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MIXING CHARACTERISTICS FOR GAS-LIQUID SYSTEM IN AN EXTERNAL-LOOP AIR-LIFT COLUMN

CHARAKTERYSTYKI MIESZANIA DLA UKŁADU CIECZ-GAZ W KOLUMNIE AIR-LIFT Z ZEWNĘTRZNĄ CYRKULACJĄ PŁYNU

A b s t r a c t

This paper presents the results of the experimental investigations of hydrodynamics for an external-loop air-lift column. Process characteristics (gas hold-up, liquid velocities, liquid circulation time and mixing time) were analyzed as a function of the modified Froude number. The obtained results were presented graphically and in the form of the quantitative correlations.

Keywords: *air-lift column*, *liquid velocity*, *liquid circulation time*, *mixing time*

S t r e s z c z e n i e

W tym artykule przedstawiono wyniki doświadczalnych badań hydrodynamiki dla kolumny air-lift z zewnętrzną cyrkulacją płynu. Charakterystyki procesowe (udział gazu zatrzymanego w cieczy, prędkości płynu, czas cyrkulacji oraz czas mieszania) analizowano w funkcji zmodyfikowanej liczby Froude'a. Wyniki badań opracowano graficznie i matematycznie.

Słowa kluczowe: kolumna air-lift, prędkość cieczy, czas cyrkulacji cieczy, czas mieszania

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1. Introduction

Air-lift reactors are classified as one of the important groups of bubble reactors. They have advantages such as higher liquid circulation and higher intensity of turbulence. Moreover, they can be characterized as reactors with good gas dispersion, simple construction and low costs [2]. Taking into account the results of the studies reported in literature at the last years, it can be stated that air-lift columns gain more popularity. It is reflected also by their application in various industries. They are used, for example, in mixing processes as well as bioprocesses or wastewater treatment.

Air-lift reactors are distinguished by internal-loop and external-loop columns. The internal-loop air-lift reactor consists of two concentric columns – a vertically central tube installed along the bubble column. The gas is fed to the inner part, which is shorter than the other. The design of external-loop air-lift reactor contains two parallel columns connected to each other at the top and at the bottom. In case of each type of the air-lift column, the gas–liquid mixture circulates in the reactor under the influence of difference in fluid density arising in both columns [9].

Experimental investigations of two-phase flow in the internal-loop air-lift column were conducted, among others, by Kawalec-Pietrenko et al. [10], Šimčik et al. [14], Keshavarz et al. [11] and Luo et al. [13]. However, investigations of external-loop air-lift reactor are rather limited. The results of experimental and numerical studies in such column were analyzed, among others, by Hari et al. [3], Wang et al. [15], Karcz et al. [4–8]. In the present study, the mixing process in an external-loop air-lift reactor is investigated.

The aim of the study presented in this paper was to experimentally analyze the hydrodynamics in an external-loop air-lift column (gas hold-up φ liquid velocity w_c liquid circulation time t_c and mixing time t_m) for different orifices number at perforated plate used as a gas sparger.

2. Range of the study, experimental set-up and details of the measurements

The simplified scheme of the system used in the study is shown in Figure 1. An external-loop air-lift column consisted of two columns (4) and (5), riser (R) and downcomer (D), respectively. Inner diameter of the riser (R) was equal to $D_R = 0.1056$ m, and its height was $H_R = 1.932$ m. The downcomer (D) was described by inner diameter $D_D = 0.0464$ m and height $H_D = 1.69$ m. The columns were connected at the top and at the bottom. The distance between the vertical center lines of both columns was equal to 0.5 m. The gas sparger (3) had the form of perforated plate with symmetrically placed orifices of a diameter $d_o = 0.002$ m. The studies were carried out for three different numbers of the orifices in the plate, equal to 3, 6 or 12, respectively. The gas flow rate was equal to $V_g \cdot 10^5 \in \langle 3{,}64; 31{,}8 \rangle$ [m^3/s].

Experimental set-up (Fig. 1) was also equipped with the installation of compressed air feed, valves (1), measuring instruments: rotameter (2), inverted-tube manometer (6) and electrode for the measurement of conductivity (7), laboratory meter (8), as well as computer (9) for data logging.

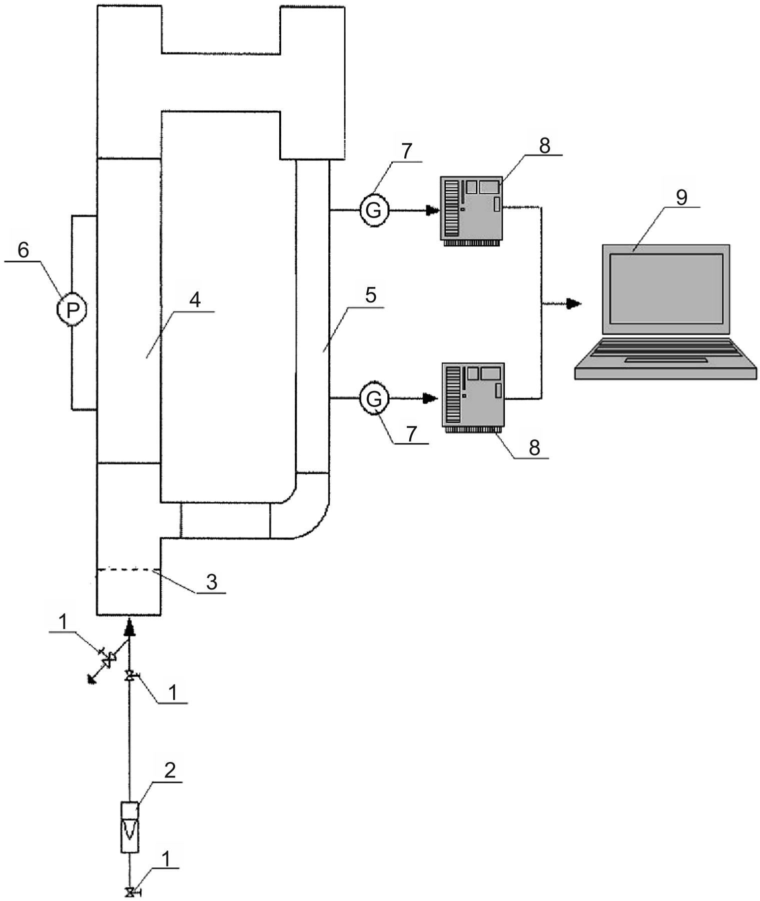

Fig. 1. The scheme of an external-loop air-lift column: 1 – valve, 2 – rotameter, 3 – gas sparger, 4 – the riser, 5 – the downcomer, 6 – inverted-tube manometer, 7 – electrode for measurement of conductivity, 8 – laboratory meter, 9 – computer

2.1. Gas hold-up

The gas hold-up was measured by the inverted-tube manometer method. Due to the degassing of the separation zone, the gas hold-up was analyzed only in the riser. The values of the gas hold-up φ_R were calculated from equation (1):

$$\varphi_R = \frac{\rho_c}{(\rho_c - \rho_g)} \cdot \frac{\Delta h_m}{l} \tag{1}$$

where:

- φ_R – gas hold-up in the riser [–],
- ρ_c – density of liquid [kg/m^3],

ρ_g – density of gas [kg/m^3],
Δh_m – difference in level of the liquid at the arms of the manometer [m],
l – the distance between the manometric stub [m].

The obtained 3 values of the gas hold-up in the riser φ_R for each value of the gas flow rate were averaged. These averaged values were analyzed as a function of the modified Froude number Fr defined as follows:

$$\mathrm{Fr} = \frac{w_{0g}^2}{D_R \cdot g} \tag{2}$$

where:
Fr – modified Froude number [–],
w_{0g} – superficial gas velocity, calculated on an empty cross-section of the riser [m/s],
D_R – inner diameter of the riser [m],
g – acceleration due to gravity [m/s^2].

2.2. Liquid circulation time and mixing time

Tracer method was used to determine the liquid circulation time t_c and mixing time t_m. 10 cm^3 of saturated aqueous solution of sodium chloride was introduced into the upper part of the downcomer and the changes in the conductivity G of the liquid were recorded using the system consisted of the conductivity probes connected with laboratory meters.

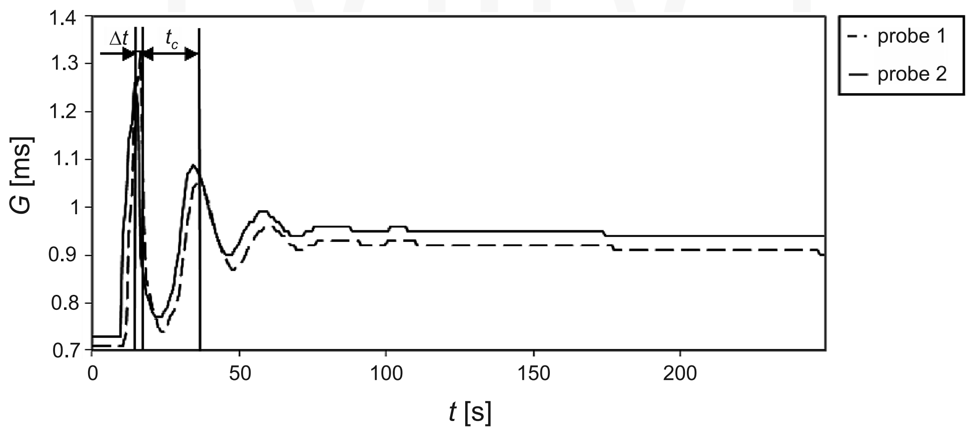

Fig 2. The dependence of the conductivity, G, on the time t

Figure 2 shows exemplary dependence of the liquid conductivity G on the time t for both conductivity probes arranged in the column. Difference in the time between both neighboring peaks appearing in the graph $G = f(t)$ for a given conductivity probe was defined as liquid circulation time t_c. Moment at which the tracer was completely mixed with the fluid in the column was assumed as mixing time t_m. It corresponded to disappearance of the conductivity fluctuations on the graph $G = f(t)$.

2.3. Liquid velocity

The tracer method was used to determine the liquid velocity $w_{c,}$ in the externl-loop air-lift column. The measurement was based on reading differences between neighboring maxima (or minima) occurring for two probes in the graph of conductivity changes over time. In this way, time Δt of the fluid flow between the probes was obtained. With a known distance s the liquid velocity in the downcomer w_{cD} was calculated from the equation (3):

$$w_{cD} = \frac{s}{\Delta t} \tag{3}$$

where:

- w_{cD} – velocity of the liquid in the downcomer [m/s],
- s – the distance between the probes [m],
- Δt – the liquid flow time between the probes [s].

The liquid velocity in the riser, $w_{cR,}$ was calculated from equation (4). It takes into account the gas hold-up in the riser φ_R and the continuity equation:

$$w_{cR} = w_{cD} \frac{A_D}{A_R(1-\varphi_R)} \tag{4}$$

where:

- w_{cR} – liquid velocity in the riser [m/s],
- w_{cD} – liquid velocity in the downcomer [m/s],
- A_R – cross-section of the riser [m^2],
- A_D – cross-section of the downcomer [m^2],
- φ_R – gas hold-up in the riser [–].

3. Results

On the basis of the results of experimental studies of the hydrodynamics in the external-loop air-lift column gas hold-up in the riser φ_R liquid velocity w_c liquid circulation time t_c and mixing time t_m were determined. These results were obtained for three perforated plates used as a gas sparger differing in number of orifices (3, 6 or 12) and for the gas flow rate in the range of $V_g \cdot 10^5 \in <3,64; 31,8>$ [m^3/s].

The experimental results show that the effect of the orifices number at the perforated plate on the hydrodynamic parameters tested is small and it can be neglected at further analysis. Therefore, values of those parameters were averaged for all three perforated plates tested. Such averaged values of the hydrodynamic parameters are presented as a function of the modified Froude number *Fr* in Figure 3 (within the range of Fr $\in < 1.67 \times 10^{-5}; 1.27 \times 10^{-3}>$) and superficial gas velocity w_{0g} in Figures 4–7 (where $w_{0g} = 4V_g/\pi D^2$; $w_{0g} \in < 4.15 \times 10^{-3}; 3.63 \times 10^{-2}>$).

Figure 3 shows the dependence of gas hold-up in the riser φ_R on Froude number Fr within the range of the Fr number varied from 1.67×10^{-5} to 1.27×10^{-3}. These results are described by means of the following equation:

$$\varphi_R = 0.81 \cdot \mathrm{Fr}^{0.36} \tag{5}$$

with the mean relative error $\pm$10%. Confidence intervals for each value of the φ_R are also estimated. Within the range of the performed measurements, gas hold-up values increase almost three times. Due to the degassing of the separation zone, the data for the downcomer was not analyzed. The results obtained for the gas hold-up in the riser φ_R are comparable with the literature data corresponding to the bubble columns (Akita and Yoshida (1973), Kulkarni et al. (2001)). Akita and Yoshida (1973) obtained the values of the gas hold-up varying from the 0.038 to 0.285 within the range of the Fr number from 1.17×10^{-4} to 4.16×10^{-2} (1.32×10^{-2} m/s < w_{0g} < 0.25 m/s) for the water – air system of temperature 20° produced in bubble column of diameter 0.152 m. Radial profiles of gas hold-up, obtained by Kulkarni et al (2001) for the 0.2 M aqueous solution of sodium sulfite and $w_{0g} = 3.9 \times 10^{-2}$ m/s in the bubble column of diameter 0.1 m and 0.15 m, were described by the φ values from the range <0.02; 0.12>.

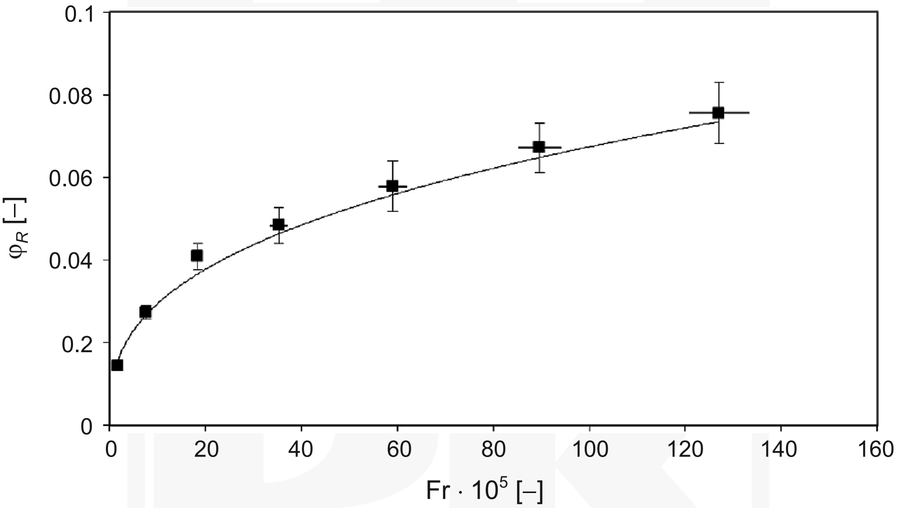

Fig. 3. The dependence of gas hold-up φ_R on the Froude number Fr for the riser of an external--loop air-lift reactor

It can be seen in Figure 4 that the liquid circulation time t_c decreases with an increase of the superficial gas velocity w_{0g}. Very similar measured values of the t_c were obtained for all perforated plates tested, therefore, narrow confidence intervals for the t_c values are obtained. Experimental results of the liquid circulation time t_c are approximated with the mean relative error $\pm$4% using following equation:

$$t_c = 4.21 \cdot w_{0g}^{-0.39} \tag{6}$$

where variables are expressed in SI units, i.e. w_{0g} [m/s] and t_c [s]. Eq. (6) describes the results within the range of the w_{0g} [m/s] $\in$ <4.15×10^{-3}; 3.63×10^{-2}>.

Figure 5 shows the dependence of the mixing time t_m on the superficial gas velocity w_{0g}. This dependence is described with the mean relative error ±24% by means of the following equation:

$$t_m = 26.69 \cdot w_{0g}^{-0.27} \tag{7}$$

where the variables are expressed as follows: w_{0g} [m/s] ∈ <4.15 × 10^{-3}; 3.63 × 10^{-2}> and t_m [s]. The curve $t_m = (w_{0g})$ shown in Figure 5 diminishes according to course of the power function with the increase of the superficial gas velocity values.

Figures 6 and 7 present the dependences of the liquid velocities, w_{cR} in the riser (Fig. 6) and w_{cD} in the downcomer (Fig. 7), as the function of the superficial gas velocity w_{0g}. In both cases, w_{cR} and w_{cD} values increase with the increase of the superficial gas velocity w_{0g}, but it should be noted that the order of the liquid velocities in both cases is different. Values of the w_{cD} are about five times higher than w_{cR} values.

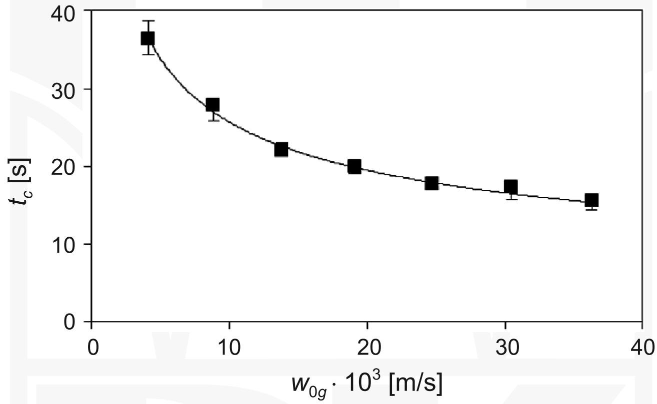

Fig. 4. The dependence of liquid circulation time t_c on the superficial gas velocity w_{0g} for an external-loop air-lift reactor

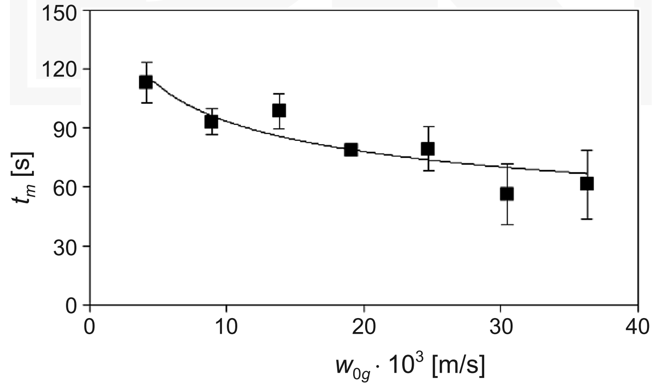

Fig. 5. The dependence of mixing time t_m on the superficial gas velocity w_{0g} for an external--loop air-lift reactor

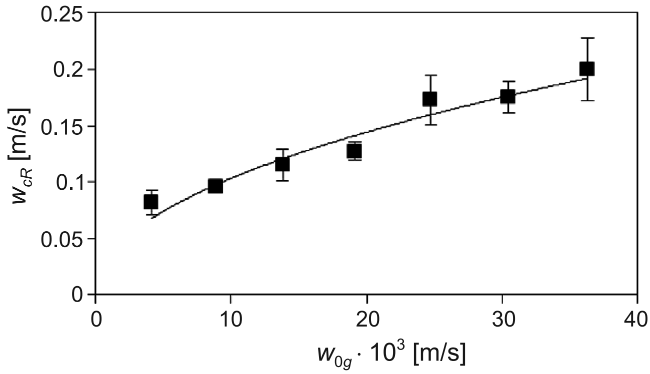

Fig. 6. The dependence of liquid velocity w_{cR} on the superficial gas velocity w_{0g} in the riser of an external-loop air-lift reactor

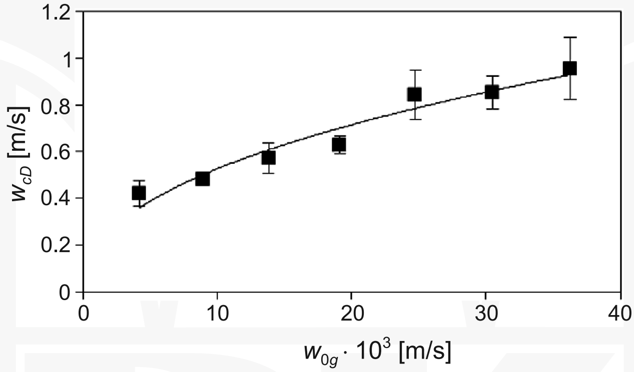

Fig. 7. The dependence of liquid velocity w_{cD} on the superficial gas velocity w_{0g} in the downcomer of an external-loop air-lift reactor

The results of liquid velocities in the riser w_{cR} and in the downcomer w_{cD} were approximated by means of the following equations, respectively:

$$w_{cR} = 0.95 \cdot w_{0g}^{0.48} \tag{8}$$

$$w_{cD} = 4.07 \cdot w_{0g}^{0.44} \tag{9}$$

where the variables are expressed as follows: $w_{cR,}$ [m/s], w_{cD} [m/s] and w_{0g} [m/s] $\in$ <4.15 × 10^{-3}; 3.63 × 10^{-2}>. These equations describe the results obtained with mean relative errors equal to $\pm$17% and $\pm$14%, respectively.

4. Conclusions

Considering the results of experimental study obtained for the external-loop air-lift reactor, it can be concluded that the mixing characteristics depend on the gas flow rate. Modified Fr number has the greatest effect on the gas hold-up φ_R. Within the range of the performed measurements, values of the φ_R increase about three times with the increase of the gas flow rate V_g. The influence of the the superficial gas velocity w_{0g} on the liquid velocities in the riser w_{cR} and downcomer w_{cD} is practically identical, but w_{cD} values are about five times higher than w_{cR} ones. The liquid circulation time t_c and mixing time t_m decrease with the increase of the the superficial gas velocity w_{0g}. The effect of the the superficial gas velocity w_{0g} on the mixing time t_m is somewhat lower than that on the liquid circulation time t_c. These experimental results can be used for the verification of the numerical data, obtained by CFD method, for hydrodynamics in an external-loop air-lift column.

References

[1] Akita K., Yoshida F., *Gas holdup and volumetric mass transfer coefficient in bubble columns*, Ind. Eng. Chem. Process Des. Develop., 12, 1, 1973, 776-80.

[2] Chisti M.Y., *Airlift bioreactors*, Elsevier Applied Science, London and New York, 1989.

[3] Hari M., Tan R.B.H., *A dynamical systems approach to mixing in circulating flows*, Chem. Eng. Technol., 25, 2002, 811-818.

[4] Karcz J., Bitenc M., Domański M., Kacperski Ł., *Badania numeryczne przepływu ciecz-gaz w kolumnie air-lift z zewnętrzną cyrkulacją cieczy*, Inżynieria i Aparatura Chemiczna, 51, 6, 2012, 330-331.

[5] Karcz J., Bitenc M., Domański M., Kacperski Ł., *Analiza numeryczna zawartości gazu w cieczy i rozkładu rozmiarów pęcherzyków gazu w kolumnie air-lift*, Inżynieria i Aparatura Chemiczna, 51, 6, 2012, 332-333.

[6] Karcz J., Bitenc M., Domański M., Musiał M., *Analiza eksperymentalna i numeryczna bioprocesu w kolumnie air-lift z zewnętrzną cyrkulacją płynu*, Inżynieria i Aparatura Chemiczna, 52, 4, 2013, 334-335.

[7] Karcz J., Musiał M., Bitenc M., Domański M., *Charakterystyka wielkości pęcherzy gazowych w strefie wznoszenia kolumny air-lift z zewnetrzną cyrkulacją cieczy*, Inżynieria i Aparatura Chemiczna, 52, 4, 2013, 336-337.

[8] Karcz J., Musiał M., Bitenc M., Domański M., *CFD modelling of the fluid flow characteristics In an external-loop air-lift reactory*, Chemical Engineering Transactions, 32, 2013, 1435-1440.

[9] Kawalec-Pietrenko B., *Charakterystyka hydrodynamiczna i wymiana masy w trójfazowym reaktorze airlift z cyrkulacją wewnętrzną*, Politechnika Gdańska, 1992.

[10] Kawalec-Pietrenko B., Cisiak Z., Mrowiska M., *Cyrkulacja cieczy w wewnątrzbiegowym reaktorze air-lift z komorą mieszania pod dystrybutorem gazu*, Inżynieria Chemiczna i Procesowa, 18, 1997, 661-674.

[11] Keshavarz Moraveji M., Sajjadi B., Jafarkhani M., Davarnejad R., *Experimental investigation and CFD simulation of turbulence effect on hydrodynamic and mass transfer in a packed bed airlift internal loop reactor*, International Communications in Heat and Mass Transfer, 38, 2011, 518-524.

[12] Kulkarni A.A., Joshi J.B., Kumar V.R., Kulkarni B.D., *Simultaneous measurement of gas hold-up profiles and interfacial area using LDA in bubble columns: predictions by multiresolution*

analysis and comparison with experiments, Chemical Engineering Science, 56, 2001, 6437-6445.

[13] Luo H-P, Al-Dahhan H. M., *Verification and validation of CFD simulations for local flow dynamics in a draft tube airlift bioreactor*, Chemical Engineering Science, 66, 2011, 907-923.

[14] Šimčik M., Mota A., Ruzicka M. C., Vicente A., Teixeira J., *CFD simulation and experimental measurement of gas holdup and liquid interstitial velocity in internal loop airlift reactor*, Chemical Engineering Science, 66, 2011, 3268-3279.

[15] Wang T., Wang J., Jin Y., *Experimental Study and CFD Simulation of hydrodynamic behaviors in an external loop airlift slurry reactor*, The Canadian Journal of Chemical Engineering, 82, 2004,1183-1190.