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Intensification of bubble column performance by introduction pulsation of liquid

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ABSTRACT

The application of pulsations at determined parameters to a bubble column can significantly modify the process of mass transfer. However, determination of these parameters is so difficult that it has not been done so far in a satisfactory way even for technical purposes. Hydrodynamics of pulsed-bubble columns has been a subject of a few research works published so far. This paper presents results of studies on flow hydrodynamics of gas bubbles in a glass pulsed-bubble column of square cross section with side $D = 0.14$ m and height $H = 2.25$ m, filled with water. Experiments were carried out at air superficial velocity UG ranging from 1.6 to 13.9 mm/s. Operating parameters of the pulsed-bubble column were measured in the frequency range f from 0 to 100 Hz and the amplitude of vibration exciter Xp from 0.25 to 2 mm. On the basis of results obtained so far it was shown that the application of pulsations at determined parameters to a bubble column caused a significant increase in the gas holdup. Based on the analysis of results of the measurements, model equations were developed to determine the Sauter diameters of bubbles and gas holdup during the pulsed-bubble column operation.

1. Introduction

Recently, many papers on the intensification of technological processes and unit operations have been published in the field of chemical engineering. The aim of these studies is to improve the efficiency of technological processes and quality of products, to reduce the dimensions of equipment and energy demand, to improve the conditions of heat and mass transfer and to reduce pollutants emitted to the environment [1–5]. One of the elements of these studies is the intensification of mass transfer in bubble columns.

By applying pulsations to a classical bubble column, we change substantially the hydrodynamics of bubbles flowing through the liquid layer because the bubbles are subjected to an additional force opposite to buoyancy, a so-called Bjerknes force. This force decreases the bubble velocity and hence enhances the contact time. Also, due to the disappearance of the circulation zones the bubbles occupy the whole liquid volume of the column, including dead zones. This, in turn, increases the mass transfer coefficient several times higher than in the classical bubble column (without vibrations). The increase of mass transfer coefficient due to mixture pulsations is a result of not only an increase of gas holdup and uniform distribution of bubbles in the whole reaction volume of the column, but also of decreasing diameters of bubbles formed at the diffuser outlet [6–10] and a remarkable increase of free liquid/mixture surface [11].

The main problem in the description of processes that occur during the operation of pulsed-bubble columns are synergic phenomena of dynamic and pulsating (quasi-acoustic) character. In the range of applied frequencies and amplitudes of pulsations each of these phenomena is significant for the process and mutually for each other. Elimination or simplification of the description of any of these phenomena causes that the obtained relations predict values which are far from experimental results and as a consequence appear useless in practice.

Based on earlier studies of Hinze [12], Buchanan et al. [13], Jameson and Davidson [14], Jameson [15], Knopf et al. [16,17], and Waghmare et al. [18,19] proposed a model of gas bubble flow through a pulsating liquid, based on the classical balance of buoyancy and drag forces acting on a gas bubble in the pulsating liquid, taking additionally into account the action of so-called first Bjerknes kinetic buoyancy (the Bjerknes effect) induced by liquid pulsation. According to this, gas holdup increases monotonically with increasing frequency of pulsations. Actually, Waghmare et al. [18] observed a limited range of compatibility of the proposed equation with experimental data and suggested to reduce applicability of their model to the frequency below $f < 25$ Hz, i.e. the frequency at which column flooding occurred. It can be observed easily that the phenomenon which is called by these authors the

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"point of column flooding", is nothing but a point of column operation at which there is a resonant frequency of pulsations in the column produced by the exciter and first frequencies of the system pulsations Bretsznajder and Pasiuk [11].

Notation

a_0	constant in Eq. (24)
A_D	column cross-section area, m
A_p	exciter disk surface, m
B_i	constant in Eq. (1)
b_M	exponent in Eq. (4)
d_b	Sauter diameter of bubble, m
d_o	nozzle diameters, m
d_p	disc diameters, m
H	height column, m
H_{oi}	height of the liquid- from the column bottom, m
H_{mi}	height of the liquid-gas mixture surface from the column bottom, m
f_w^*	the first basic frequency of pulsations (resonance), which corresponds to the frequency of the first specific pulsations of the system, Hz
f_1^*	the second frequency of specific (resonance) pulsations, Hz
f_2^*	the third frequency of specific (resonance) pulsations, Hz
g	gravitational acceleration, ms^{-2}
k	coefficient, dimensionless
M	pulsating mass, kg
p	pressure [Pa]
P_G	power input for gas injection (per unit mass), $\mathrm{W\,kg}^{-1}$
P_M	power input from applied pulsation (per unit mass), $\mathrm{W\,kg}^{-1}$
P_c	power input (per unit mass), $\mathrm{W\,kg}^{-1}$
U_G	superficial gas velocity, ms^{-1}
V_b	bubble volume, m^3
V_m	volume occupied by the gas–liquid mixture, m^3
w_m	propagation velocity of pulsation wave in the liquid–gas mixture, ms^{-1}
w_G	propagation velocity of pulsation wave in the gas phase, ms^{-1}
w_L	propagation velocity of pulsation wave a in the liquid phase, ms^{-1}
X_M	the amplitude of total pulsating mass in the column, m
X_p	amplitude of disk vibrations, m

Greek letters

ϵ_G	gas holdup in, dimensionless
μ	viscosity, Pas
Γ	coefficient of pulsation intensity, dimensionless
λ_i	wave length of the *i*-th resonant standing wave, m
ρ	density, $\mathrm{kg\,m}^{-3}$
σ	surface gas–liquid tension, $\mathrm{N\,m}^{-1}$
υ	kinematic viscosity, $\mathrm{m}^2\,\mathrm{s}^{-1}$
ω	angular frequency = $2\pi f$, s^{-1}

Subscripts

G	gas
L	liquid
(*)	resonance pulsation
min	minimum
max	maximum

A disadvantage of the presented model considerations [18] is an assumption that the amplitude of wave pulsations in the liquid X is approximately equal to the amplitude of the exciter vibrations X_p", which is a convenient but far reaching simplification Budzyński [6].

Baird [20], Ellenberger et al. [10] and Budzyński [6,7] found that periodic growth and next decrease of gas holdup at increasing frequency of pulsations was an evidence of standing waves in the column. The pulsations at which standing waves occur correspond to specific frequencies of the system. Then resonance waves appear. To determine the amplitude of resonance waves it is necessary to solve differential wave equations for pressure changes along the open column height filled with a two-phase mixture. These equations should refer to the column geometry, properties of material from which the column is made, physicochemical properties of phases as well as the size and distribution of bubbles in the volume being considered. To define gas holdup in the mixture pulsating at a resonant frequency, Ellenberger et al. [10] propose to solve the system of two equations. The first one is a classical balance equation of forces acting on the bubble during flow through the liquid which additionally includes Bjerknes forces, and the second one is the Rayleigh–Plaset equation which describes changes in bubble volume during flow through the column with reference to resonance standing waves of pressure in the column. Ellenberger et al. [10] provided a numerical solution to the proposed system of equations and presented the result in a graphic form. However, due to a number of simplifying assumptions, this solution should be treated only as a visual presentation [6,7]. The solution was prepared for a column with constant height $H = 1.2$ m and stable amplitude of pulsations expressed in pressure units $X = 15$ kPa and at constant frequency 75 Hz. Such an assumption is completely false. It is obvious that at a constant height of the liquid–gas mixture in the column the next resonant frequencies cannot occur when pulsations of constant frequency 75 Hz are applied. It is known that the ratio of resonant frequencies is 1:3:5:7. Finally, to calculate resonant frequencies Ellenberger et al. [10] suggested to use the equation for sound wave velocity in the two-phase mixture as proposed by Prosperetti [21].

Based on the results of our studies, we found that both results presented by Ellenberger et al. [10] and our results differ significantly from the resonant frequencies predicted with the use of Prosperetti's equation [21]. This follows from the fact that Prosperetti made far-reaching simplifications in his theoretical considerations.

The aim of this study was to carry out a series of experiments which would verify results of model investigations presented in the so far published works and to propose equations to calculate Sauter diameter of the bubbles and gas holdup during the pulsed-bubble column operation.

2. Experimental

2.1. Experimental set-up, material and scope of tests

Experiments were carried out in the pulsed-bubble column made of glass, with square cross section of side $D = 0.134$ m and height $H = 2.25$ m, shown schematically in Fig. 1.

Operating parameters of the pulsed-bubble column were measured in the frequency range f from 0 to 100 Hz and at pulsation amplitudes of the exciter disk X_p from 0.25 mm to 2 mm.

Air was supplied to the column through a rotameter and next through a duct with a nozzle at its end. The nozzle diameters were d_o = 1 mm, d_o = 2 mm and d_o = 4 mm.

The experimental medium was tap water of viscosity $\mu_L = 0.001$ Pa/s, interfacial tension $\sigma = 726.7 \times 10^{-4}$ N/m and density $\rho_L = 1000\ \mathrm{kg/m}^3$. A disperse phase was air supplied to the liquid