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Studies on Minimum Fluidization Velocity and Liquid Hold in an Internal Loop Airlift Fluidized Bed Reactor

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Studies on Minimum Fluidization Velocity and Liquid Hold in an Internal Loop Airlift Fluidized Bed Reactor

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Abstract

The influence of superficial gas and liquid velocities, particle diameter and sphericity, physical and rheological properties of liquids on minimum fluidization velocity and liquid holdup were studied in an internal loop airlift fluidized bed reactor. Spheres, Bearl saddles and Raschig rings were used as solid phases. Water, n-Butanol, two concentrations of Glycerol (60 and 80%) were used as Newtonian liquids and three concentrations (0.25%, 0.6% and 1.0%) of Carboxy Methyl Cellulose (CMC) solutions were used as non-Newtonian liquids. Superficial gas velocity was varied from 0.142 x 10^{-3} m/s to 5.662 x 10^{-3} m/s and superficial liquid velocity was varied from 0.001 to 0.12 m/s. The experimental results showed that increase in particle size and sphericity increased minimum fluidization velocity whereas increase in superficial gas velocity decreased minimum fluidization velocity. The liquid holdup increased with increase in particle size and superficial liquid velocity. An increase in superficial gas velocity decreased the liquid holdup for Newtonian and non-Newtonian systems. Based on the experimental results separate correlations were developed for the prediction of minimum fluidization velocity and liquid holdup for both Newtonian and non-Newtonian liquids for a wide range of operating conditions.

KEYWORDS: internal loop airlift fluidized bed reactor, minimum fluidization velocity, liquid holdup

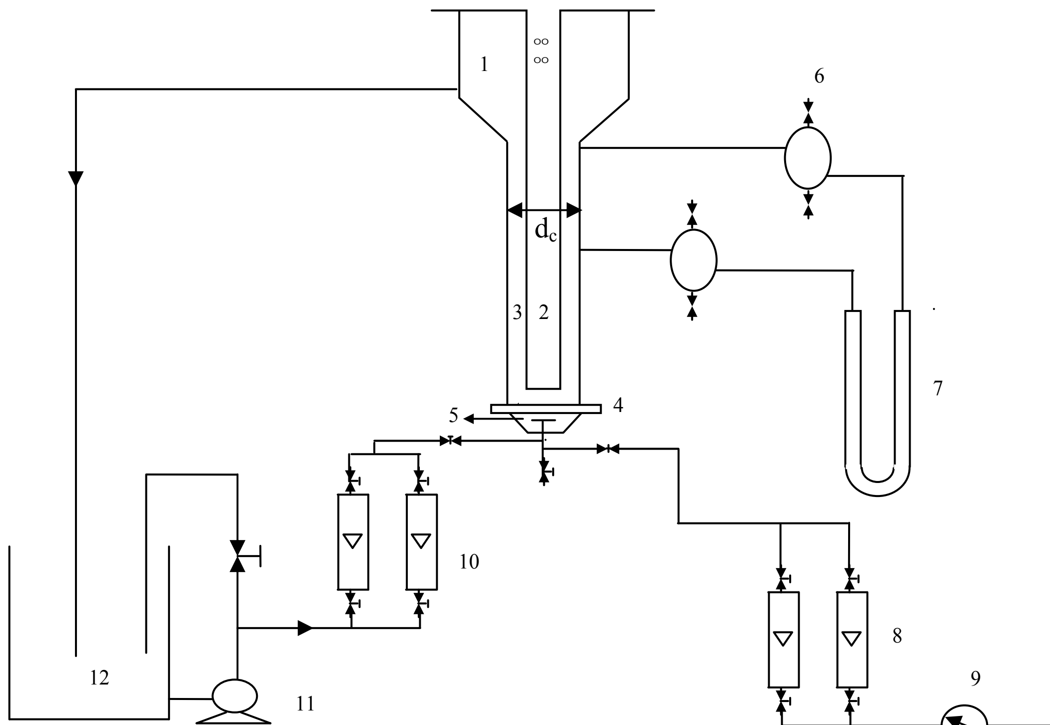
INTRODUCTION

Internal loop airlift fluidized bed reactors are widely used in chemical industries for their advantages like superior mixing performance with low power consumption, intimate contact between the phases, achieving fluidization of solid particles at low gas velocity, operational flexibility, etc. Recently in biochemical industries, internal loop airlift fluidized bed reactors were used because of high oxygen transfer rate. Apart from this internal loop airlift fluidized bed reactors provide better mixing and minimum cell rupture compared to external driven mixing system such as agitated vessels. Hemming (1979) observed that the airlift reactors increased oxygen transfer approximately five times higher than conventional stirred tanks for the same power consumption. Visnovsky et al. (2003) used internal loop airlift fluidized bed reactors to cultivate insect cells and noticed that the death of cells due to rupture came down owing to good mixing and low shear stress extended on the cell surface. Viggiani et al. (2006) used internal loop airlift reactors to carry out biodegradation of phenol using pseudomonas stetzeri Ox1. In order to design, scale-up and for flexible operation of three-phase internal loop air-lift fluidized bed reactors for continuous treatment of effluents or bioprocess applications knowledge of the hydrodynamic parameters such as minimum fluidization velocity and liquid holdup are essential. Minimum fluidization velocity is defined as the liquid velocity required for fluidizing the solid particles and maintaining at the same state. Liquid holdup is the fraction of the liquid occupied in the reactor and it plays a vital role in determining the interfacial area between the phases. Petrovic et al. (1993) studied the influence of liquid phase properties, solids loading, particle diameter and draft tube diameter to outer column diameter on minimum fluidization velocity using 1, 3 and 6 mm spheres as solid phases and water, 46 % Glycerol & 0.5% n-Butanol as liquid phases and developed correlations to predict minimum fluidization velocity function of terminal settling velocity of the particle which is the function of fundamental and operating variable. From the analysis of literature, it is found that most of the authors have concentrated their studies to determine the influence of operating variables on gas holdup and liquid circulation velocity (Jin et al.(2006), Chisti et al. (1988 & 1995), Kilonzo et al.(2006) and Garcia Calvo 1989). Only a few researchers dealt with the minimum fluidization velocity (Koide et al.1984, Muroyama et al.1985**,** Heck and Onken 1987, Petrovic et al. 1989 and 1993) and liquid holdup (Garcia et al. 2000a, b) in internal loop airlift reactors and also their studies were restricted to stagnant Newtonian liquid systems. Since effluent treatment process is continuous and nature of effluent may be either Newtonian or non-Newtonian depending on the source and concentration of pollutants, there is need to study the influence of fundamental and operating variable on the above-mentioned parameters and hence in this paper an attempt has been made to study the influence of superficial gas and liquid velocities, particle diameter, sphericity, physical and rheological properties of Newtonian and non-Newtonian liquids on minimum fluidization velocity and liquid holdup. Unified correlations have been developed to determine the minimum fluidization velocity and liquid holdup from the fundamental and operating variable.

EXPERIMENTAL SETUP AND PROCEDURE

All the experiments have been carried out in a Perspex column 0.15 m id, 1.63 m height, with a flat bottom and draft tube 1.54 m in height with 0.084 m diameter as shown in Fig. 1. 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 triangular pitch sparger which was 0.08 m in diameter with 180 holes of 0.8×10^{-3} m diameter each located slightly below the perforated plate as shown in Figure 1. 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 Brookfiled Rheometer (Model LVDV-II+). Superficial gas and liquid velocities were calculated based on the column diameter. Superficial liquid velocities were varied from 0.001 to 0.12 m/s. Superficial gas velocities were varied from 0.142×10^{-3} m/s – 5.662×10^{-3} m/ s. These superficial phase velocities of both gas and liquid were calculated based on column diameter (0.15 m). Minimum fluidization velocity was determined by visual observation (Koide et al.1984). The minimum fluidization velocity results obtained by visual observation of spherical, Raschig rings and Bearl saddles were compared with the results obtained from pressure drop method. Almost 80 % of results obtained by visual observation method were found to be good fit with the results obtained by pressure drop method with less than ± 2 % error and maximum deviation was found to be ± 5 % for Air-Water system using Raschig ring particles. The detail of measurement of minimum fluidization velocity by using pressure drop method is given elsewhere (Sivakumar and Senthilkumar, 2010). Liquid holdup was measured by volumetric method (Nacef et al.1992 and Miura et al .2001). Air and liquid flow rates were suddenly stopped by simultaneous closing of both the valves. The liquid holdup was determined by the volume of liquid to the total volume of the bed.

In the present work, Water, n-Butanol and various concentrations of Glycerol were used as Newtonian fluids and various concentrations of Carboxy Methyl Cellulose (CMC) were used as non-Newtonian fluids. 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. A minimum of 3-5 readings were taken and the average value was used for calculations and the error was found to be less than ± 3 %. The properties of solid particles and liquids used in the present study are given in Tables 1 and 2.



1. Degassing zone 2. Riser 3. Downcomer 4. Perforated plate
5. Sparger 6. Pressure taps 7. Manometer 8. Gas rotameter
9. Compressor 10. Liquid rotameter 11. Liquid pump 12. Liquid storage tank

Figure 1. Schematic diagram of internal loop airlift fluidized bed reactor

Table-I Properties of solids

Sl.No.	Particle Description	Size, dp, m	Density,kg/m^3	Particle Sphericity
1	Particle 1 (Spheres)	0.001	2478	1
2	Particle 2 (Spheres)	0.002	2478	1
3	Particle 3 (Spheres)	0.003	2478	1
4	Particle 4 (Spheres)	0.004	2478	1
5	Particle 5 (Spheres)	0.005	2478	1
6	Particle 6 (Spheres)	0.006	2478	1
7	Particle 7 (Spheres)	0.01036	2478	1
8	Particle 8 (Bearl saddles)	0.0115	2456	0.33
9	Particle 9 (Raschig rings)	0.01366	2083	0.58

Table-II Properties of liquids

Type of liquids	Density of liquids,(ρ_L) kg/m^3	Surface tension (σ_L) N/m	Viscosity	
			K kg m^{-1}s^{2-n}	n
Water	1000	0.0700	0.00083	1
n-Butanol	1008	0.0350	0.00098	1
80% Glycerol	1180	0.0650	0.030	1
60% Glycerol	1155	0.0660	0.0185	1
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

RESULTS AND DISCUSSIONS

EFFECT OF GAS VELOCITY AND PARTICLE SIZE ON MINIMUM FLUIDIZATION VELOCITY

The results of influence of superficial gas velocity and particle diameter on minimum fluidization velocity are shown in Fig.2. It shows that an increase in superficial gas velocity decreases the minimum fluidization velocity because increasing gas flow creates high density difference between riser and downcomer which leads to more liquid circulation and hence decreases minimum fluidization velocity. It is also observed that an increase of particle diameter increases minimum fluidization velocity. The same phenomenon was also observed by Petrovic et al.(1993).

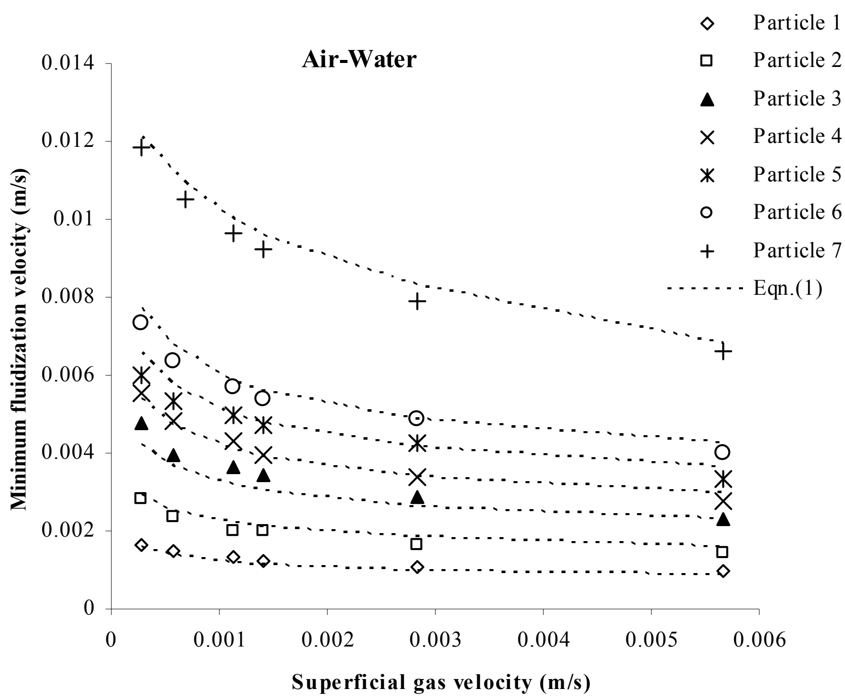


Figure 2 . Effect of particle diameter on minimum fluidization velocity

EFFECT OF SPHERICITY OF PARTICLE ON MINIMUM FLUIDIZATION VELOCITY

Three different particles with sphericity of 0.33, 0.58 and 1 were used to find the effect of particle shape on minimum fluidization velocity. From fig. 3 it is observed that when the particle sphericity increases minimum fluidization velocity increases. The similar trend of result was also observed for Air- 0.6 % CMC system which is shown in fig.4.

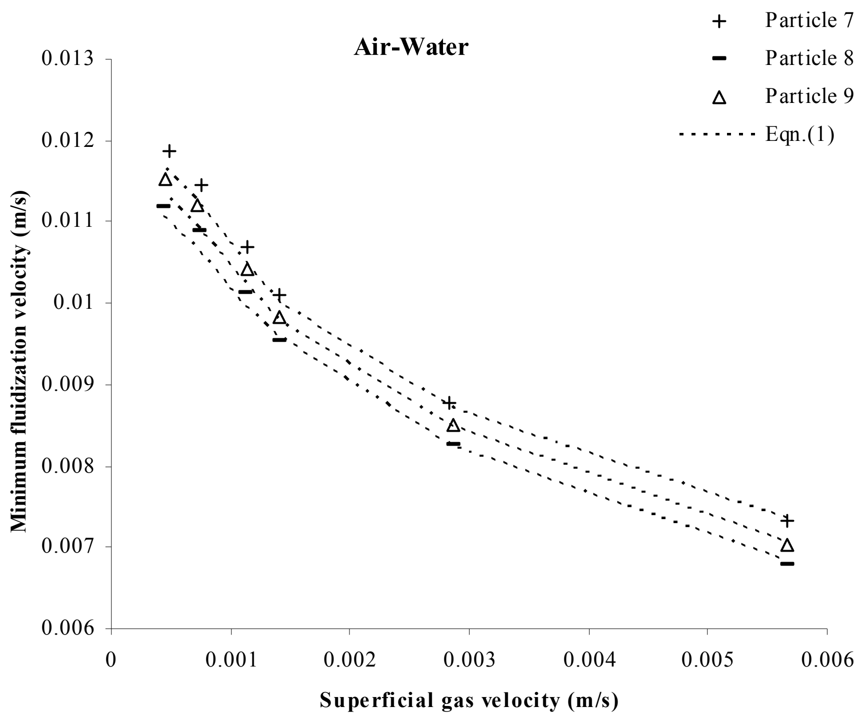


Figure 3 . Effect of particle sphericity on minimum fluidization velocity

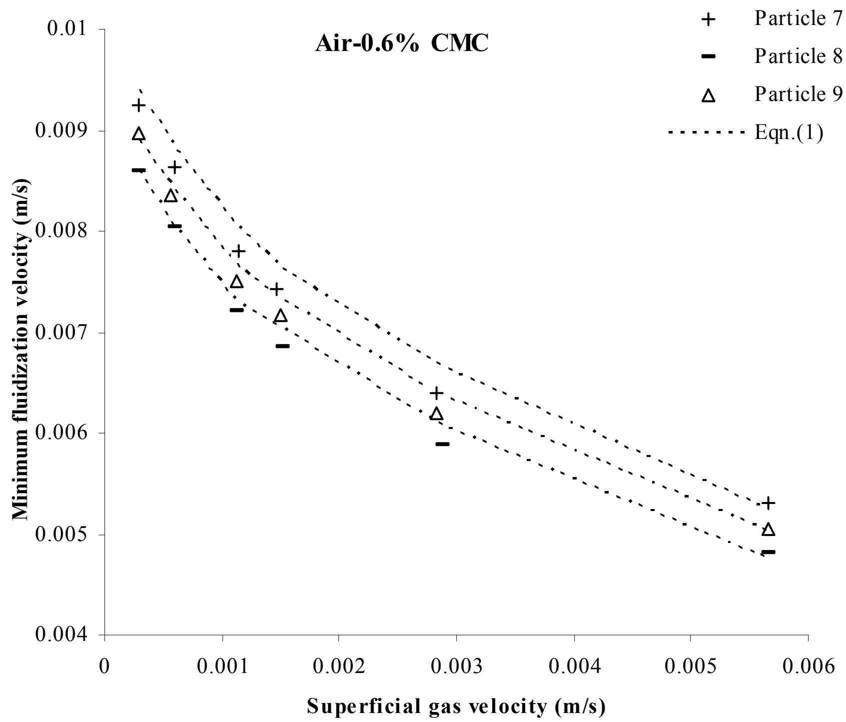


Figure 4 . Effect of particle sphericity on minimum fluidization velocity

EFFECT OF PHYSICAL PROPERTIES OF LIQUIDS ON MINIMUM FLUIDIZATION VELOCITY

Fig.5 shows the effect of physical properties of Newtonian liquids on minimum fluidization velocity. From the figure, it is observed that when the viscosity of liquids increases the minimum fluidization velocity decreases ,this is due to the fact that pure liquids always promote the bubble coalescence and the mixture of aqueous solutions hinder the bubble coalescence. From Fig. 5 it, it is observed that the surface tension of liquids does not have significant influence on the minimum fluidization velocity. Fig. 6 shows the effect of flow consistency index of non-Newtonian liquids on minimum fluidization velocity. Three concentrations of 0.25 %, 0.6 % and 1.0 % of carboxy methyl cellulose (CMC) were used as liquid phase. It is observed that an increase in flow consistency index decreases minimum fluidization velocity.

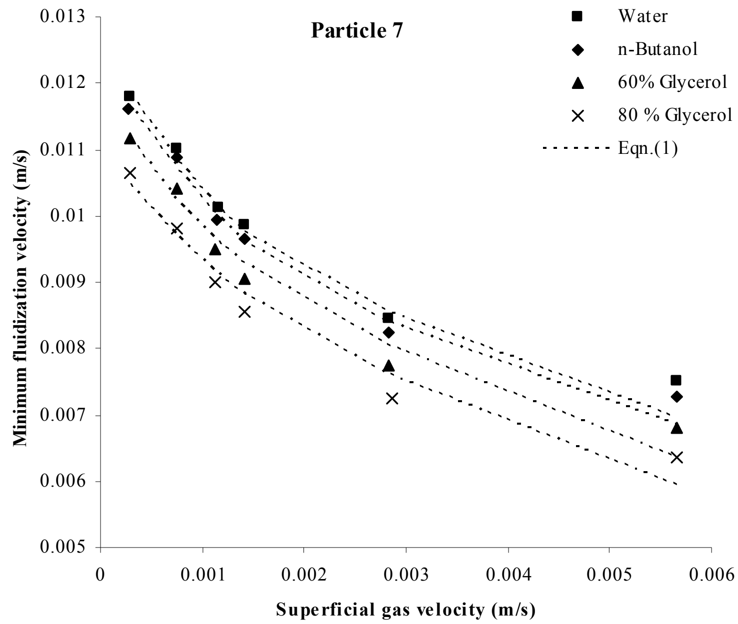


Figure 5. Effect of physical properties of Newtonian liquids on minimum fluidization velocity.

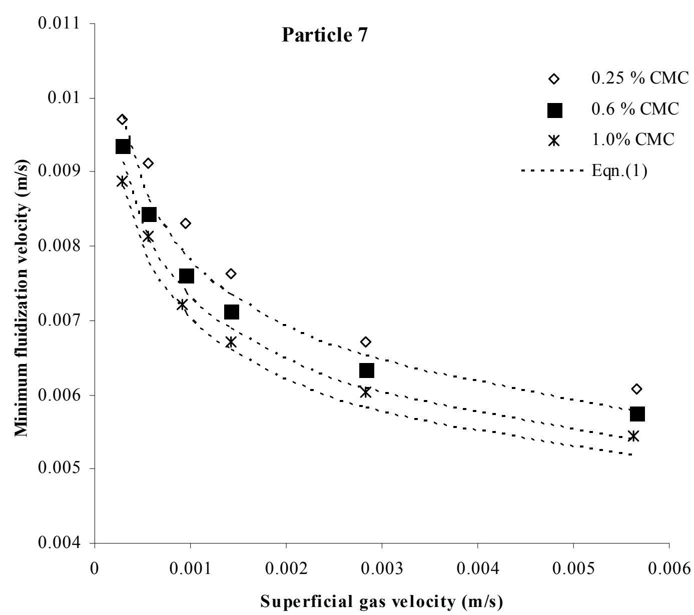


Figure 6. Effect of flow consistency index of non-Newtonian liquids on minimum fluidization velocity.

EFFECT OF PHASE FLOW RATES ON LIQUID HOLDUP

Fig.7 shows the effect of superficial gas and liquid velocity on liquid holdup for Air-Water system. It is observed that an increase in superficial liquid velocity increases the velocity of the gas bubble and therefore the liquid holdup increases. Increase in superficial gas velocity increases the fraction of gas bubbles in the column and hence liquid holdup decreases. The same trend was also observed for Air- n- Butanol, Air- 80 % Glycerol systems and Air-0.25% CMC which is shown in Figs. 8, 9 and 10.

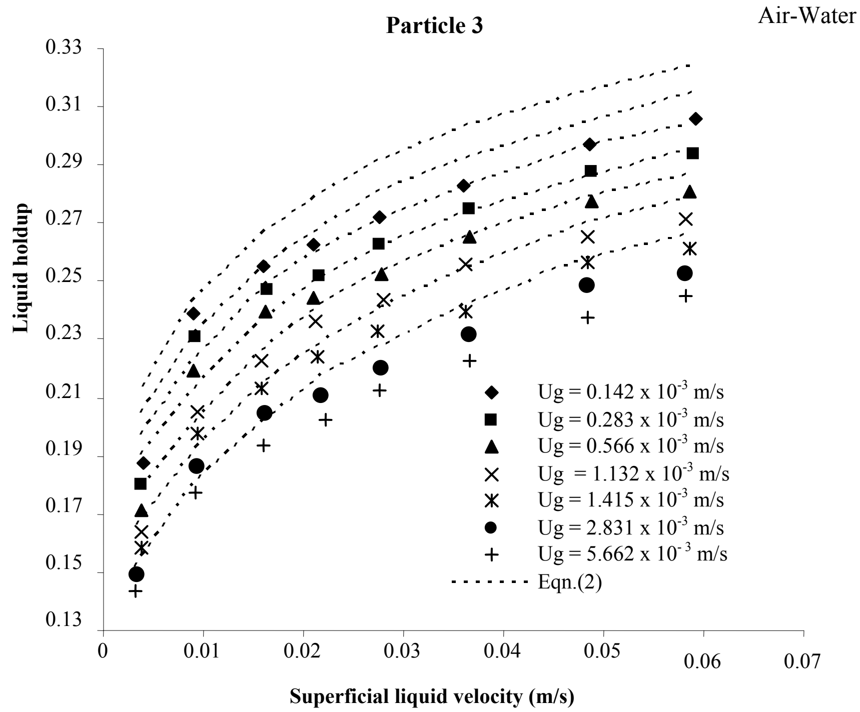


Figure 7. Effect of phase flow rates on liquid holdup

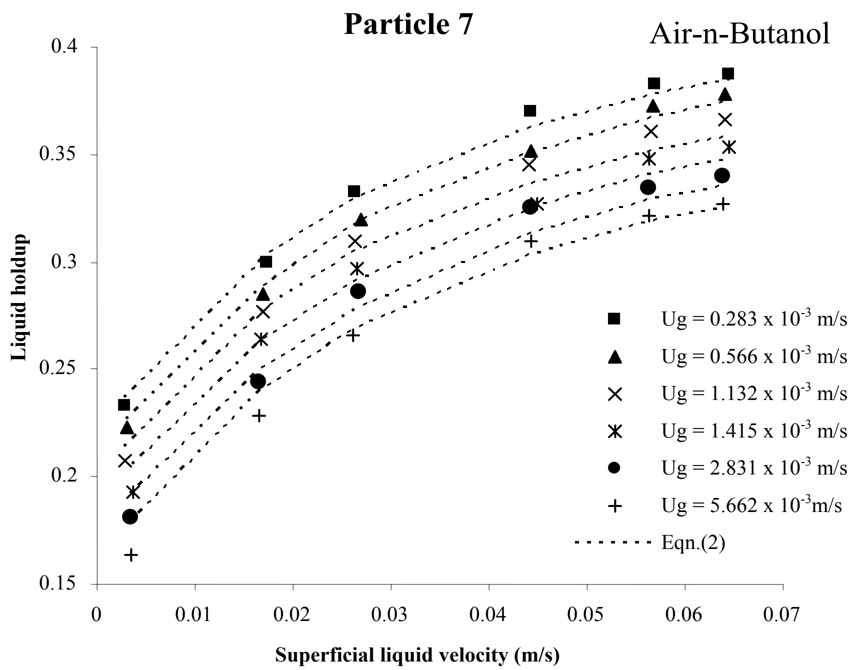


Figure 8. Effect of phase flow rates on liquid holdup for Air-n-Butanol system

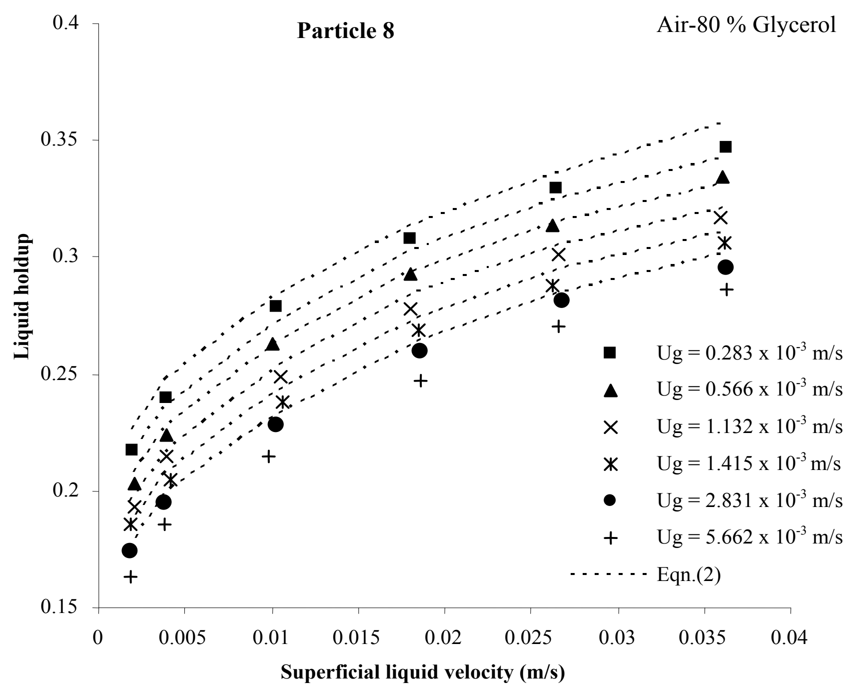


Figure 9. Effect of phase flow rates on liquid holdup for Air-80% Glycerol system

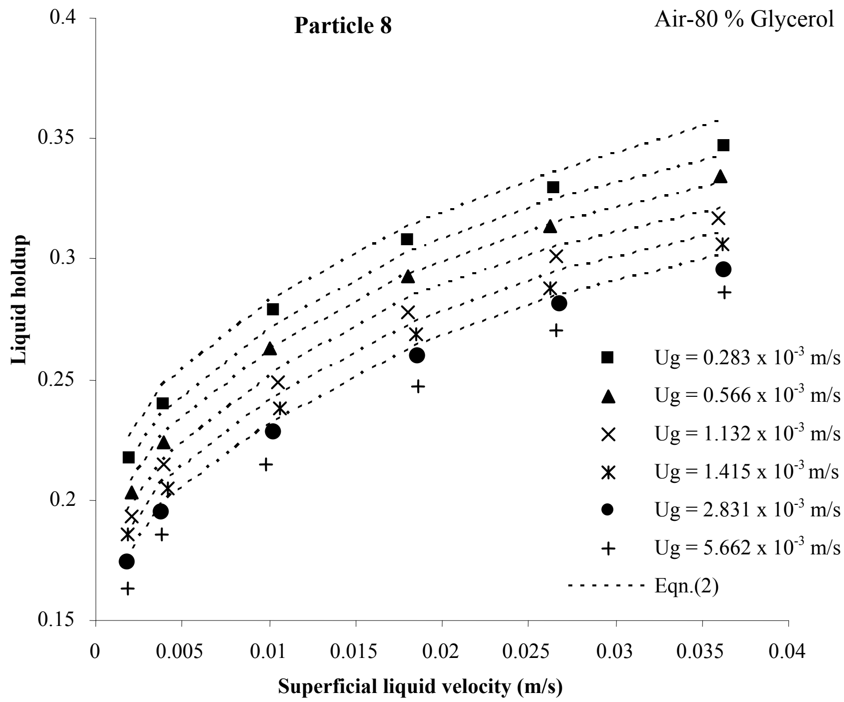


Figure 9. Effect of phase flow rates on liquid holdup for Air-80% Glycerol system

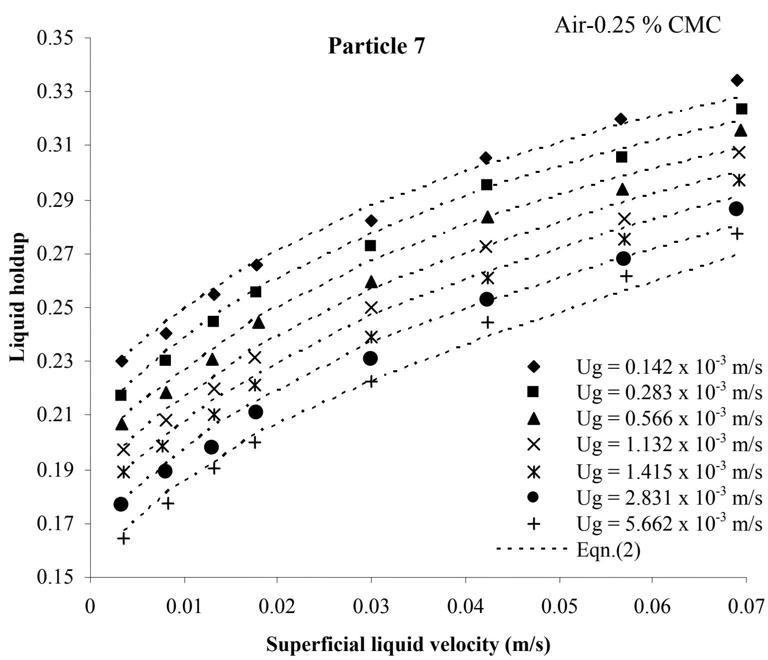


Figure 10. Effect of phase flow rates on liquid holdup for Air-0.25% CMC

EFFECT OF PARTICLE DIAMETER AND SPHERICITY ON LIQUID HOLDUP

Effect of particle diameter on liquid holdup for Air-Water system is shown in Fig.11 which is drawn between superficial liquid velocity and liquid holdup. From this graph it is observed that an increase in particle diameter increases liquid holdup in the column .This is due to the fact that increase in particle diameter does not break the gas bubbles as the smaller particles, so large gas bubbles move faster in the column, hence the liquid holdup increases. Fig.12 shows the effect of sphericity of particles on liquid holdup for the superficial gas velocity 0.283 x 10^{-3} m/s for Air-Water system. It is observed that increase in particle sphericity does not have any significant influence on liquid holdup .The same trend was also observed for Air-0.6 % CMC system, which is shown in Fig.13.

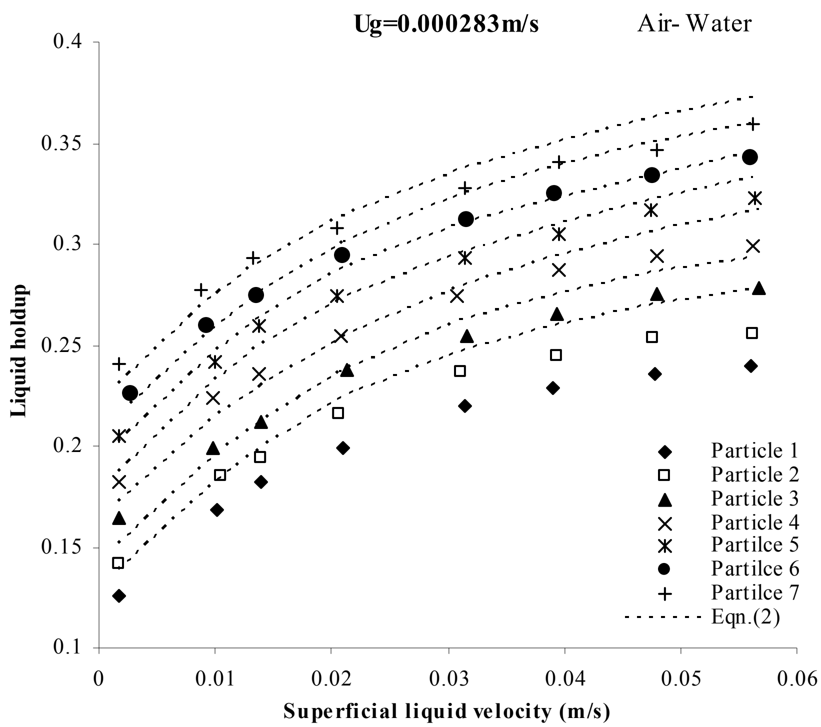


Figure 11. Effect of particle diameter on liquid holdup

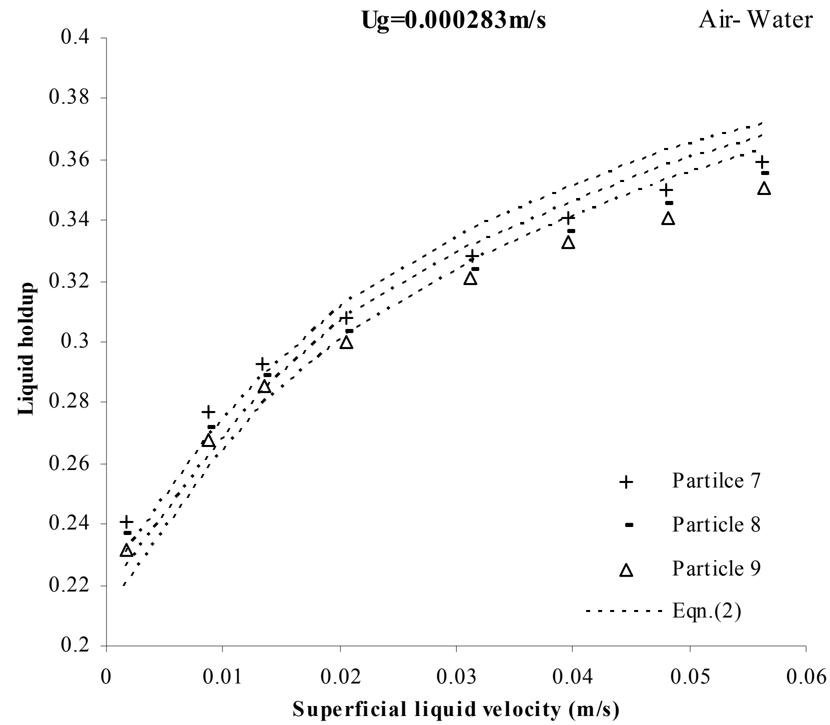


Figure 12. Effect of particle sphericity on liquid holdup

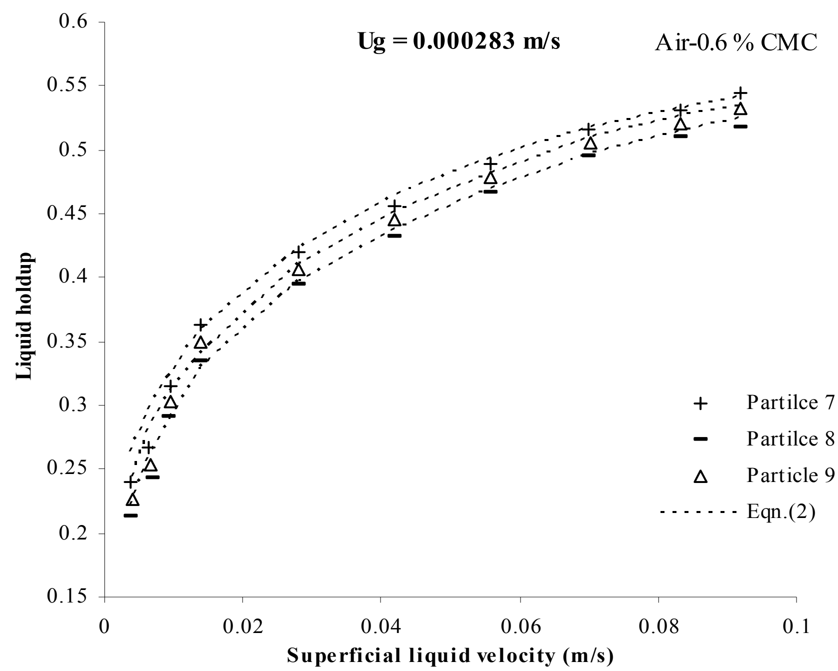


Figure 13. Effect of particle sphericity on liquid holdup

EFFECT OF PHYSICAL PROPERTIES OF LIQUIDS ON LIQUID HOLDUP

Figs.14 & 15 show the effect of physical properties of Air-Water, Air-n-Butanol, Air-60 % Glycerol and Air-80% Glycerol systems on liquid holdup for the superficial gas velocity 0.001415 m/s and 0.005662 m/s respectively. The figures show that an increase in viscosity of liquid increases the liquid holdup. From these figures it is also observed that decreasing surface tension of liquid increases liquid holdup. Fig 16 shows the effect of fluid behavior index for 0.25 %, 0.6 % and 1.0 % CMC liquids. From the experimental results it is observed that an increase in flow consistency index of non-Newtonian liquids increases the liquid holdup.

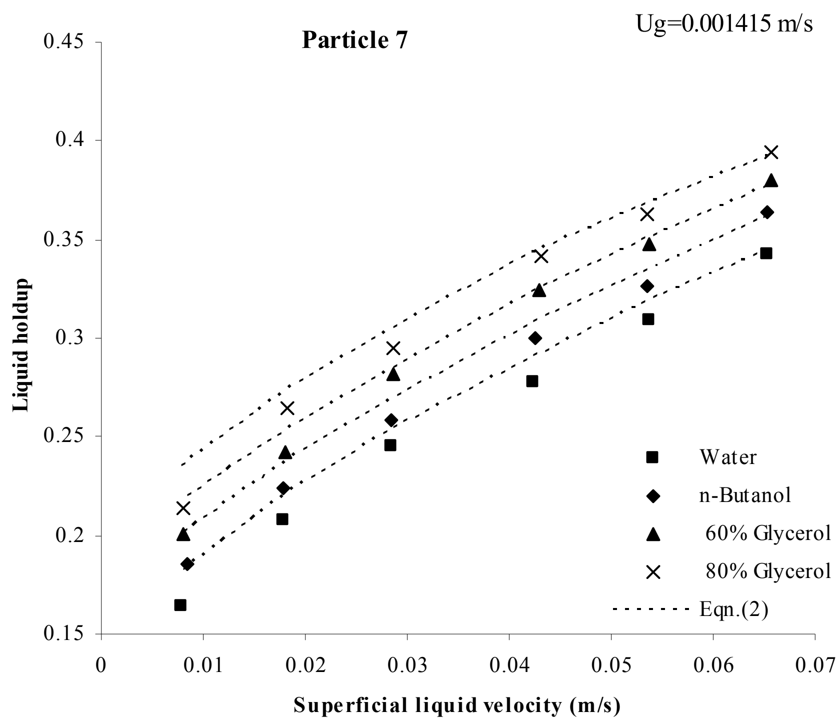


Figure 14. Effect of physical properties of Newtonian liquids on liquid holdup

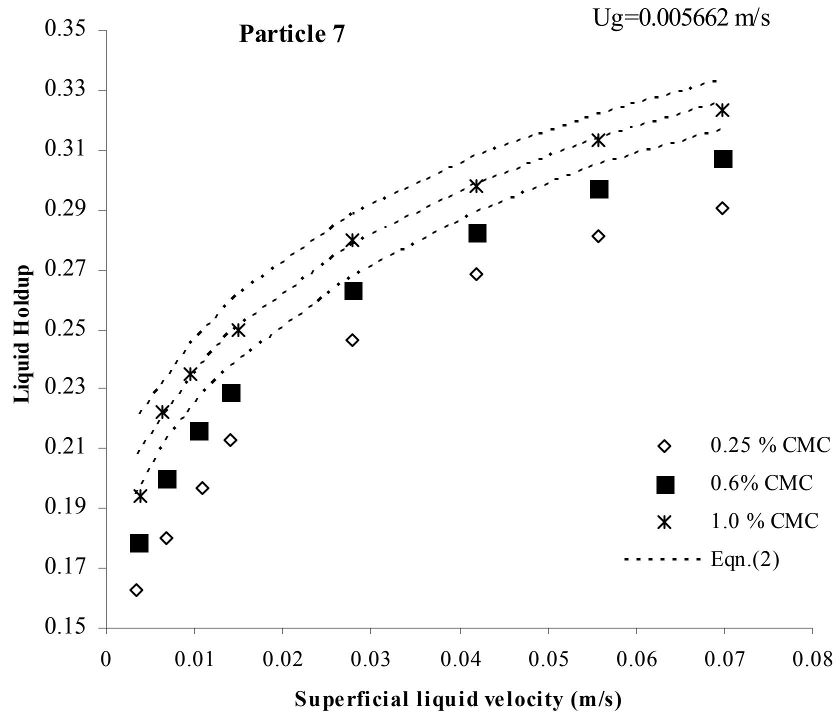


Figure 16. Effect of flow consistency index of non-Newtonian liquids on liquid holdup

CORRELATION

From the analysis of literature it is found that none of the authors developed correlation to predict minimum fluidization velocity and liquid holdup for a wide range of operating variables using Newtonian and non-Newtonian liquids. From the experimental data (174 for minimum fluidization velocity and 1600 for liquid holdup), two separate dimensionless correlations were developed to predict the minimum fluidization velocity and liquid holdup,

$$N_{\mathrm{Re}\,mf} = 0.98\left(Fr_g\right)^{-0.1}\left(\frac{\rho_p-\rho_l}{\rho_l}\right)^{0.076}\left(\frac{d_p}{d_c}\right)^{0.29}(\phi)^{0.12}\left(Ar\right)_m{}^{0.5} \qquad \text{---------} \quad \text{(Eqn.1)}$$

$$\varepsilon_L = 0.98\left(Fr_g\right)^{-0.026}\left(Fr_l\right)^{0.08}\left(\frac{d_p}{d_c}\right)^{0.42}\left(\frac{\rho_p-\rho_l}{\rho_l}\right)^{0.98}Mo^{0.002} \qquad \text{------------} \; \text{(Eqn.2)}$$

The predicting ability of the proposed correlation 1 and 2 were calculated and shown in figure 17, 18, 19 and 20 for Newtonian and non-Newtonian liquids.

Figure 17 and 18 show good agreement between the experimental and calculated minimum fluidization velocity with the average deviation of 15 %. Fig. 19 and 20 show the comparison between the experimental and calculated values of liquid holdup for Newtonian and non-Newtonian liquids and found to be in good agreement with experimental data with average deviation of 12 %. None of the authors have been reported their hydrodynamic results such minimum fluidization velocity and liquid holdup etc, in terms of fundamental operating variable such as phase flow rates, particle diameter, physical properties of liquids etc, and also their works were restricted to stagnant liquid and hence the proposed correlations (Eqn.1 and Eqn.2) have not able to validate with reported literature data (Petrovic et al. 1993).

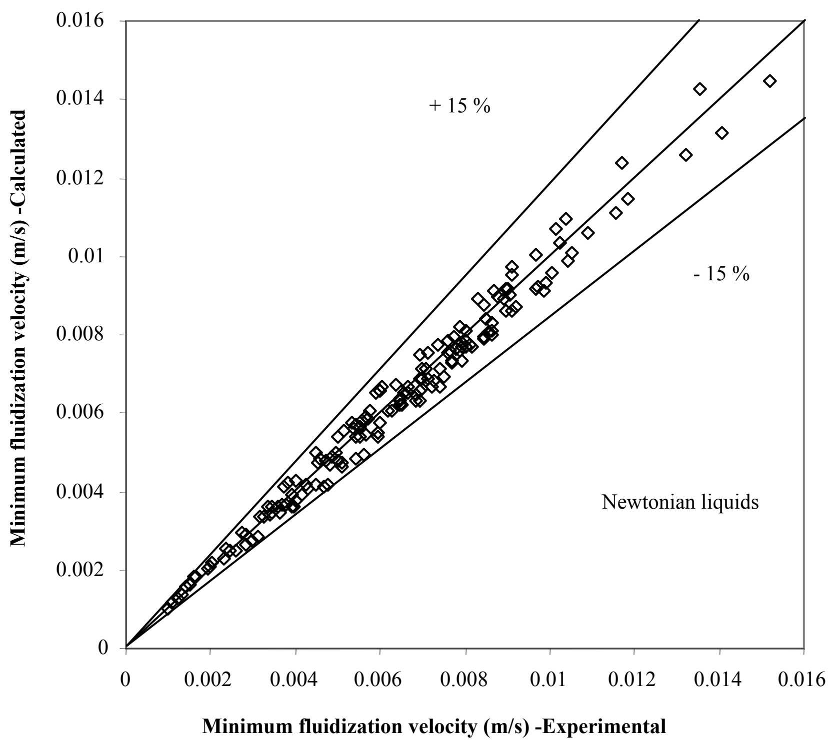


Figure 17. Comparison between the experimental and calculated values of minimum fluidization velocity for Newtonian liquids

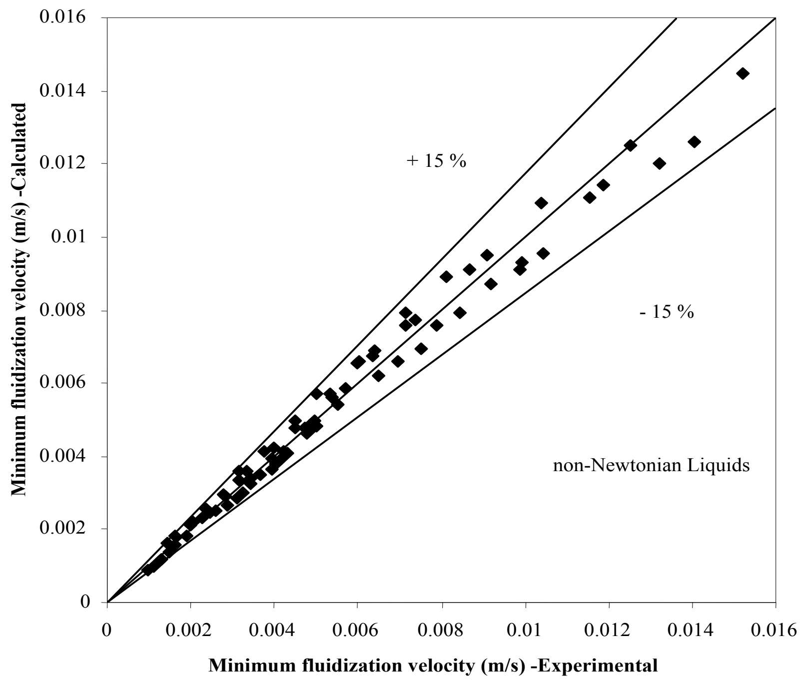


Figure 18. Comparison between the experimental and calculated values of minimum fluidization velocity for non-Newtonian liquids

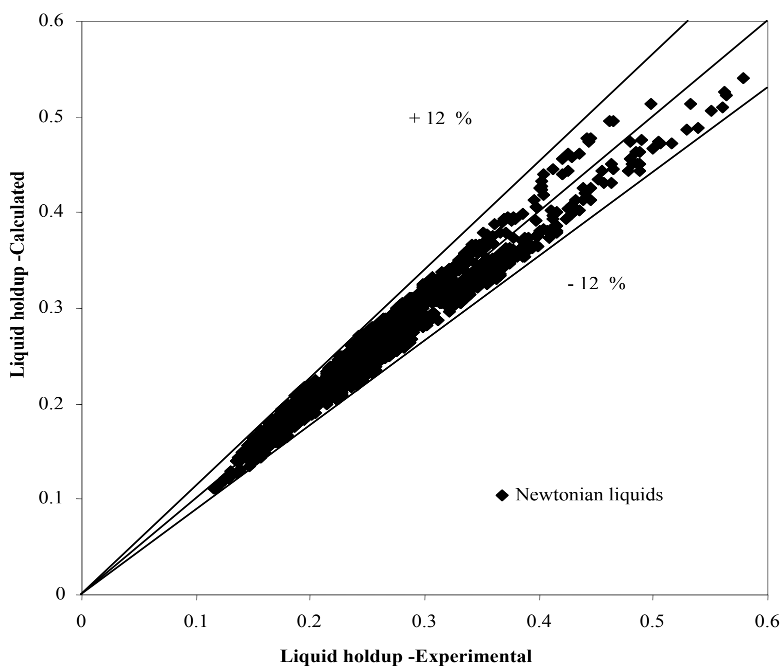


Figure 19. Comparison between the experimental and calculated values of liquid holdup for Newtonian liquids

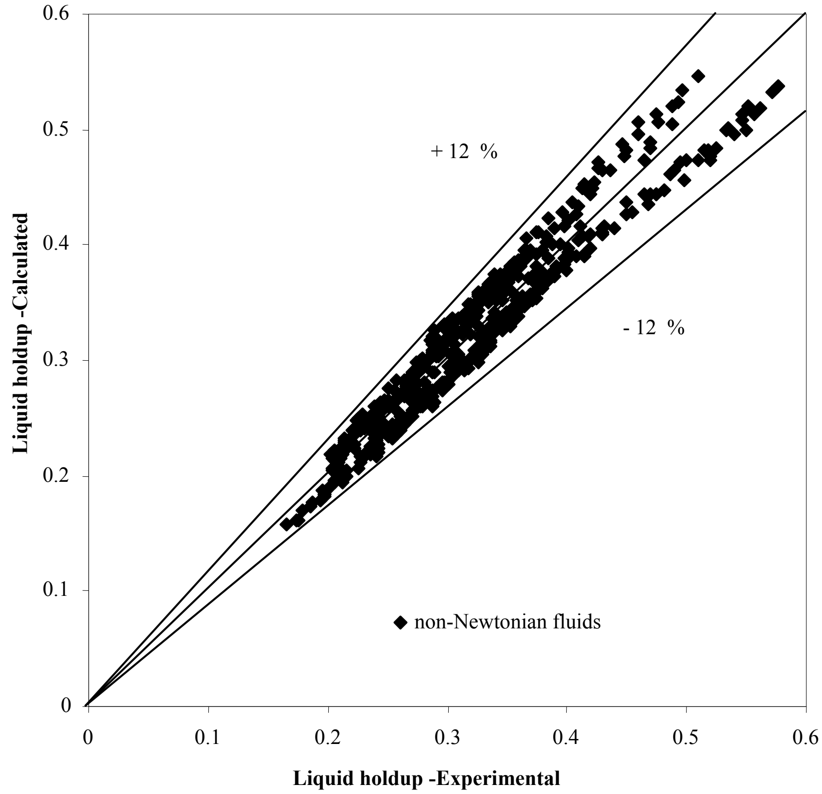


Figure 20. Comparison between the experimental and calculated values of liquid holdup for non-Newtonian liquids

CONCLUSION

The experimental results show that the increase in particle diameter increases the minimum fluidization velocity and decreases with increase in superficial gas velocity. The increase in viscosity of liquids and superficial gas velocity decreases minimum fluidization velocity. The increase of flow consistency index of non-Newtonian fluid decreases the minimum fluidization velocity also decreases with increasing superficial gas velocity. The increase in superficial gas and liquid velocities increases the liquid holdup for the systems Air-Water, Air-n-Butanol, Air-80% Glycerol and Air-0.25% CMC. The same trend is observed for the different particle diameters for Air-Water system. The increase in viscosity of liquids and superficial liquid velocity increases the liquid holdup. The increase in flow consistency index increases the liquid holdup.

NOTATION

$(A_r)_m$- Modified Archimedes number $= \dfrac{g.d_p^{\left(\frac{2+n}{2-n}\right)} \rho_l^{\left(\frac{n}{2-n}\right)} \left(\rho_s - \rho_l\right)}{K^{\left(\frac{2}{2-n}\right)}}$,dimensionless

d_p- Diameter of the particle, m
d_c- Overall column diameter, m

Fr_g- Froude number for gas- $Fr_g = \dfrac{U_g^{\ 2}}{g.d_p}$

Fr_l- Froude number for liquid- $Fr_l = \dfrac{U_l^{\ 2}}{g.d_p}$

g - Acceleration due to gravity, m/s^2
K – Flow consistency index, kg $m^{-1}s^{2-n}$

M_O- Morton number- $= \dfrac{\left[K\left(\dfrac{U_l}{d_p}\right)^{n-1}\right]^4}{\rho_l \sigma_l^{\ 3}} g$

n- Flow behavior index, dimensionless
$N_{Re\,mf}$ - Modified Reynolds number at minimum fluidization,

$N_{Re\,mf} = \dfrac{d_p^{\ n} U_{mf}^{\ 2-n} \rho_l}{K}$,dimensionless

U_g- Superficial gas velocity, m/s
U_l- Superficial liquid velocity, m/s
U_{mf}-Minimum Fluidization velocity, m/s
ρ_s- Density of the solid, kg/m^3
ρ_l- Density of the liquid, kg/m^3
ρ_g – Density of the gas ,kg/m^3
ϕ - Particle sphericity
ε_L- Liquid holdup
σ_L – Surface tension of liquid, N/m

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