Prediction of Liquid Holdup and Solid Holdup in Three-phase Fluidized Bed: Air/Newtonian and non-Newtonian Liquid Systems

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Three-phase fluidizing beds have emerged in recent years as one of the most promising devices for three-phase operations. Such a device is of considerable industrial importance in chemical and biochemical industries, wastewater treatment and other biochemical processes. For the design and development of three-phase fluidized bed reactors, knowledge of hydrodynamic parameters viz., liquid holdup and solid holdup is essential. Hence, in this paper, an attempt has been made to study the effect of fundamental and operating variables on liquid holdup and solid holdup. Besides, on the basis of the experimental results, the correlations were developed to predict these holdups in a three-phase fluidized bed using Newtonian and non-Newtonian systems covering a wide range of operating and fundamental variables. The statistical analysis showed that the predictive ability of the present proposed correlations is found to be a good fit with present experimental data and literature data.

Key words:
Liquid holdup, solid holdup, multiphase reactors, non-Newtonian liquids

Introduction

Three-phase fluidized beds are widely used in many industrial applications such as hydro-desulphurization of petroleum products, Fisher-Tropsch process and coal liquefaction of unsaturated fat, etc.[1–8] Recently, the application of three-phase fluidized beds has been increased in the field of chemical and biochemical processes.[9–11] Most notably, it has been used in the area of biological oxidation process for industrial wastewater treatment.[12–20] Even though many correlations have been published in literature for the estimation of liquid holdup and solid holdup, most of them are restricted to a limited range of applications in terms of particle dimensions, physical and rheological properties of the liquid systems used.[21–27] Since most of the bioprocess fluids and effluent have non-Newtonian behavior, there is a vital need to study the effect of rheological property on liquid holdup and solid holdup, and hence in this paper, an attempt has been made to study the effect of fundamental and operating variables on both liquid and solid holdup, and also to develop the correlations for the estimation of liquid holdup and solid holdup using Newtonian and non-Newtonian liquids.

Experimental setup and procedure

The Perspex fluidized-bed column was 1.8 m high and 0.15 m in diameter (Fig. 1). A gas distributor was provided at the bottom of the fluidized column, whereas, a gas-liquid separator was provided at the top of the fluidized column. The particles were supported by a wire screen, through which liquid phase was introduced. Compressed air was used as gaseous medium, introduced through a gas-liquid distributor placed above the wire screen. The liquid phase flowed through a calming section of 0.1 m height filled with 4.8 mm Raschig rings and entered the bed. The liquid from the storage tank was pumped into the gas-liquid distributor using a centrifugal pump. The gas and liquid phase entered the bed through a wire screen supporting the particles. The liquid and gas flow rates were measured using calibrated rotameters with an accuracy of ± 2 %. Solenoid valves were used for simultaneous opening and closing of both air and liquid lines. After attaining a steady state condition, air and liquid flow rates were suddenly stopped by closing both the valves simultaneously, and liquid holdup was measured.[28,29] In this present study, liquid was used as the continuous fluid and air as the dispersed medium. Water, different concentration of glycerol and MEA are Newtonian liquid systems and different concentration of CMC, are non-Newtonian liquids and seven different particles were

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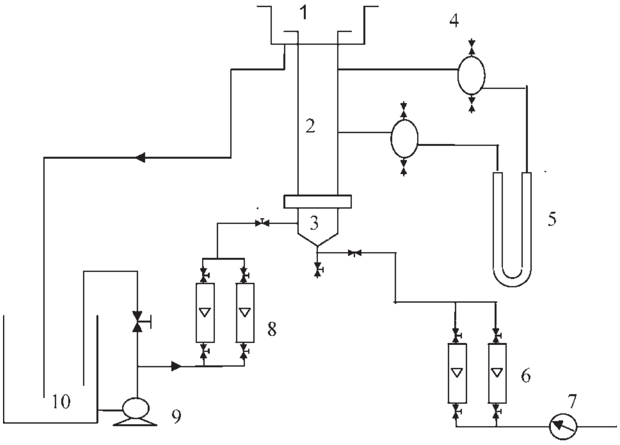

1. Disengagement section
2. Testing section
3. Claming section
4. Gas-liquid separators
5. Manometers
6. Gas rotameters
7. Pressure regulating valve
8. Liquid rotameters
9. Circulating pump
10. Liquid storage tank

Fig. 1 – *Schematic of the experimental setup*

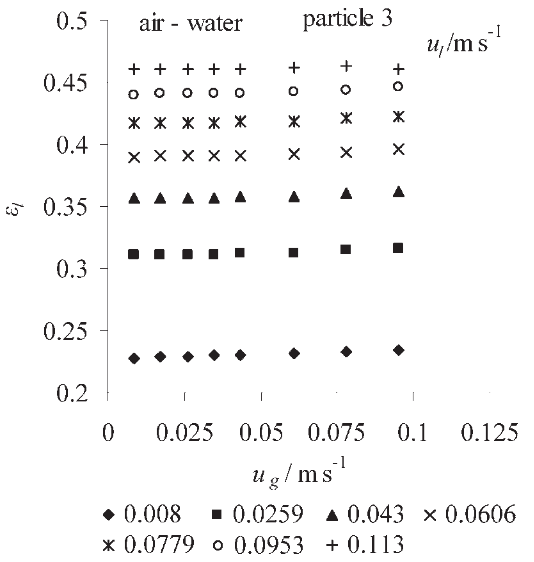

Fig. 2 – *Effect of gas and liquid velocities on liquid holdup*

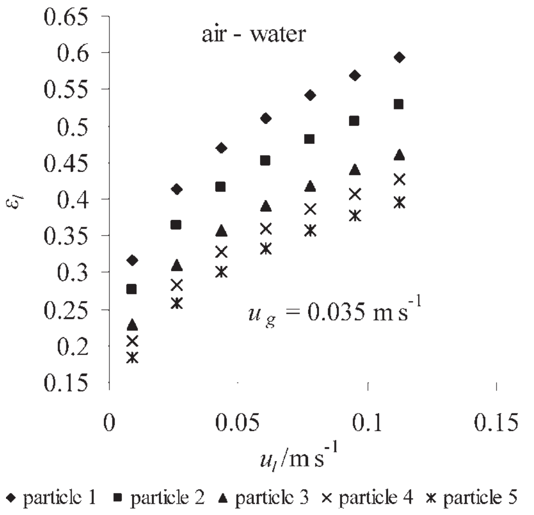

Fig. 3 – *Effect of particle diameter on liquid holdup*

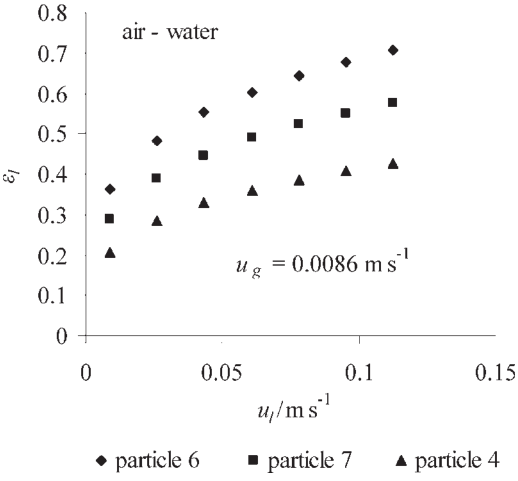

Fig. 4 – *Effect of particle sphericity on liquid holdup*

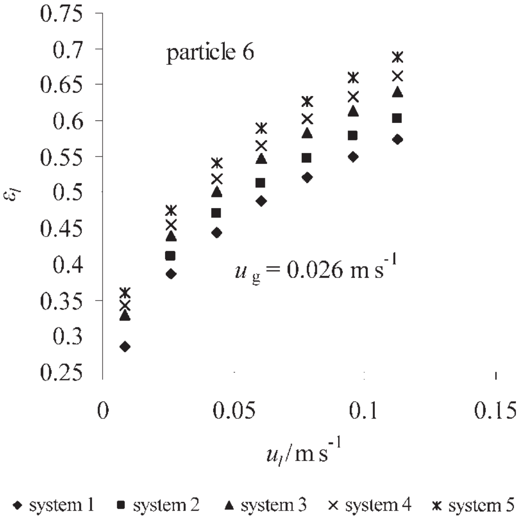

Fig. 5 – *Effect of physical properties of liquids on liquid holdup*

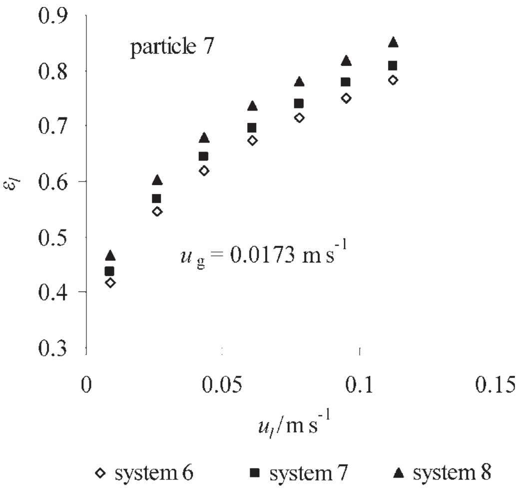

Fig. 6 – *Effect of rheological properties of non-Newtonian liquids on liquid holdup*

Table 1 – *Details of the particles and liquid systems used in this work*

Bed characteristics		d_p/mm	ρ_s/kg m^{-3}	ϕ_s	D/mm
particle 1	spheres	1	2480	1	150
particle 2	spheres	2	2480	1	150
particle 3	spheres	4	2480	1	150
particle 4	spheres	5.5	2480	1	150
particle 5	spheres	7.2	2480	1	150
particle 6	berl saddles	4.8	2050	0.33	150
particle 7	raschig rings	5.1	2480	0.58	150

Properties of fluids		ρ_l/kg m^{-3}	μ_l/kg m^{-1} s^{-1}		σ_l/N m^{-1}
			K/kg m^{-1} s^{n-2}	n	
system 1	air-water	1000	0.00085	1	0.072
system 2	φ = 20 % glycerol	1010	0.002	1	0.069
system 3	φ = 60 % glycerol	1020	0.006	1	0.069
system 4	φ = 90 % glycerol	1040	0.01	1	0.068
system 5	MEA	1050	0.015	1	0.045
system 6	w = 0.1 % CMC	1020	0.00842	0.92	0.072
system 7	w = 0.5 % CMC	1020	0.01838	0.88	0.072
system 8	w = 1 % CMC	1020	0.0548	0.86	0.069

Table 2 – *Details of the literature particles used for the liquid holdup analysis*

Bed characteristics	d_p/mm	ρ_s/kg m^{-3}	ϕ_s	D/mm	Authors
spheres	6	2300	1	660	Kim *et al.*[24]
spheres	2.6	2520	1	660	
spheres	1	2950	1	660	
spheres	8	2500	1	152	Han *et al.*
spheres	6	2500	1	152	
spheres	1.2	2500	1	152	Dargar-Macchi
spheres	5	2500	1	152	
spheres	1.2	2500	1	152	Nacef *et al.*
spheres	3.1	2500	1	152	
spheres	3.5	1245	1	152	
spheres	2.55	1380	1	52	Saberian *et al.*
alumina extrudates	2	1600	0.78	150	
alumina extrudates	1.8	1605	0.69	150	
alumina extrudates	2	2160	0.78	150	

used. The chemicals used in the present study are AR grade and procured from Loba Chemie (P) Ltd., India. Brookfield Rheometer model LVDV- II+ was used to measure the viscous properties of Newtonian and non-Newtonian liquids.[24] The details of properties of solids and liquids employed in the present study are given in Table 1.

Results and discussion

The experimentally measured liquid holdup values obtained in this present work have been analyzed for their dependency on the fundamental and operating variables viz., flow rates of gas and liquid phases, physical and rheological properties of the phases and the characteristics of the solid materials. Fig. 2 shows the variation in the liquid holdup with respect to the superficial gas and liquid velocities for the particle diameter (d_p) of 4 mm. The larger drag forces applied to the solid particles by an increase in liquid velocity cause an increase in liquid holdup. However, for a constant liquid velocity, variation in liquid holdup with an increase of gas velocity was not significant. These trends coincided with the results published in earlier studies.[14,23,24,26,29] From Fig. 3, it is observed that liquid holdup was decreased with an increase of particle diameter, which is in agreement with Chiu and Ziegler and Han *et al*. The influence of particle sphericity on liquid holdup is shown in Fig. 4. From the results, it is observed that an increase of particle sphericity reduces the surface area of particle per unit volume, which leads more bubble breakage and hence liquid holdup decreases. The dependency of the liquid holdup on the liquid properties was analyzed using eight different liquid systems (water, φ = 20 % glycerol, φ = 60 % glycerol, φ = 90 % glycerol, MEA, w = 0.1 % CMC, w = 0.5 % CMC, w = 1 % CMC). At constant fluid velocities, increase in liquid viscosity yields higher drag forces on the solid particles resulting in an increase in liquid holdup, as shown in Fig. 5. Similar observations were made by previous studies also.[31–34] For the non-Newtonian fluids, the influence of fluid consistency index (K) on liquid holdup is shown in Fig. 6. These results reveal that the increase of fluid consistency index causes an increase in liquid holdup. Increasing liquid viscosity/fluid consistency index enhances the liquid shear stress at liquid-solid interface and hence an increase in liquid holdup.

The influence of fundamental and operating variables viz., flow rates of gas and liquid phases, physical and rheological properties of the fluids, dimension and shape of the solid materials etc., on experimentally measured solid holdup have been analyzed. Fig. 7 shows the effect of gas and liquid velocities on solid holdup for a given solid particle diameter (d_p = 5.5 mm). As evident from Fig. 7, solid holdup decreases with the increase of liquid velocity, for any given constant gas velocity. When the liquid velocity increases, the larger drag forces applied to the solid particles will make the solid bed to expand and hence decrease in solid holdup. This results in considerable decrease in the solid holdup. Similarly, for any constant liquid velocity, the increase of gas velocity will not have any significant effect on solid holdup. The same trend was observed in the literature.[35,36] The effect of particle diameter on solid holdup (Fig. 8) showed that solid holdup decreases with increasing particle diameter and increases with increasing particle sphericity, as shown in Fig. 9. The dependency of the solid holdup on the properties of liquids was analyzed using different liquid systems. Figs. 10 and 11 show that the solid holdup decreases with increasing viscosity of Newtonian liquids (Fig. 10) and increasing fluid consistency index (K) of non-Newtonian liquids (Fig. 11). Similar results were observed by earlier studies also.[31,35]

The statistical analysis of the present experimental and literature data (Tables 2 and 3 for liquid holdup and Table 4 for solid holdup) with the established literature correlations (Tables 5 and 6) showed that most of the correlations were restricted to the individual author's own range of data (Tables 7 and 8). A few researchers have failed to consider the effect of fundamental variables like particle characteristics, physical and rheological properties of the liquids on the liquid holdup and solid holdup.[21,22,26,27] Graphical analysis of the present data (Fig. 2 – Fig. 11) shows that the variation of liquid holdup and solid holdup can be attributed to the effect of all the above-said variables. In this study, the approach of dimensionless grouping was adopted for the establishment of liquid holdup and solid holdup correlations. Regression analysis of the available liquid holdup using 2,582 data points yielded the following constants and indices for the equation,

$$\varepsilon_l = 0.94(1+Fr_g)^{-0.42}(Fr_l)^{0.15}(Mo_{l,M})^{0.0027}\cdot \\ \cdot(\rho_s/\rho_l)^{-0.4}(d_p/D)^{-0.0043}(\phi_s)^{-0.37} \quad (1)$$

Regression analysis of data consisting of 1, 671 measurements, using various liquids and different particles, gave the constants and indices for the solid holdup correlation as given below:

$$\varepsilon_s = 0.94(1+Fr_g)^{0.238}(Fr_l)^{-0.15}(Mo_{l,M})^{0.006}\cdot \\ \cdot(\rho_s/\rho_l)^{0.87}(d_p/D)^{0.117}(\phi_s)^{0.665} \quad (2)$$

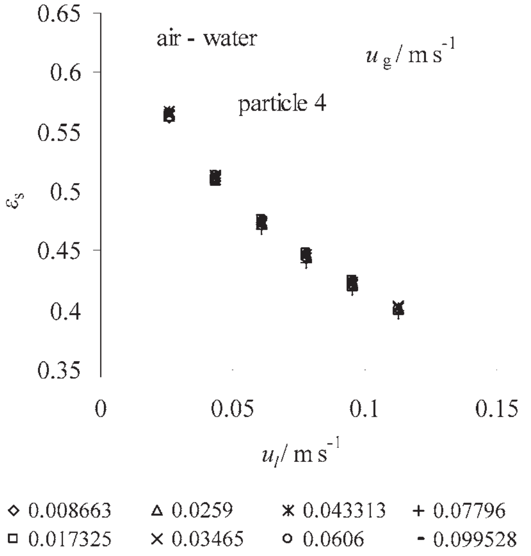

Fig. 7 – *Effect of liquid and gas velocities on solid holdup*

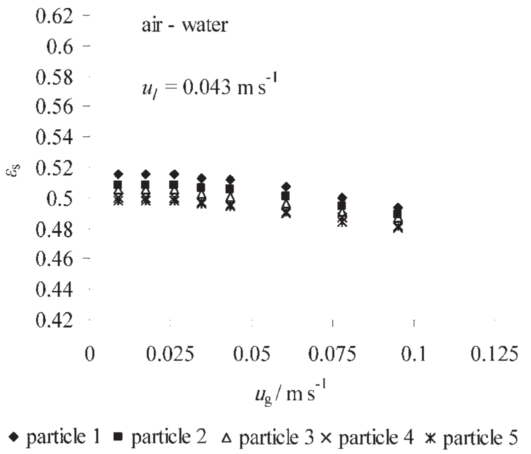

Fig. 8 – *Effect of particle diameter on solid holdup*

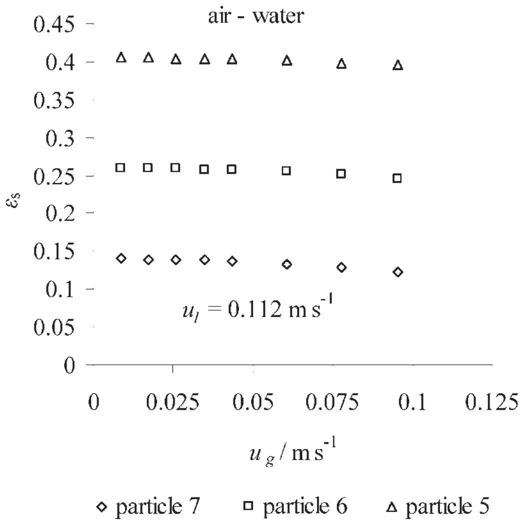

Fig. 9 – *Effect of particle sphericity on solid holdup*

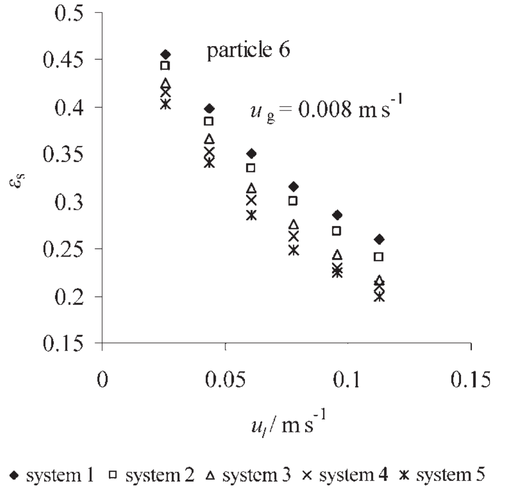

Fig. 10 – *Effect of physical properties of liquids on solid holdup*

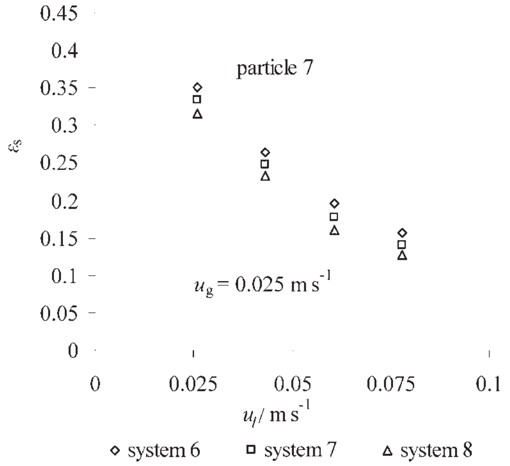

Fig. 11 – *Effect of rheological properties of non-Newtonian liquids on solid holdup*

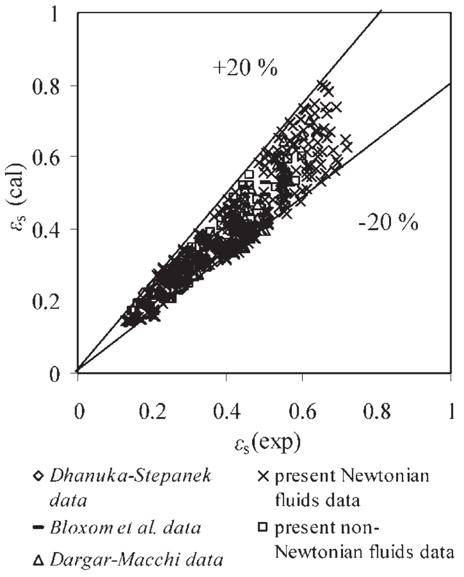

Fig. 12 – *Comparison of experimental and calculated values of solid holdup for Newtonian and non-Newtonian fluids*

Table 3 – *Details of the literature liquid systems used for liquid holdup analysis*

Properties of fluids	ρ_l/kg m^{-3}	μ_l/kg m^{-1} s^{-1}		σ_l/N m^{-1}	Authors
		K/kg m^{-1} s^{n-2}	n		
water	1000	0.001	1	0.0728	Kim *et al.*[24]
w = 25 % sugar solution	1090	0.00237	1	0.0729	
w = 36 % sugar solution	1150	0.00464	1	0.0755	
w = 42 % sugar solution	1170	0.0076	1	0.0759	
w = 0.09 % CMC solution	1004	0.0057	0.976	0.0728	
w = 0.15 % CMC solution	1003	0.013	0.927	0.073	
w = 0.35 % CMC solution	1001	0.07	0.914	0.0738	
φ = 10 % acetone solution	990	0.00111	1	0.060	
φ = 20 % acetone solution	980	0.00126	1	0.0502	
φ = 40 % acetone solution	960	0.00143	1	0.0398	
water	1000	0.001	1	0.0728	Han *et al.*
φ = 75 % glycerol	1002	0.02	1	0.0665	
φ = 83 % glycerol	1001	0.04	1	0.0641	
φ = 86 % glycerol	1001	0.06	1	0.0628	
water	1000	0.001	1	0.0723	Dargar-Macchi
w = 0.5 % ethanol	989	0.001	1	0.0685	
w = 0.5 % pentanol	989	0.001	1	0.0455	
w = 5 % ethanol	989	0.001	1	0.0552	
w = 0.01 % SDS	989	0.001	1	0.05	
water	1000	0.001	1	0.072	Nacef *et al.*
φ = 1 % ethanol	1000	0.001	1	0.067	
cyclohexane	775	0.001	1	0.027	Saberian *et al.*
tetrachloroethane	1620	0.0009	1	0.032	
kerosine	780	0.0011	1	0.0011	
water	998	0.001	1	0.0728	

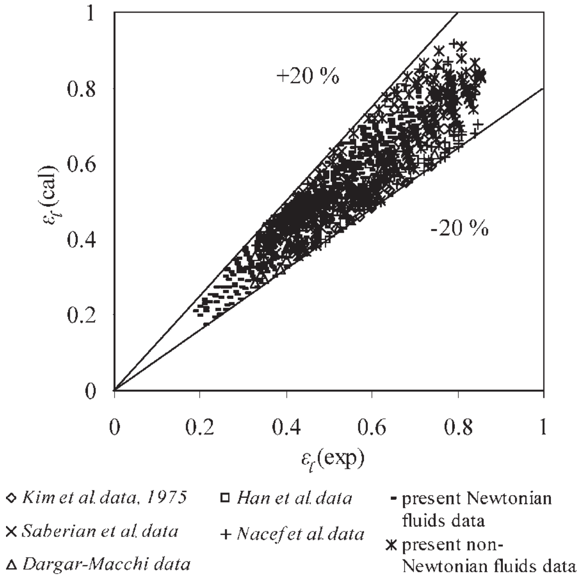

Fig. 13 – *Comparison of experimental and calculated values of liquid holdup for Newtonian and non-Newtonian fluids*

Statistical error analysis of the proposed correlations (eqs. (1) and (2)) showed an AARD of ± 9.41 % for liquid holdup and ± 12.28 % for solid holdup indicating a satisfactory representation of the available data. The applicability of the present correlations was tested with the available liquid holdup literature data[14,24,29,30,36] and solid holdup literature data,[12,35,36] and it is found to be in satisfactory agreement. Figs. 12 and 13 represent the plots of experimental and calculated values of the solid holdup and liquid holdup for the present and literature data of both Newtonian and non-Newtonian liquid systems.

Table 4 – *Details of literature data used for solid holdup analysis*

Bed characteristics	d_p/mm	ρ_s/kg m^{-3}	ϕ_s	D/mm	Authors
spheres	1.98	2960	1	50	Dhanuka-Stepanek
spheres	4.08	2960	1	50	
spheres	5.86	2960	1	50	
spheres	4.62	2260	1	76.2	Bloxom *et al.*
spheres	1.2	2500	1	152	Dargar-Macchi
spheres	5	2500	1	152	

Properties of fluids	ρ_l/kg m^{-3}	μ_l/kg m^{-1} s^{-1}		σ_l/N m^{-1}	Authors
		K/kg m^{-1} s^{n-2}	n		
water	1000	0.001	1	0.0723	Dargar-Macchi
w = 0.5 % ethanol	989	0.001	1	0.0685	
w = 0.5 % pentanol	989	0.001	1	0.0455	
w = 5 % ethanol	989	0.001	1	0.0552	
w = 0.01 % SDS	989	0.001	1	0.05	
water	1000	0.001	1	0.0728	Dhanuka-Stepanek
glycerol	1160	0.0038	1	0.064	Bloxom *et al.*
glycerol	1100	0.0092	1	0.065	

Table 5 – *List of important literature correlations for liquid holdup*

Authors	Correlations	System	Range of variables
Kim *et al.*[21]	$\varepsilon_{l,u_g=0} = 0.409\,(Fr_l\,\rho_s/\rho_l)^{0.193}(Re_l)^{0.074}$	air-water	d_p = 0.0026–0.006 m ρ_s = 2300–2520 kg m^{-3} u_l = 0.014–0.102 m s^{-1} u_g = 0.0–0.26 m s^{-1}
Razumov *et al.*	$\varepsilon_l = 0.422 + \left(\dfrac{0.135\,u_l}{d_p^{0.562}}\right) - 1.82\,u_g$	air-water	d_p = 0.0002–0.00167 m ρ_s = 2810 kg m^{-3} ρ_l = 1000 kg m^{-3} υ_l = 10–6 m^2 s^{-1} D = 0.300 m u_g = 0.0125–0.005 m s^{-1} u_l = 0.01–0.09 m s^{-1}
Kim[23] (cited in Kim *et al.*[24])	$\varepsilon_l = 1.353\,Fr_l^{0.206}N_{\mathrm{Re},l}^{-0.1}$	air-water air-sugar solution air-CMC air-acetone	d_p = 0.001–0.006 m ρ_s = 2300–2950 kg m^{-3} μ_l = 0.001–0.070 kg m^{-1} s^{-1}

Table 5 – *continue*

Authors	Correlations	System	Range of variables
Bloxom *et al.*	correlation 1: $\varepsilon_l = 0.45\, u_l^{0.269}\ u_g^{-0.146} (\rho_s - \rho_l)^{-1.072}$ correlation 2: $\varepsilon_l = 4.28\, u_l^{0.374}\ u_g^{-0.221}\ \rho_l^{1.64}\ D^{-1.25}$	air-water, air– (0–66 %) glycerine	d_p = 0.00462 m ρ_s = 2260 kg m^{-3} u_g = 0.035–0.14 m s^{-1} u_l = 0.01–0.083 m s^{-1} μ_l = 0.0009–0.0115 kg m^{-1} s^{-1}
Kim *et al.*[24]	$\varepsilon_l = 1.504\ (Fr_l)^{0.234}\ (Fr_g)^{-0.086} (Re_{l,M})^{-0.082}\ (We_l)^{0.092}$	air-sugar solution air-CMC air-acetone air-water	d_p = 0.001–0.006 m ρ_s = 2300–2950 kg m^{-3} ρ_l = 960–1230 kg m^{-3} μ_l = 0.001–0.070 kg m^{-1} s^{-1} σ_l = 0.0398–0.0759 m s^{-1} u_g = 0.007–0.161 m s^{-1} u_l = 0.027–0.102 m s^{-1}
Oh-Kim	$\varepsilon_l = 0.26\ (Fr_l)^{0.44} (Fr_g)^{-0.032} (Re_l)^{-0.006}$	air – water	d_p = 0.00163–0.00785 m ρ_s = 2500 kg m^{-3} u_g = 0–0.12 m s^{-1} u_l = 0–0.14 m s^{-1}
Lee-DeLasa	correlation 1: $\varepsilon_l = 0.006\ u_l^{0.246}\ u_g^{-0.059}$ correlation 2: $\varepsilon_l = 1 - 0.535 \exp(-0.378\ u_l + 0.093\ u_g)$	air – water	d_p = 0.00025 m ρ_s = 2500 kg m^{-3} u_g = 0.0128–0.02 m s^{-1} u_l = 0.0039–0.0156 m s^{-1}

Table 6 – *List of important literature correlations for solid holdup*

Authors	Correlations	System	Range of variables
Razumov *et al.*	$\varepsilon_s = 0.578 - 3.198\ u_l - 0.538\ u_g$	air-water	d_p = 0.0002–0.00167 m ρ_s = 2810 kg m^{-3} u_g = 0.0125–0.005 m s^{-1} u_l = 0.01–0.09 m s^{-1} ρ_l = 1000 kg m^{-3}
Bloxom *et al.*	correlation 1: $1 - \varepsilon_s = 1.03\ Fr_l^{0.094} Ga^{-0.026}$ correlation 2: $1 - \varepsilon_s = 1.53\ Re_l^{0.275} Ga^{-0.171}$	air-water, air– (0–66 %) glycerine	d_p = 0.00462 m ρ_s = 2260 kg m^{-3} u_g = 0.035–0.14 m s^{-1} u_l = 0.01–0.083 m s^{-1} μ_l = 0.0009–0.0115 kg m^{-1} s^{-1}
Begovich-Watson	$1 - \varepsilon_s = 0.371\, u_l^{0.271} u_g^{0.041} (\rho_s - \rho_l)^{-0.316} d_p^{-0.268}\ \mu_l^{0.055} D^{-0.033}$	air – water	d_p = 0.0046–0.0062 m ρ_s = 1170–2240 kg m^{-3} u_g = 0–0.173 m s^{-1} u_l = 0–0.12 m s^{-1} D = 0.0762 m and 0.152 m

Table 7 – *Statistical comparison of liquid holdup with the present and literature data*

	Present data		Kim *et al.* data[24]		Han *et al.* data		Dargar-Macchi data		Nacef *et al.* data		Saberian *et al.* data	
	AARD %	Bias	AARD %	Bias	AARD %	Bias	AARD %	Bias	AARD %	Bias	AARD %	Bias
Razumov *et al.* correlation	26.4	1.0	21.89	0.88	18.42	0.94	25.5	0.84	21.7	1.05	18.6	1.04
Kim[23] (cited in *Kim* et al[24])	16.7	1.1	14.4	0.89	6.8	0.9	11.6	0.94	25.3	1.26	21.7	1.1
Kim *et al.* correlation[21]	33.4	1.3	19.6	1.1	25.11	0.99	18.25	0.94	32.21	1.47	37.24	1.61
Oh-Kim correlation	82.1	6.5	75.2	4.1	75.8	4.2	73.2	3.9	82.9	6.57	88.9	9.6
Kim *et al.* correlation[24]	22.5	1.3	10.1	1.0	11.2	1.1	20.3	1.2	36.8	1.6	35.4	1.5
Bloxom *et al.* correlation –1	24.7	1.2	25.4	1.3	15.2	1.2	21.3	1.2	179.3	0.5	93.4	0.5
Bloxom *et al.* correlation –2	58.6	2.5	92.3	13.4	50.2	2.2	54.4	2.3	61.8	2.7	103.7	0.53
Lee-De Lasa correlation –1	98.3	62.3	98.2	56.7	97.9	50.5	98.1	53.9	98.4	68.3	98.4	66.3
Lee-De Lasa correlation –2	66.5	0.6	83.1	0.6	106.4	0.49	87.9	0.6	55.1	0.6	46.1	0.8
present correlation (eq. (1))	9.41	0.96	13.20	1.05	13.97	1.01	14.67	1.06	15.94	1.17	11.03	0.98

Table 8 – *Statistical comparison of solid holdup with present and literature data*

	Present data		Dhanuka-Stepanek data		Bloxom *et al.* data		Dargar-Macchi data	
	AARD %	Bias	AARD %	Bias	AARD %	Bias	AARD %	Bias
Razumov *et al.* correlation	25.55	1.0	97.08	2.06	12.01	1.14	39.18	1.59
Bloxom *et al.* correlation 1	33.61	0.78	32.82	0.79	56.68	2.35	13.97	0.93
Bloxom *et al.* correlation 2	16.39	1.01	68.24	3.46	118.94	3.32	32.71	1.57
Begovich-Watson correlation	102.9	0.52	153.3	0.4	14.42	1.1	78.3	0.57
present correlation (eq. (2))	12.28	1.06	9.99	0.99	13.59	1.15	13.01	1.11

Conclusion

In this present work, a thorough analysis of the effect of fundamental and operating variables on liquid holdup and solid holdup in a three-phase fluidized bed has been studied. Liquid holdup increases with increased liquid velocity, viscosity/fluid consistency index (*K*) of the liquid, and it decreases with increased particle diameter and sphericity. Solid holdup decreases with increased liquid velocity, particle diameter and viscosity of liquids, and increases with increased particle sphericity and fluid consistency index (*K*). The statistical analysis showed that the predictive ability of the present proposed correlations is good. Therefore, the proposed correlations can be used confidently for estimating the liquid holdup and solid holdup in three-phase fluidized bed, with the knowledge of the fundamental and operating variables.

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Nomenclature

AARD – $\frac{1}{N}\sum_{i=1}^{N}\frac{|\,\text{experimental} - \text{calculated}\,|}{\text{experimental}}$, –

Bias – $\exp\frac{1}{N}\sum_{i=1}^{N}\ln\frac{\text{experimental}}{\text{calculated}}$, –

D – column diameter, m, mm

d_p – particle diameter, m, mm

Fr_g – Froude number of gas, $u_g^2\, g^{-1}\, d_p^{-1}$, –

Fr_l – Froude number of liquid, $u_l^2\, g^{-1}\, d_p^{-1}$, –

g – acceleration due to gravity, m s^{-2}

Ga – Galileo number, $d_p^3\, \rho_p (\rho_s - \rho_p) g\, \mu_l^{-2}$, –

K – flow consistency index, kg m^{-1} s$^{\mathrm{n}-2}$

$Mo_{l,M}$ – modified Morton number of liquid, $We_l^3\, Fr_l^{-1}\, \mathrm{Re}_{l,M}^{-4}$, –

N – number of data points, –

n – fluid behavior index, –

Re_l – Reynolds's number of liquid, $d_p\, u_l\, \rho_l\, \mu_l^{-1}$, –

$Re_{l,M}$ – modified Reynolds's number of liquid, $d_p^n\, u_l^{2-n}\, \rho_l\, K^{-1}$, –

u_g – superficial gas velocity, m s^{-1}

u_l – superficial liquid velocity, m s^{-1}

w – mass fraction, %

We_l – Weber number, $d_p\, u_l^2\, \rho_l\, \sigma_l^{-1}$

Greek letters

ρ_l – liquid density, kg m^{-3}

σ_l – liquid surface tension, N m^{-1}

μ_l – liquid viscosity, kg m^{-1} s^{-1}

υ_l – kinematic viscosity, m^2 s^{-1}

ρ_s – particle density, kg m^{-3}

ε_s – solid holdup, –

ε_l – liquid holdup, –

ϕ_s – sphericity of particle, –

ρ_g – gas density, kg m^{-3}

μ_g – gas viscosity, kg m^{-1}s^{-1}

φ – volume fraction, %

Abbreviations

AARD – absolute average relative deviation

CMC – carboxy methyl cellulose

MEA – mono ethanol amine

SDS – sodium dodecyl sulfate

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