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GAS HOLDUP AND LIQUID VELOCITY IN A TRIPHASIC EXTERNAL-LOOP AIRLIFT REACTOR

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ABSTRACT. Airlift reactors are heterogeneous contactors suitable for processes in which a close contact between phases and a good mixing are required. Airlift reactors are attractive for research and industry due to their particular hydrodynamic characteristics, which can be easily modified by the selection of a set of geometrical and operating parameters. Under these concerns, experiments were conducted to discern the relationship between the hydrodynamics of a solid-suspended external-loop airlift reactor of laboratory scale, and the operating conditions such as the gas velocity, the solids loading and density. The air flow rate, solids loading and solids density significantly affect the hydrodynamic characteristics of the investigated external-loop airlift reactor. Empirical correlation for gas holdup and liquid circulation velocity were proposed and found to be functions on the above-mentioned operating parameters. A reasonable agreement is found between the predicted and the measured values.

1. Introduction

Airlift reactors are heterogeneous contactors suitable for processes in which a close contact between phases and a good mixing are required. They are attractive for research and industry due to their particular hydrodynamic characteristics, which can be easily modified by the selection of a set of geometrical and operating parameters.

Airlift reactors are largely applied in biotechnology and environmental engineering, so that they appear to be one of the must important bioreactor configurations. They are most particularly employed in cultivation of plant and animal cells, as well as for waste water treatment, where combine a high treatment capacity with a low ground area occupied [1-3].

Airlift reactors are column reactors divided into two sections [4-6]:

- the riser, where the gas is injected;
- the downcomer.

They are classified according to the way in which the loop for circulating liquid is arranged, as follows:

- the internal-loop airlift reactors, which contain the riser and the downcomer in the same column;
- the external-loop airlift reactors, where the riser and the downcomer are separated tubes, side-by-side and connected at the top and the bottom by pipes.

External-loop airlift bioreactors have been frequently used in laboratory investigations, as well as in bench-scale and pilot-plant systems, because of the more-defined conditions and characteristic properties:

- a complete degassing of the liquid at the top which prevent the accumulation of gases produced during biological processes, which can reduce the mass transfer driving force;

- no zones of irregular flow at top and bottom of the bioreactor;
- easy removal of heat from the device;
- easy measurement and control of liquid circulation rate in the downcomer without complications arising from the gas content.

External-loop airlift reactors have also been used as gas-liquid (-solid) contacting devices in biological processes, preferentially at large scale, due mainly to their high controllable liquid circulation rates, a key design/operating parameter [7].

Some of the hydrodynamic parameters of interest in reactor design are the gas holdup, the magnitude of induced liquid circulation, and the liquid phase dispersion coefficient in various regions of the reactor. The gas holdup impacts upon reactor design because the total volume of the reactor for any range of operating costs and conditions depends on the maximum holdup that must be accommodated. The gas holdup also determines the residence time of the gas and liquid and, in combination with the bubble size, it influences the gas-liquid interfacial area available for mass transfer. The liquid circulation originates from the difference in the bulk densities of the fluids in the riser and downcomer [2,4,6,8-10].

The investigation is simpler when a two-phase system is involved. The complexity increases when a third phase (solid) is present into the system. The fermentation processes, as well as the biological waste treatment are characterized by the presence of a solid phase, slightly denser than water and where dynamic solid concentrations and density may occur. Usually, these investigations are performed at laboratory or pilot scales.

The main problem encountered when passing from laboratory to a larger scale is the changes of the fluid dynamics in the system. In environmental biological remediation processes, the microorganisms used for removal of polluting compounds can be immobilized as biofilm on solid particles of 1-2 mm diameter (sand, beads, charcoal), which are entrained by the liquid circulation flow. Because particle density changes as the biofilm grows, it is important to investigate the effect of solid loading and density on the airlift behavior. Therefore, mathematical models that should quantify these influences are valuable.

Several authors investigated the effect of the solid phase presence in airlift reactors on the hydrodynamic behavior [4,11-15]. Working with a low-density solid phase and with high amounts of solids, Freitas and Teixeira [11] found that liquid velocity in an external-loop reactor was drastically reduced by the presence of high-density solid particles. Kochbeck et al. [12] stressed that the liquid velocity in an external-loop airlift reactor was affected by the solid presence. Freitas et al. [13] found that solid loading and density had a considerable influence on gas holdup, liquid velocity and mixing time of an internal-loop airlift reactor with an enlarged degassing zone.

The flow and pathway complexity of these mixtures make difficult the hydrodynamic modeling of the airlift reactors. This problem becomes complicate when the solid density is variable, as in the biofilm processes [2,16]. Also, the influence of the solids on hydrodynamics is significant and hard to be predicted, because it can be in a continuous dynamic:

- changing quantity
- changing density
- changing size.

Only few of the models in literature describe the hydrodynamic of three-phase airlift reactors [2,4,13].

In this work, the behavior of a laboratory three-phase external-loop reactor was investigated. The objective of this study was to examine the hydrodynamic behavior when the hydrodynamic parameters are affected by the operating parameters. Therefore, the effect of gas superficial velocity, solid loading and solid density on gas holdup and liquid velocity were determined experimentally. Also, mathematical correlation between the gas holdup as well as the liquid velocity, and the specified parameters, respectively were developed and validated.

2. Experimental

Experiments were performed in an external-loop airlift reactor of laboratory scale, made of glass, with a working volume of 1.8 L, schematically depicted in Fig.1. The main geometrical parameters are presented in Table 1.

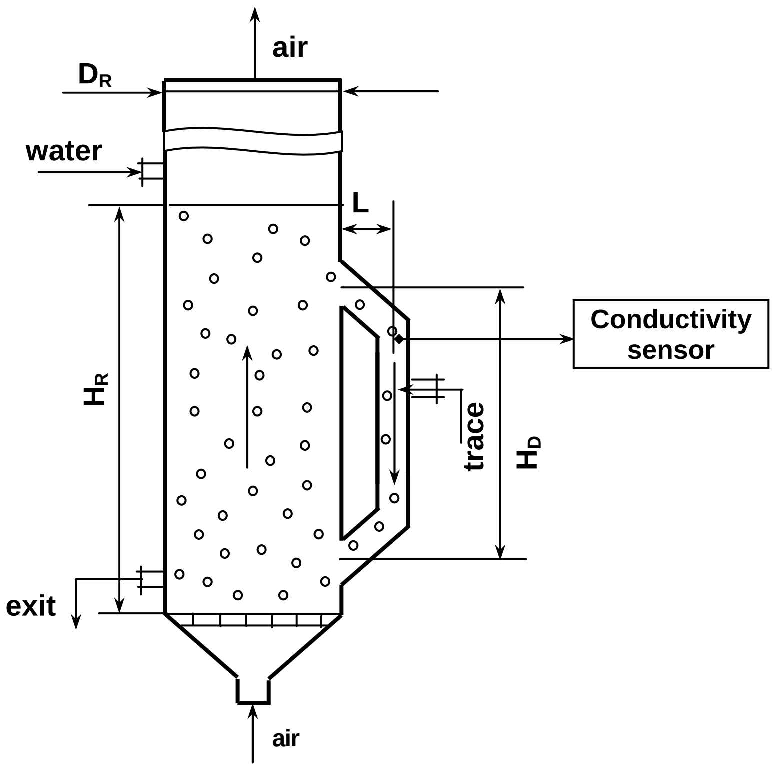


Fig. 1. Experimental setup

The downcomer joins the riser 0.20 m above the distributing plate. Air was used as gas phase, injected through a porous plate (G1 type). The superficial gas velocity ranged initially between v_{SGR} = 0.006 – 0.11 m/s. The superficial gas velocities are based on the riser cross sectional area, at normal conditions (10^5 Pa, 20^0C). Tap water was used as liquid phase. The particles used as solid phase were polypropylene (d_s = 2.3 ± 0.125 mm) and glass (d_s = 2.5 ± 0.150 mm) beads, respectively. The density values were as follows: ρ = 1200 kg/m^3, for the polypropylene beads and ρ = 3200 kg/m^3 for the glass beads. The solid fraction ranged between ε_S = 0 – 20 %.

The experiments were performed at room temperature ($20 \pm 2^o C$) in batch mode. The average volumetric riser gas hold-up (ε_{GR}) was determined from the manometric measurements of the hydrostatic pressure in the riser [4,9]. The sensor was connected to the reference via a differential manometer. Air bubbles in the manometer line were removed by frequent bleeding of the system; pressure oscillations were dampened out by the insertion of capillary sections in the line. It was assumed that the separation of the gas from the liquid phase is complete at the top of the reactor and the liquid flowing in the downcomer was bubble-free.

A tracer method was employed for liquid circulation measurement. The liquid velocity in downcomer was measured with a conductivity probe, as follows: for each set of experimental conditions, a pulse of saturated NaCl solution was injected into the downcomer entrance [4,8,10]. The response was determined by the conductivity probe placed under the injection point at a distance of 0,8 m. The data acquisition was stopped once a constant conductivity value was achieved. Three replicates were made for each set of experimental conditions, with a mean error of 5%.

Table 1.

Geometric characteristics of the laboratory external-loop airlift reactor

Characteristic	***Symbol***	***Units***	***Value***
Riser height	H_R	m	1.16
Downcomer height	H_D	m	0.55
Connecting pipes length	L	m	0.05
Riser cross sectional area	A_R	m^2	0.22
Riser diameter	D_R	m	0.06
Downcomer diameter	D_D	m	0.025
Downcomer cross sectional area	A_D	m^2	0.031
Downcomer to riser cross sectional areas ratio	A_D/A_R	-	0.14
Liquid volume	V_L	m^3	0.0018

The downcomer linear velocity, v_{LD} was determined from the length of the liquid path and the period between two adjacent conductivity maxima of the pulse propagation, using the following relation:

$$v_{LD} = \frac{x}{\Delta t} \tag{1}$$

where x is the distance between the injection point and the probe, Δt is the time required by the tracer to travel from the injection point to the probe (the first peak of the response curve).

3. Results and Discussion

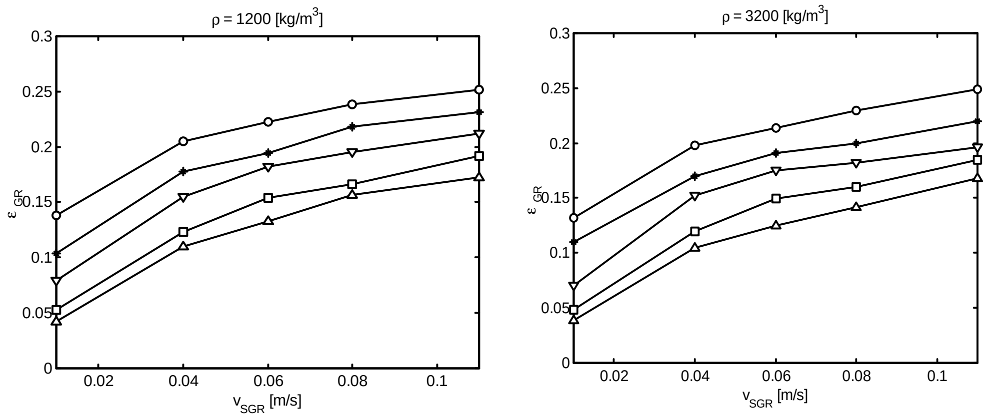
The need to work with triphasic dispersions is common seen in chemical engineering and biotechnology. Information on the behavior of suspensions and the gas and liquid flow required to attain the fully suspended state is essential for design and operation, knowing that airlift reactors are better to suspending solids than bubble columns [1, 17,18].

Preliminary experiments made with the two categories of beads showed that the solid distribution in the airlift device generally tend to be uniform for gas superficial velocities higher than v_{SGR} = 0.01 m/s, although the lower limit for v_{SGR} was 0.006 m/s in biphasic systems. Information on minimum fluidization velocity, concentration of solids in riser and downcomer, and solid segregation in solid mixtures will be published in a future work.

No experiments were made with different sparger configurations. There are data in literature on the influence of the gas sparger on hydrodynamics in airlift contactors. Most of them show that the gas sparger has little influence on the hydrodynamic parameters in airlift reactors, as long as the entire cross-section of the riser is uniformly sparged [4,19,20]. Merchuk [20] found that there is no difference in the gas holdup and liquid velocity for different distributing plates, in gas-liquid systems circulating in an external-loop airlift reactor. Chisti [3,4] showed that the sparger had a little effect on gas holdup in tall airlift reactors, when plates were properly designed. Contrary reports showed that this influence exists. Freitas et al. [13] reported that a distributing plate of 0.5 mm orifices has shown a different gas holdups when compared with those having 1.0; 1.6 mm hole diameters. Similar results were reported by Snape et al. [21]. Also, transition between homogeneous to heterogeneous regime differs when plates with different hole diameters were used [11,13], the transition being most pronounced for the smallest orifices. For triphasic gas-liquid solid systems it was reported that the solid content supress the differences between initial bubble size generated by different types of plates, enhanced by the influence of liquid circulation. This makes also the difference between the airlift and bubble column bioreactors [3-6].

Gas holdup

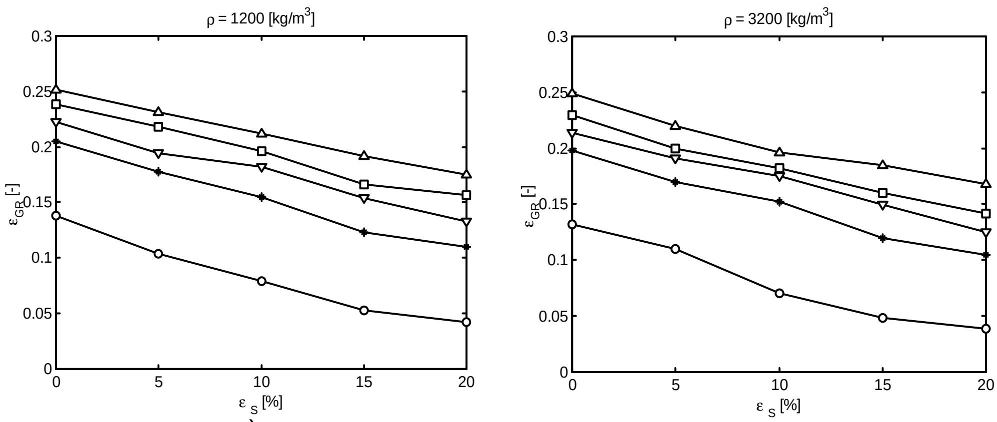
For different experimental conditions, gas hold-up measured in the riser was found dependent on the riser gas superficial velocity, solid loading and solid density (Fig. 2).



a) b)

Fig. 2. Dependence of the gas holdup in the riser on the gas superficial velocity (a - ρ = 1200 kg/m^3; b - ρ = 3200 kg/m^3; ε_S: --o-- 0%; --∗--5%; -- —10%; --x-- 15%; --Δ-- 20%).

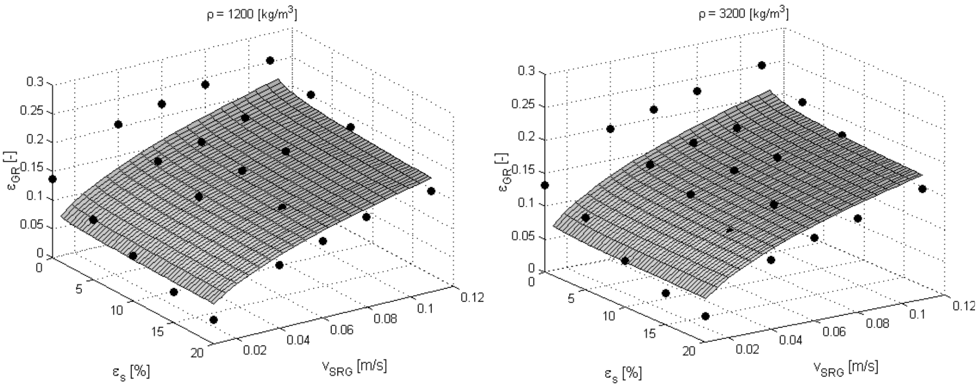
Gas holdup increases rapidly with gas superficial velocity up to a certain value of v_{SGR} and then changes the slope of the dependence. This can be ascribed to the change of bubbling flow in the riser to transition ($v_{SGR} \cong 0.04$ m/s) and turbulent ($v_{SGR} \cong 0.08$ m/s) flow respectively. This behavior was reported in literature often comparative to that in a bubble column where the transition is less smoother than in the airlift reactors, because the superimposed liquid circulation reduces the influence of sparger configuration on bubbling regime [4,13-15].



a) b)

Fig. 3. Effect of solid loading on gas holdup (a - ρ = 1200 kg/m^3; b - ρ = 3200 kg/m^3; v_{SGR}: --o—0.01 m/s; --∗--0.04 m/s -- — 0.06 m/s; --x—0.08 m/s; --Δ-- 0.11 m/s).

The effect of solid loading is marked: the progressive solid loading in the system results in a significant decrease in riser gas holdup (Fig. 3). This behaviour can be considered as the result of reduced flow area of gas and liquid phase and coalescence development and increasing. Also, it seems that solid density has a comparable influence on riser holdup with that solid loading. It can be also seen in Fig. 4 the combined effect of gas superficial velocity and solid loading on gas holdup for the particles with different densities.



a) b)

Fig.4. Influence of solids loading and riser superficial gas velocity on the riser gas holdup for two densities of the solid particles (a - ρ = 1200 kg/m^3; b - ρ = 3200 kg/m^3).

For lower air flow rates, riser gas holdup is a strong function of the riser superficial gas velocity, increasing with the increase of the air flow rate. For higher air flow rates, gas holdup dependence on gas superficial velocity becomes smaller. The effect of solid loading is clear, once the progressive introduction of solids in the system results in gas holdup decreasing, as a result of diminishing in flow area and as a consequence of coalescence intensification. Also from Fig. 4 (a,b) it seems that solid density has little influence on riser gas holdup, being observed a small decreases of ε_{GR} with the increase of solid density.

Liquid velocity

As was expected, downcomer liquid velocity increases with any increasing in riser gas superficial velocity (Fig.5).

At small gas flow rates, the riser gas holdup increases considerably more with increasing gas velocity than that in the downcomer [26]. Thus, the resulting large driving force leads to a larger increase of liquid velocity for low superficial gas velocity, whereas at larger gas throughputs, the liquid velocity tends to level [11-13]. As can be seen from Fig. 6, the dependence of downcomer liquid velocity becomes less marked with increasing solid loading. Also, the effect of solid density on downcomer linear liquid velocity consists in an increasing of v_{SLD} with density increase, probably because of the inertial effects. Also, the solid particles cause frictional loss as a consequence of the reduction of the flow area of gas and liquid phases. Similar results were reported by Freitas et al. [13], Lu et al. [27]. Downcomer liquid velocity on gas superficial velocity in the riser decreases with solid loading, mainly as a consequence of circulation driving force diminishing, reflected by the decrease of riser holdup because of bubble coalescence development.

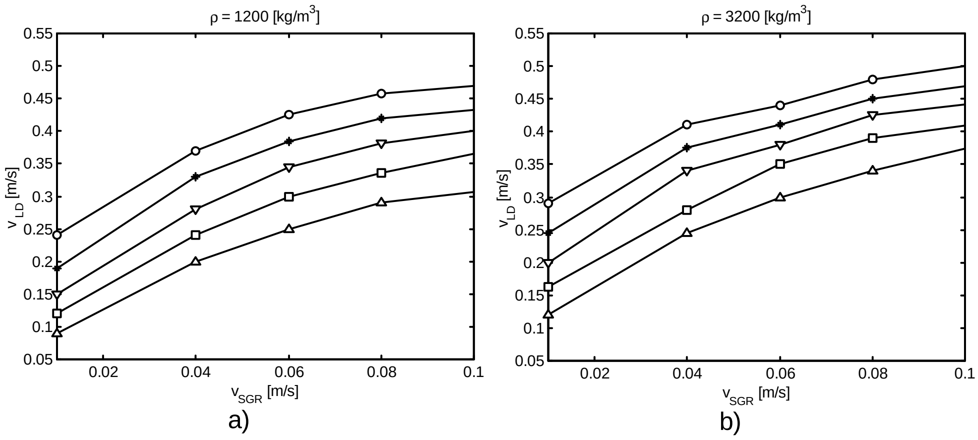


Fig. 5. Variation of the downcomer liquid velocity with the superficial gas velocity in the riser (signification of symbols as in Fig.2).

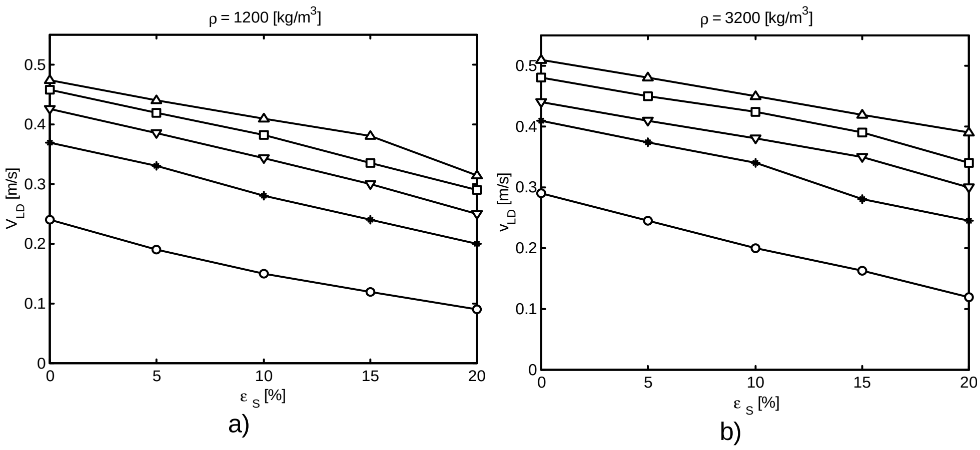
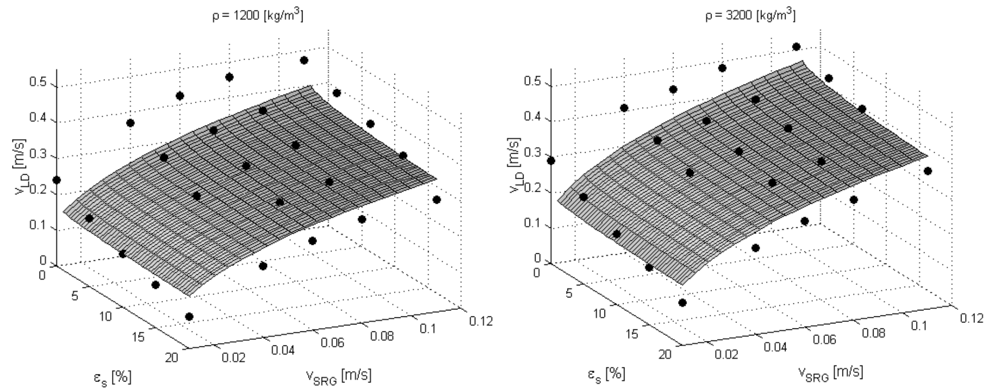


Fig. 6. Effect of solid loading on downcomer liquid velocity (signification of symbols as in Fig.3).

The influence of solid loading and gas superficial velocity on the downcomer liquid velocity is represented tridimensionally in Fig. 7. The increase of solid loadings produces a decrease of the liquid velocity, due to the decrease of driving force for circulation, and riser holdup is also reduced by the introduction of solids (Figs 3,4). Figs. 7a and 7b compares the downcomer liquid velocity for low and high density solids, allowing for the conclusion that, generally, solid density produces a small increase in v_{LD}.

Correlation of data

The hydrodynamic variables ε_{GR} and v_{LD} were correlated to the main operating parameter v_{SGR} and the solid loading and density using non-linear regression. The following equations resulted:



a) b)

Fig. 7. Influence of riser superficial velocity and solid loading on downcomer linear liquid velocity, for two densities of solid particles (a - ρ = 1200 kg/m^3; b - ρ = 3200 kg/m^3).

$$\varepsilon_{GR} = 0.835\, v_{SGR}^{0.45}\, \varepsilon_S^{-0.055}\, \rho^{-0.043} \quad (2)$$

r = 0.900, $s^2 = 6.59 \cdot 10^{-4}$

$$v_{LD} = 0.28\, v_{SGR}^{0.39}\, \varepsilon_S^{-0.042}\, \rho^{0.175} \quad (3)$$

r = 0.923, $s^2 = 2{,}06 \cdot 10^{-3}$

Comparison of the calculated and measured ε_{GR} and v_{LD} values are given in Figs. 8 and 9. ε_{GR} predictions based on eq. 2 generally are in good agreement with the experimental data, with an average error of 6%. The comparison between experimental v_{LD} data and those calculated with eq. (3) shows a good concordance, the average error being 5%.

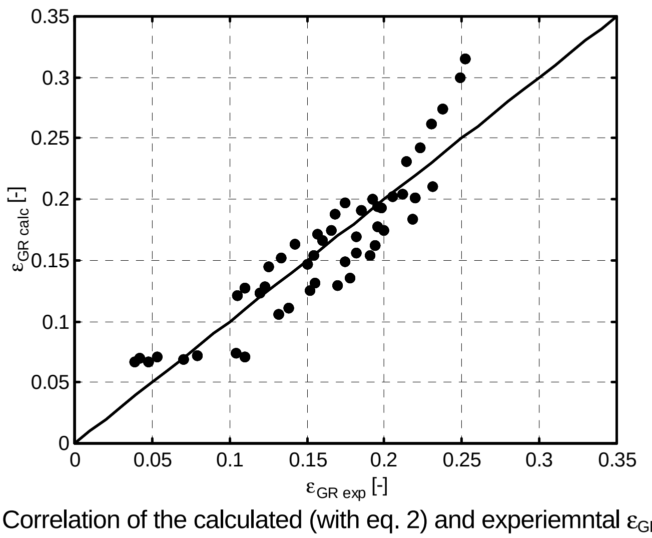


Fig. 8. Correlation of the calculated (with eq. 2) and experiemntal ε_{GR} data.

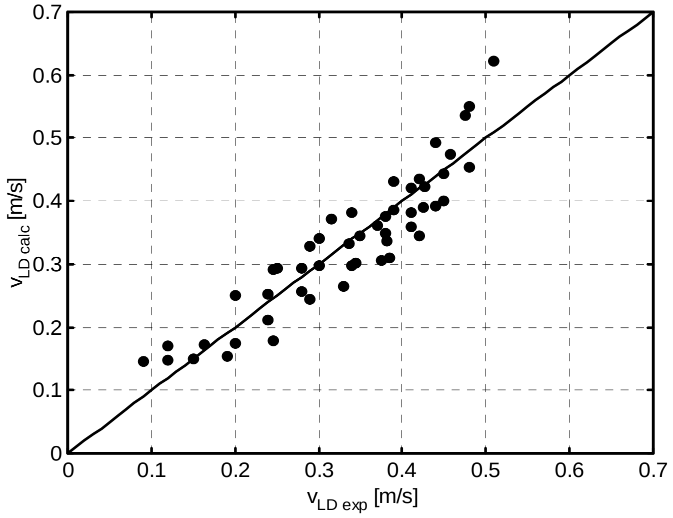


Fig. 9. Correlation of the calculated (with eq. 3) and experiemntal v_{LD} data

4. Conclusions

Gas holdup and liquid velocity were measured in a laboratory external-loop airlift reactor with gas-liquid-solid dispersions. Experiments were performed to investigate the effect of the operating parameters, the riser gas superficial velocity, the solid loading and density on the riser gas holdup and the downcomer liquid velocity. No experiments were conducted to found the effect of the distributor on hydrodynamics.

Both hydrodynamic parameters investigated were found to vary with the gas superficial velocity and solid loading, dependent on the particle density.

Airflow rate and solid loading have a great effect on riser gas holdup and downcomer liquid velocity. The increase in riser air velocity leads to an increase in riser gas holdup and liquid velocity. In opposition, the introduction of solids generates a tendency of decreasing of the gas holdup and liquid velocity. The solid density increase affect gas holdup and liquid velocity.

The present investigation clearly evidenced that the presence of the third phase (solid) in an airlift reactor can have a strong influence on performance of these contactors.

In terms of these adjustable parameters, it is possible to predict ε_{GR} and v_{LD} with the correlation developed by non-linear regression. Therefore, knowledge of the hydrodynamic behavior of the triphasic airlift reactors and the factors that influence it is necessary for design, modeling and operation, being of particular importance during the process of scaleup from laboratory to industrial scale.

Additional investigations have to be performed in large-scale external-loop airlifts to verify the proposed correlation between parameters.

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