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PREDICTION OF GAS HOLD-UP IN A COMBINED LOOP AIR LIFT FLUIDIZED BED REACTOR USING NEWTONIAN AND NON-NEWTONIAN LIQUIDS

Many experiments have been conducted to study the hydrodynamic characteristics of column reactors and loop reactors. In this present work, a novel combined loop airlift fluidized bed reactor was developed to study the effect of superficial gas and liquid velocities, particle diameter, fluid properties on gas holdup by using Newtonian and non-Newtonian liquids. Compressed air was used as gas phase. Water, 5% n-butanol, various concentrations of glycerol (60 and 80%) were used as Newtonian liquids, and different concentrations of carboxy methyl cellulose aqueous solutions (0.25, 0.6 and 1.0%) were used as non-Newtonian liquids. Different sizes of spheres, Bearl saddles and Raschig rings were used as solid phases. From the experimental results, it was found that the increase in superficial gas velocity increases the gas holdup, but it decreases with increase in superficial liquid velocity and viscosity of liquids. Based on the experimental results a correlation was developed to predict the gas hold-up for Newtonian and non-Newtonian liquids for a wide range of operating conditions at a homogeneous flow regime where the superficial gas velocity is approximately less than 5 cm/s.

Key words: combined loop airlift fluidized bed reactor; gas hold-up; Newtonian liquids; non-Newtonian liquids.

Industrial reactors are mainly classified into stirred tank reactors and column reactors. In biochemical processes, column reactors replace the stirred tank reactors for their advantages, like mild agitation and oxygen transfer. Among different configurations of three-phase column reactors, the advantages of three--phase combined loop airlift fluidized bed reactors over three-phase fluidized bed reactor and other configuration of airlift reactors are that they require lower liquid flow rate for complete suspension of solid. Apart from this, the external loop airlift reactor provides good contact among the phases, easy removal of particles, rapid mixing, reasonable interface mass transfer rates and easier scale up. In the combined loop reactor, a draft tube is inserted into the column and a separate tube is put side by side and connected at the top and bottom of the column. The draft tube acts as a riser, through which compressed gas is passed, and the annulus of the column and external tube act as down comers. The presence of the internal draft tube in an external loop three phase fluidized bed reactor provides more liquid circulation, which enhances the mixing between fluids and particles. The liquid inside of the column circulates when there is density difference between the riser and down comers. This reactor configuration provides a well distributed shear stress, self induced circulation, improved mixing and heat transfer characteristics provide a more advantageous environment for biological processes, slow reactions like oxidation and chlorination [1-3].

Klein *et al.* [4] studied the influence of a gas-liquid separator on the hydrodynamic characteristics in an internal loop airlift reactor. At low air flow rates, the gas-liquid separator had no influence on liquid circulation velocities and gas holdup in the down comer and separator, whereas at higher velocities, separator design had strong influence on the gas holdup and liquid circulation velocity in the down comer and the separator. Blazej *et al.* [5] studied the circulation velocity, overall riser and down comer gas holdup using

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three airlift reactors of different scale. Based on the results, they suggested using a larger reactor volume to avoid unfavorable influence of wall effects on gas holdup. Kilonzo *et al.* [6] studied the influence of baffle clearance on the liquid circulation velocity, gas hold-up and pressure drop in a two riser rectangular airlift reactor with inverse internal loop and expanded gas-liquid separator using different concentrations of CMC solutions and developed gas holdup and liquid circulation velocity correlations using experimental data based on dimensional analysis. Bentifraouine *et al.* [7] studied the hydrodynamics of external loop airlift reactor using Newtonian and non-Newtonian liquids and they found that for highly viscous non-Newtonian solutions, the gas flow was strongly influenced by the gas distributor. Law *et al.* [8] studied the gas--liquid flow dynamics of external airlift reactor using a Eulerian-Eulerian ensemble averaging method and they found that the 2D simulation predicted the growth of bubble in the down comer of the external loop airlift reactor. Liu *et al.* [9] studied the effects of the superficial gas velocity and liquid level in the gas-liquid separator on the liquid dispersion coefficient and developed a model and a good agreement with experimental results. Choi *et al.* [10] studied the influence of unaerated liquid height on the hydrodynamic characteristics of external loop airlift reactor and found that liquid height, superficial gas velocity and down comer to riser cross section area ratio had strong influence on the hydrodynamic characteristics of the airlift reactor. Though detailed hydrodynamic studies have been carried out using internal loop [11-14] and external loop separately [15-18], to date no work has been carried out to study the influence of fundamental and operating variable on gas holdup of airlift combined loop configuration using Newtonian and non--Newtonian liquids. Since combined loop reactors are gaining application in the area of bioprocessing and effluent treatment application, it is a vital need to the study the influence of fundamental and operating variables such as phase velocities, particle size and shape and physical properties of liquids on the design parameter such as gas holdup for using Newtonian and non-Newtonian liquids. Hence, in this present work an attempt has been made to study the influence of superficial liquid and gas velocities, particle diameter and sphericity, physical and rheological properties of Newtonian and non-Newtonian liquids on gas hold-up and to develop a dimensionless correlation to determine the gas holdup from the fundamental and operating variables using a three-phase combined loop airlift reactor.

MATERIALS AND METHODS

All the experiments were carried out in a combined loop airlift fluidized bed reactor made up of a Perspex column with 0.15 m inner diameter and 1.63 m height, with a flat bottom and draft tube 1.54 m in height with 0.084 m diameter. An external down comer connected at the top and bottom of the column, as shown in Figure 1. This reactor is divided into three zones; gas sparged riser, an unsparged down comer, a degassing zone at the top of the column removes gas bubbles from the riser. The bottom clearance between draft tube and gas distributor was 0.09 m and the top clearance between the free-gas liquid level and the draft tube was 0.12 m. Air was sparged through a triangular pitch sparger which was 0.08 m in diameter with 180 holes of 0.0008 m diameter each located slightly below the perforated plate. The gas holdup in riser creates a density difference between the riser and down comers induces liquid circulation. This liquid circulation that enhances heat and mass transfer between phases depends on the gas hold-up, which is major hydrodynamic parameter for scale up. The gas flow rate was measured by calibrated rotameters with an accuracy of ±2%. The properties of the liquids were measured at room temperature. The densities of the liquids were measured with a specific gravity bottle and the rheological properties of non-Newtonian liquids were measured by using Brookfield rheometer (Model LVDV-II+). The superficial gas and liquid velocities were calculated by volumetric flow rate of the fluids divided by cross sectional area of the column (0.15 m). Superficial gas velocities were varied from 0.000142 to 0.005662 m/s. Superficial liquid velocities were varied from 0.001 to 0.12 m/s. Phase velocities of both gas and liquid were calculated based on column diameter. Gas holdup was determined by volume expansion method [19].

In the present work, water, 5% *n*-butanol and various concentrations of glycerol (60 and 80%) were used as Newtonian fluids (commercial grade) and different concentrations of carboxy methyl cellulose (0.25, 0.6 and 1.0%) were used as non-Newtonian liquids. Different diameters of spheres, Bearl saddles and Raschig rings were used as solid phases. All the experiments were carried out in an atmospheric temperature with oil free compressed air as gas phase. After attaining the steady state, for every 5 min time interval, readings were taken and the error was found to be less than ±3%. A minimum of 3-5 readings were taken and the average value was used for calculations. The properties of solid particles and liquids used in the present study are given in Tables 1 and 2.

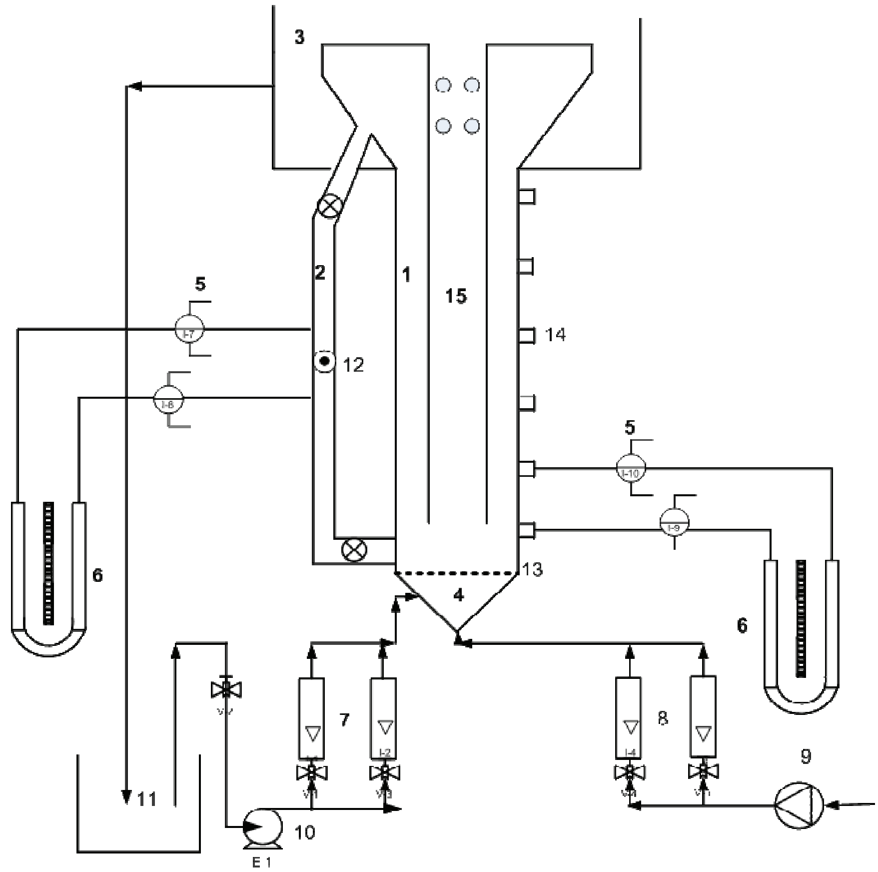

Figure 1. Schematic diagram of combined loop experimental setup; 1) riser, 2) down comer, 3) gas liquid separator, 4) calming , 5) gas liquid separator for manometer, 6) manometer, 7) rotameter for liquid flow rate, 8) rotameter for gas flow rate, 9) gas inlet valve, 10) liquid circulating pump, 11) liquid storage tank, 12) orifice, 13) supporting screen, 14) manometer tapings and 15) draft tube.

Table 1. Properties of solids used in the present study

Sl. No.	Particle description	Size, d_p / m	Density, ρ_s / kg m^{-3}	Particle sphericity, ϕ_s
1	Spheres	0.001	2478	1
2		0.002		
3		0.003		
4		0.004		
5		0.005		
6		0.006		
7		0.01036		
8	Bearl saddles	0.0115	2456	0.33
9	Raschig rings	0.01366	2083	0.58

RESULTS AND DISCUSSIONS

Effect of superficial gas and liquid velocities on gas hold-up

The effects of superficial gas and liquid velocities on gas holdup for air-5% *n*-butanol system are shown in Figure 2. It shows that an increase in superficial gas velocity increases the gas holdup in the column, which is in agreement with the previously published results [11,12,14,20]. The increase in superficial liquid velocity increases the velocity of the gas bubbles in the column and hence gas hold-up decreases. The same trend was also observed for air - 80% glycerol system, which is shown in Figure 3.

Effect of particle diameter and sphericity on gas hold-up

The effect of particle diameter on gas holdup for air-water system is shown in Figure 4, which is drawn between superficial liquid velocity and gas hold-up.

Table 2. Properties of liquids used in the present study

Type of liquids	Density of liquids, ρ_L / kg m^{-3}	Surface tension, σ_L / N m^{-1}	Viscosity, kg m^{-1} s^{-1}	
			K / kg m^{-1} s^{n-2}	n
Water	1000	0.0700	0.00083	1
5 % n-Butanol (commercial grade)	1008	0.0350	0.00098	
80 % Glycerol (commercial grade)	1180	0.0650	0.030	
60 % Glycerol (commercial grade)	1155	0.0660	0.0185	
0.25 % CMC	1026	0.0730	0.0197	0.87
0.6 % CMC	1020	0.0735	0.0308	0.86
1.0 % CMC	1017	0.0740	0.0565	0.85

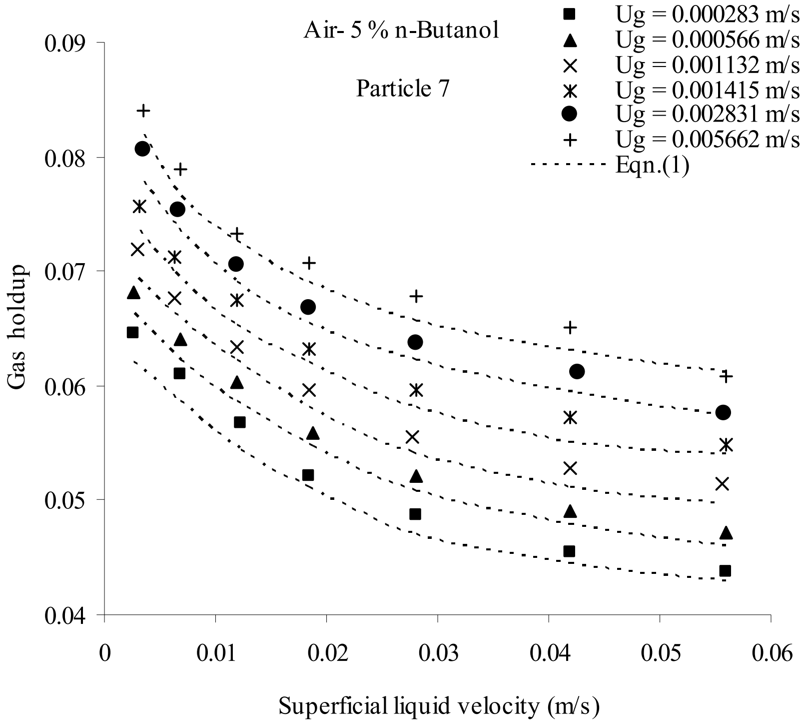

Figure 2. Effect of superficial gas and liquid velocities on gas hold-up for air-5% n-butanol system using particle 7.

From Figure 4, it is observed that an increase in particle diameter increases gas holdup. The increase in particle size suppresses bubble coalescence, which causes gas holdup to get increased. The influence of sphericity of particle on gas holdup is shown in Figure 5. The experimental results revealed that an increase of particle sphericity decreases gas hold-up. This may be due to the fact that decreasing the surface area per unit volume of the particle leads to less bubble breakage.

Effect of physical properties of liquids on gas hold-up

Figure 6 shows the effect of physical properties of air-water, air-5% n-butanol, air-60% glycerol and air-80% glycerol systems on gas hold-up for the superficial gas velocity 0.000283 m/s. From Figure 6 it is observed that an increase in viscosity of liquid decreases the gas hold-up, and also that increase in surface tension of liquid increases gas holdup. Figure 7 shows the effect of fluid consistency index for 0.25, 0.6 and 1.0% CMC liquids for the superficial gas velocity 0.001132 m/s. It is observed from Figure 7 that an increase in fluid consistency index (K) of liquid decreases the gas hold-up; this may be due to the formation of large bubbles at higher concentrations of solutions, the same trend was also observed in the literature studies [12,13].

Correlation

The analysis of literature shows that there is no evidence of any correlation developed to predict the gas hold-up for a wide range of operating conditions using Newtonian and non-Newtonian liquids with different solid particles for the combined loop airlift configuration. From the experimental data, a separate dimensionless correlation was developed to predict the

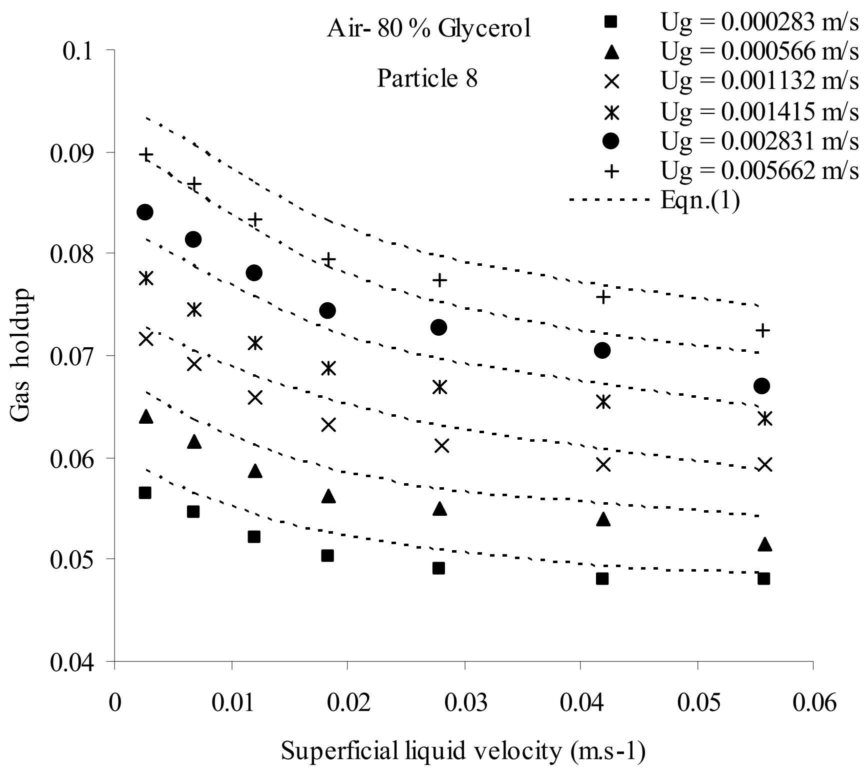

Figure 3. Effect of superficial gas and liquid velocities on gas hold-up for air-80% glycerol system using particle 8.

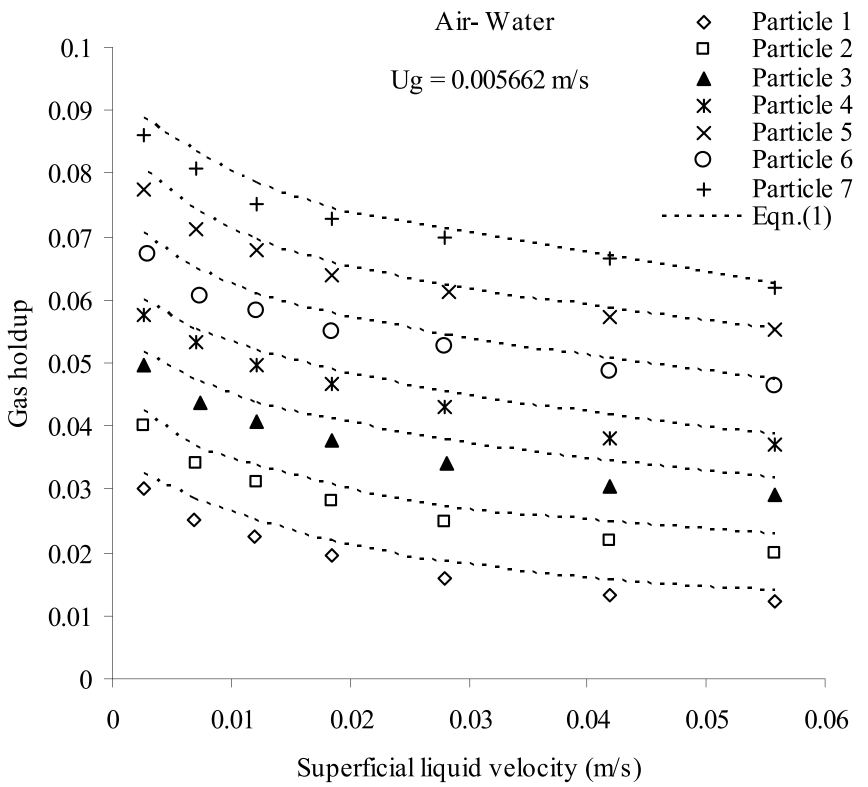

Figure 4. Effect of particle diameter on gas hold-up using air-water system for Ug = 0.005662 m/s.

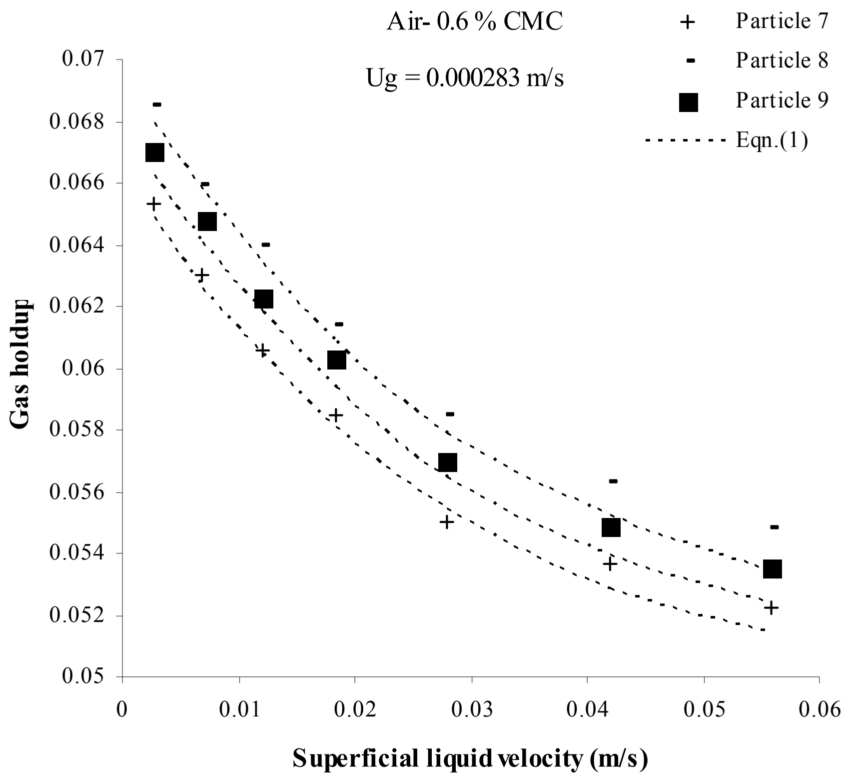

Figure 5. Effect of sphericity on gas hold-up using air-0.6% CMC for Ug = 0.000283 m/s.

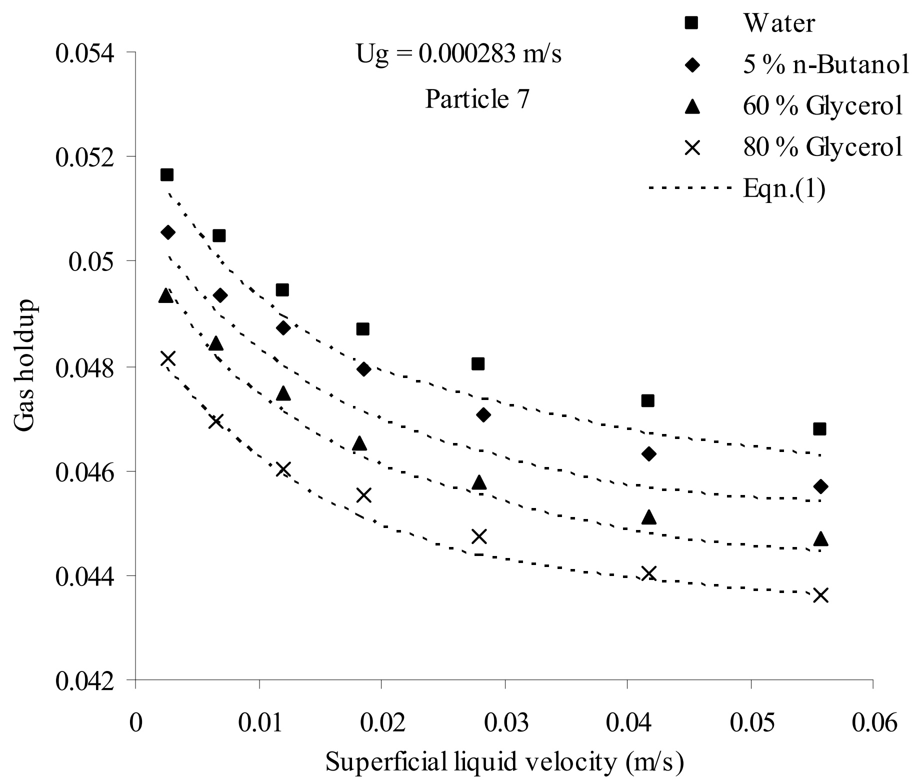

Figure 6. Effect of physical properties of liquids on gas hold-up for Ug = 0.000283 m/s using particle 7.

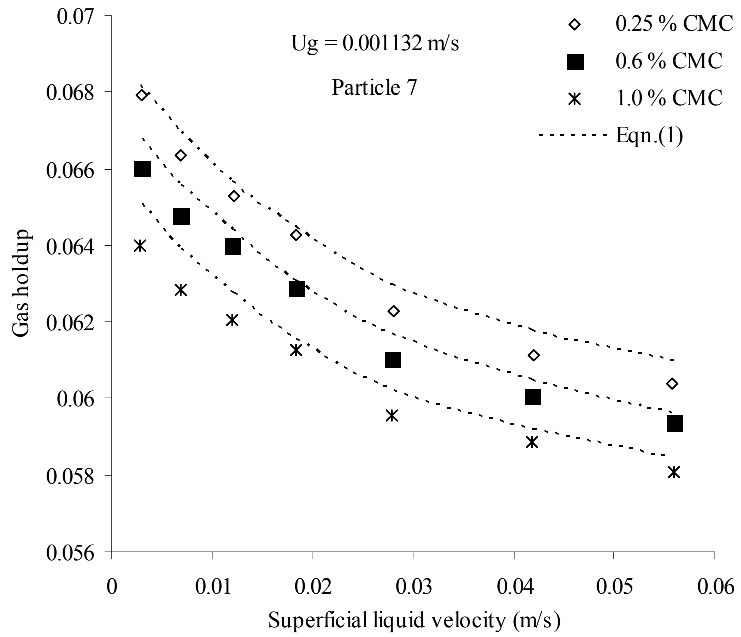

Figure 7. Effect of rheological properties of non-Newtonian liquids on gas hold-up for Ug = 0.001132 m/s using particle 7.

gas hold-up for a three phase flow. The combined effect of physical properties of non-Newtonian fluids are incorporated using modified Morton's number using regression analysis, the following correlation was developed to predict gas hold-up in a combined loop airlift three-phase fluidized bed reactor:

$$\varepsilon_g = 0.98 Fr_g^{0.12} Fr_l^{-0.01} \left(\frac{d_p}{d_c}\right)^{0.7} \varphi_s^{-0.12} Mo^{-0.025} \quad (1)$$

The comparisons of the present experimental and calculated gas hold-up data for Newtonian and non-Newtonian liquids are shown in Figures 8 and 9. They show good agreement between the experimental and calculated gas holdup with the average deviation of ±15%. The developed correlation is only applicable for homogenous flow regime where the inlet superficial gas velocity is roughly less than 5 cm/s.

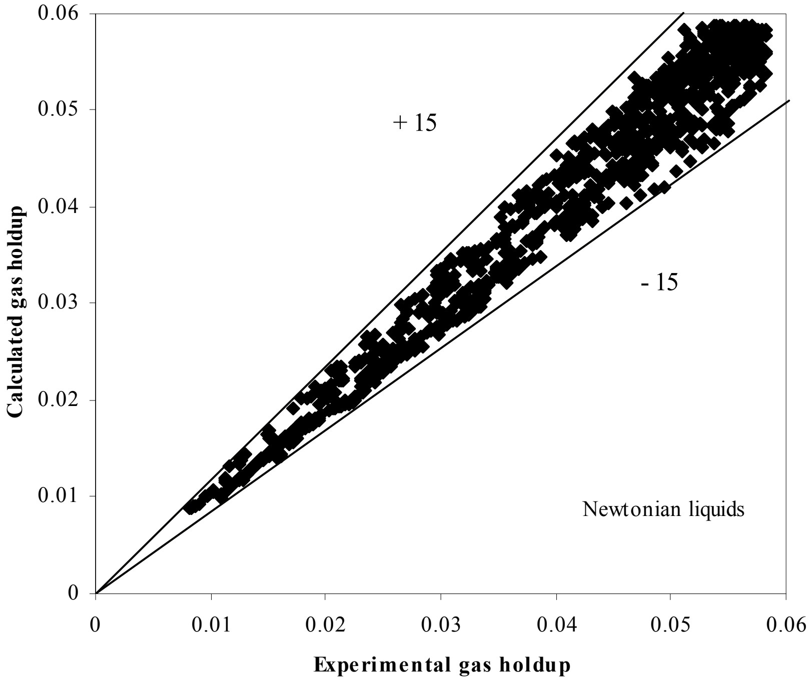

Figure 8. Comparison between the experimental and calculated values of gas hold-up for Newtonian liquids.

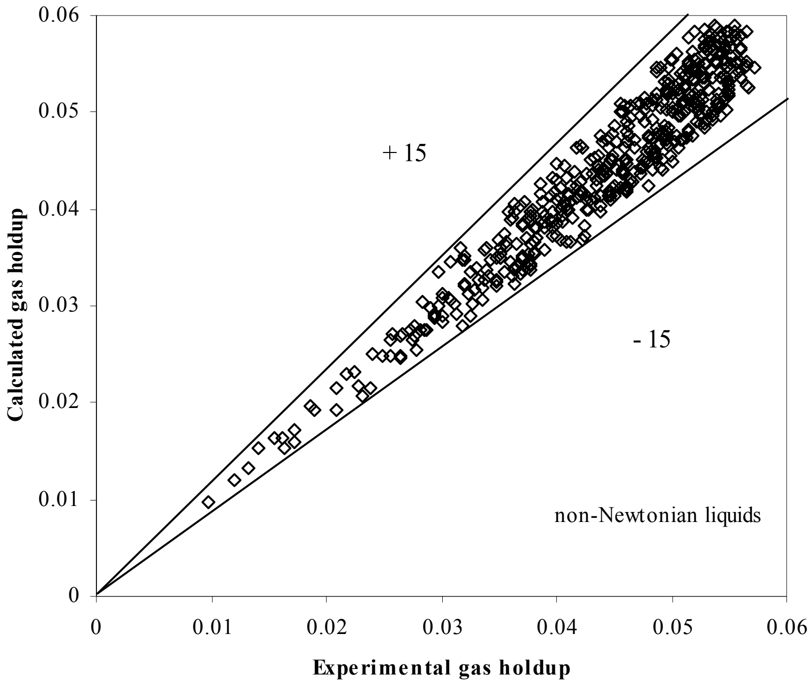

Figure 9. Comparison between the experimental and calculated values of gas hold-up for non-Newtonian liquids.

CONCLUSION

In the novel three-phase combined loop air lift fluidized bed reactor, gas hold-up was studied for different solid and liquid properties for Newtonian and non-Newtonian liquids at a homogeneous flow regime. It is observed that gas holdup in combined loop airlift fluidized bed reactor is dependent on the superficial velocities of liquid and gas. The increase in superficial gas velocity and particle diameter increases gas hold-up, but gas hold-up decreases with increase in superficial liquid velocity. The increase in viscosity and fluid consistency index of liquids decreases gas hold-up. A separate correlation was developed based on the properties of liquid and solid phases for gas hold-up and found to be coinciding with the experimental results. This correlation could be confidently used for design of commercial combined loop reactors.

Nomenclature

d_p - Diameter of the particle, m
d_c - Overall column diameter, m
Fr_g- Froude number for gas - $Fr_g = \frac{U_g^2}{gd_p}$
Fr_l - Froude number for liquid - $Fr_l = \frac{U_l^2}{gd_p}$
g - Acceleration due to gravity, m/s^2
K - Fluid consistency index, kg m^{-1} s^{2-n}
Mo - Morton number- $Mo = \frac{\left[K\left(\frac{U_l}{d_p}\right)^{n-1}\right]^4}{\rho_l \sigma_l^3}$ [g]
n - Fluid behavior index, dimensionless
U_g - Superficial gas velocity, m/s
U_l - Superficial liquid velocity, m/s
ρ_s- Density of the solid, kg/m^3
ρ_l - Density of the liquid, kg/m^3
ε_g - Gas holdup, dimensionless
ϕ_s - Particle sphericity
μ - Viscosity of liquid, kg m^{-1} s^{-1}
σ_l - Surface tension of liquid, N/m.

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NAUČNI RAD

ODREĐIVANJE SADRŽAJA GASA U KOMBINOVANOM AIR LIFT REAKTORU SA PETLJOM I FLUIDIZOVANIM SLOJEM, KORISTEĆI NJUTNOVSKE I NENJUTNOVSKE TEČNOSTI

Mnogo eksperimentalnih ispitivanja je urađeno da bi se odredile hidrodinamičke karakteristike kolonskih i reaktora sa petljom. U ovom radu razvijen je novi tip kombinovanog "air lift" reaktora sa petljom i fluidizovanim slojem da bio bio ispitivan uticaj prividne površinske brzine gasa i tečnosti, prečnika čestica i osobina fluida na sadržaj gasa u disperziji, koristeći Njutnovske i Nenjutnovske tečnosti. Kao gasna faza korišćen je komprimovani vazduh. Kao Njutnovske tečnosti korišćene su voda, 5% n-butanol i glicerol različitih koncentracija (60-80%), dok su kao Nenjutnovske tečnosti korišćeni vodeni rastvori karboksimetil celuloze (0,25, 0,6 i 1,0 %). Različite veličine sfera, Berlovih sedla i Rašigovih prstenova korićeni su kao čvrsta faza. Iz eksperimentalnih rezultata zaključeno je da porast prividne brzine gasa izaziva povećanje sadržaja gasa u disperziji, koji, međutim, opada pri porastu prividne površinske brzine i viskoznosti tečne faze. Na bazi eksperimentalnih rezultata izvedena je empirijska korelacija za predskazivanje sadržaja gasa u disperziji za Njutnovske i Nenjutnovske tečnosti, u širokom opsegu promene operativnih uslova, u režimu homogenog toka, u kojem su prividne brzine gasa manje od oko 5 cm/s.

Ključne reči: kombinovani air lift reaktor sa petljom i fluidizovanim slojem, sadržaj gasa u disperziji, Njutnovske tečnosti, Nenjtnovske tečnosti.