a) (b)

Figure 8. Dependence $t_R = f(\varphi)$ for three different type of impeller (●○ – RT, ■□ – CD6, ▲△ – A315) and two different systems: air–aqueous solution of glucose (c_g)–baker's yeast (y_{ss}) (a), air–aqueous solution of sucrose (c_s)–baker's yeast (y_{ss}) (b), and for $Q_{GV} = 0.89$ vvm (●, ■, ▲) or $Q_{GV} = 1.78$ vvm (○, □, △).

rate Q_{GV}. Increasing the volumetric gas flow rate from $Q_{GV} = 0.89$ vvm to $Q_{GV} = 1.78$ vvm caused the residence time t_R of gas bubbles in the system to decrease twice regardless of the gas hold-up value of φ. Assuming a constant gas hold-up φ value $Q_{GV} =$ const, the residence time t_R of gas bubbles increases linearly with increasing gas hold-up φ.

The effects of dimensionless retention time Θ on the gas hold-up φ are presented in Fig. 9. The dimensionless retention time Θ was calculated from Equation (5):

$$\Theta = n \cdot t_R \tag{5}$$

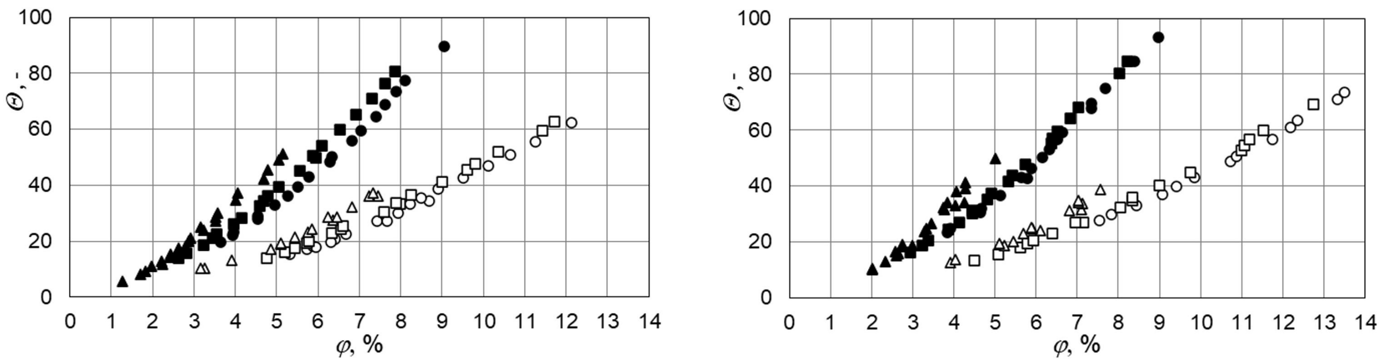
The dimensionless retention time Θ values were influenced by volumetric gas flow rate Q_{GV}, gas hold-up φ and the type of impeller. Analyzing the data presented in Fig. 9, it can be concluded that with the increase of gas-hold φ the dimensionless retention time Θ increases. Assuming constant values of $Q_{GV} = 0.89$ vvm or 1.78 vvm, an increase in the gas hold-up φ value from 5% to 8% (CD6 impeller) causes an increase in the dimensionless retention time Θ by about 2.5 times. This effect depends on the type of impeller used. Assuming a constant value of gas hold-up, the highest values of the dimensionless retention time Θ were obtained when the A315 impeller was used to mix the three-phase system.

4. CONCLUSIONS

Based on the data obtained, it was found that the type of biophase-gas-liquid used in the research influenced the hydrodynamics. The obtained values of gas hold-up and residence time of gas bubbles depend on the impeller speed, volumetric gas flow rate, impeller type and the type of medium and yeast.

The gas hold-up value is influenced by the fluid circulation generated. Higher values of φ were obtained for the Rushton or Smith turbine impellers compared to the A315 impeller. The gas hold-up φ values decrease with increasing gas flow number for the impellers used.

The influence of the yeast used for sweet products and for traditional products on the value of φ was observed. Replacing yeast for traditional products with yeast for sweet products,



(a) (b)

Figure 9. Dependence $\Theta = f(\varphi)$ for three different types of impeller (●○ – RT, ■□ – CD6, ▲△ – A315) and two different systems: air–aqueous solution of glucose (c_g)–baker's yeast (y_{ss}) (a), air–aqueous solution of sucrose (c_s)–baker's yeast (y_{ss}) (b), and for $Q_{GV} = 0.89$ vvm (●, ■, ▲) or $Q_{GV} = 1.78$ vvm (○, □, △).

when the liquid phase was an aqueous solution of glucose or sucrose, with lower gas flow rates, in most cases resulted in a reduction of the gas hold-up value.

The residence time of gas bubbles increases with the increase of the impeller speed and decreases with the increase of the volumetric gas flow rate. The type of medium used does not significantly affect the residence time of gas bubbles.

The obtained results presented in this article for two- and three-phase systems are described mathematically by Equation (4), where the values of constants: a_1, a_4, a_5 and exponents: a_2, a_3 presented in Table 2 may be useful in designing and modeling multiphase systems characterized by identical physicochemical properties.

SYMBOLS

B	width of the baffle, m
c_i	sugar (sucrose or glucose) mass fraction, kg_A/kg
D	inner diameter of the vessel, m
d	diameter of the impeller, m
d_g	sparger diameter, m
e	distance of the sparger from the bottom, m
H	liquid height in the vessel, m
h	distance of the impeller from the bottom, m
h_g	the height of a gas-liquid (biophase-gas-liquid) mixture in the vessel, m
J	number of baffles
K	consistency index, $Pa{\cdot}s^m$
m	flow index
n	impeller speed, 1/s
n_{cr}	critical impeller speed, 1/s
Q_{GV}	volumetric gas flow rate, $(m^3/min)/m^3$ = vvm
t_R	residence time of gas bubbles, s
$\dot{V}_g$	gas flow rate, m^3/s
V_l	a volume of liquid (or biophase-liquid), m^3
y_{si}	yeast mass fraction, kg_A/kg
Z	number of impeller blades

Greek symbols

$\dot{\gamma}$	shear rate, 1/s
η_{BL}	apparent viscosity, Pa·s
φ	gas hold-up
ρ	density, kg/m^3
σ	surface tension, N/m

Dimensionless numbers

$\mathrm{Kg} = \dfrac{\dot{V}_g}{nd^3}$	gas flow number
$\mathrm{We} = \dfrac{n^2 d^3 \rho}{\sigma}$	Weber number

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