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Research Article

Effect of Surfactants on Gas Holdup in Shear-Thinning Fluids

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In this study, the gas holdup of bubble swarms in shear-thinning fluids was experimentally studied at superficial gas velocities ranging from 0.001 to 0.02 $m{\cdot}s^{-1}$. Carboxylmethyl cellulose (CMC) solutions of 0.2 wt%, 0.6 wt%, and 1.0 wt% with sodium dodecyl sulfate (SDS) as the surfactant were used as the power-law (liquid phase), and nitrogen was used as the gas phase. Effects of SDS concentration, rheological behavior, and physical properties of the liquid phase and superficial gas velocity on gas holdup were investigated. Results indicated that gas holdup increases with increasing superficial gas velocity and decreasing CMC concentration. Moreover, the addition of SDS in CMC solutions increased gas holdup, and the degree increased with the surfactant concentration. An empirical correlation was proposed for evaluating gas holdup as a function of liquid surface tension, density, effective viscosity, rheological property, superficial gas velocity, and geometric characteristics of bubble columns using the experimental data obtained for the different superficial gas velocities and CMC solution concentrations with different surfactant solutions. These proposed correlations reasonably fitted the experimental data obtained for gas holdup in this system.

1. Introduction

The motion of bubble swarms in the liquid phase occurs in several natural and industrial processes, for example, wastewater treatment, fermentation, chemical industry, and metallurgical processes [1]. In those processes, gas holdup is a crucial parameter because it exerts a major impact on mass and heat transfer between the gas and liquid phases [2]. Hence, our group was motivated to intensively conduct experiments in this particular field. Urseanu et al. [3] have reported the effect of high liquid viscosity, column diameter, and operating pressure on the total gas holdup in a bubble column and found that, with increasing liquid viscosity, column diameter, and operating pressure, the total gas holdup remarkably decreases. Thorat et al. [4] have investigated the sparger design and dispersion height on fractional gas holdup in a bubble column, and the effects of sparger design, dispersion height, and gas-liquid system have also been analyzed on the basis of the drift flux model. Götz et al. [5] have experimentally examined the effect of the gas, liquid, and solid properties, as well as sparger design, reactor diameter, and gas velocity, on gas holdup in slurry bubble columns and proposed a novel correlation for calculating the gas holdup in homogeneous and pseudo-homogeneous regimes.

Nevertheless, these studies did not examine the effect of surfactants on the gas holdup in bubble swarm systems. However, it is crucial to state that, in practical industrial processes, it is difficult to maintain a pure liquid phase, and impurities are inevitably present in the majority of industrial processes, especially in some gas-liquid processes such as mineral flotation; hence, it is essential to add the surfactant for enhancing mass transfer [6]. Thus, significant attention must be focused on examining the effect of surfactants on the gas holdup in gas-liquid two-phase systems. Duerr-Auster et al. [7] have discussed the effect of surfactants on bubble coalescence and found that small amounts of surface-active additives hinder bubble coalescence and increase gas holdup. Anastasiou et al. [8] have investigated the effect of types and concentration of surfactants on gas holdup in the pseudo-homogeneous regime in bubble columns equipped with a porous sparger and proposed a general correlation, which includes dimensionless numbers (i.e., Froude, Archimedes, and Bond) as well as the geometric characteristics of the column and the sparger to predict the gas holdup in various systems (i.e., pure substances, ionic surfactants, and nonionic surfactants).

The aforementioned studies mainly focus on Newtonian fluids. However, several fluids in practical processing industries exhibit shear-thinning behavior. Thus far, numerous

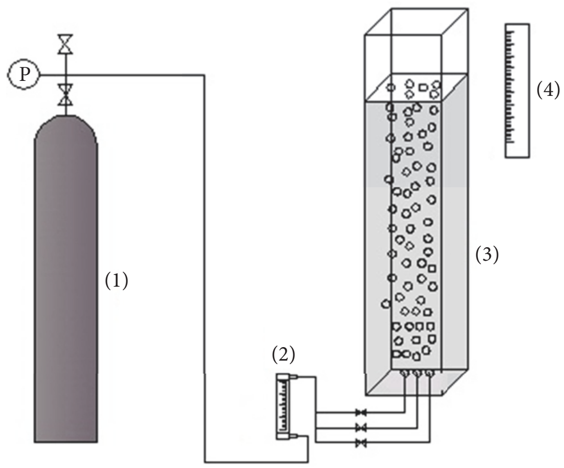

Figure 1: Schematic of the experimental apparatus ((1) nitrogen cylinder; (2) rotameter; (3) bubble column; (4) ruler).

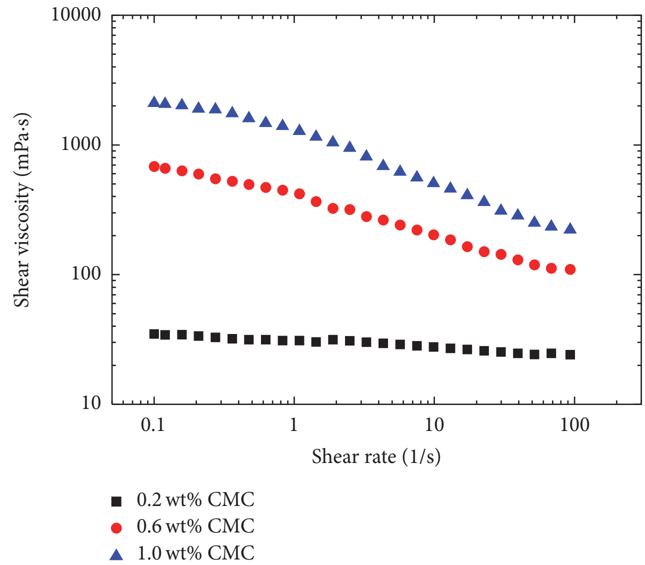

Figure 2: Variation of the viscosity of the different fluids used in this study.

studies reporting the effect of surfactants on bubble motion behavior in shear-thinning fluids mainly focus on the shape and velocity of single bubbles [9–11]. As compared to that of Newtonian fluids, significantly less is known about the effect of surfactants on the gas holdup in shear-thinning fluids because of their complicated rheological characteristics.

In this study, the effect of surfactants on gas holdup in shear-thinning fluids was investigated. The effects of surfactant concentration, superficial gas velocity, and liquid-phase rheological property on gas holdup in a bubble column were experimentally investigated. A general empirical correlation was proposed for evaluating gas holdup as a function of liquid surface tension, density, effective viscosity, rheological property, superficial gas velocity, and geometric characteristic of bubble columns using the experimental data obtained at different superficial gas velocities and CMC solution concentrations with different surfactant solutions. The predicted results of the present correlation showed reasonable agreement with the experimental values.

2. Experimental

2.1. Experimental Setup. Figure 1 shows the experimental setup, which consisted of vertical cylindrical Plexiglas tanks (with an internal diameter of 0.08 m and a height of 1 m) surrounded by a square duct (0.1 m × 0.1 m × 1 m). The square duct was filled with liquid up to 70 cm above the sparger. Nitrogen was passed into the bubble column through a gas distributor, namely, three 304 SS orifices with an internal diameter of 2 mm located at the center of the bubble column bottom side by side (15 mm apart). The superficial gas velocity was controlled by a calibrated rotameter with an experimental range of 0.001 m·s^{-1} to 0.02 m·s^{-1}, and the accuracy of rotameter is the ±5% of the full range. The gas holdup values were obtained by visual observation [15]. In this case, the total gas holdup ϕ is defined as follows:

$$\phi = \frac{H - H_L}{H}. \quad (1)$$

Here, H_L is the clear liquid height and H is the liquid dispersion height attributed to the presence of bubble swarms. The results represent the average of five repeated experiments under the same conditions, and experimental data were reproducible to within ±5%. All experiments were conducted at room temperature under constant pressure.

2.2. Material. In this study, different concentrations (0.2 wt%, 0.6 wt%, and 1.0 wt%) of aqueous CMC (guaranteed reagent, Sigma) solutions were used as experimental liquids, double-distilled water was used, and nitrogen (99.999% purity) was used as the gas phase. For every test fluid, three concentrations (0 mg·L^{-1}, 5 mg·L^{-1}, and 10 mg·L^{-1}) of sodium dodecyl sulfate (SDS) were added to examine the effect of the surfactant concentration on the bubble hydrodynamic characteristics. And the range and accuracy of electronic balance (AR124CN) were 120 g/0.1 mg.

The surface tension of the liquid was measured using a tensiometer (DCAT21, Dataphysics, Austria) with an accuracy of ±0.1 kg·m^{-3}. Densities of the liquids were measured using a density meter (Anton Paar, DMA5000, Austria) with an accuracy of ±1.0%. The rheological property was determined using a programmable rheometer (Brookfield, DV-III, USA) with a shear rate ranging from 0.1 to 100 s^{-1}. Figure 2 shows the measured results. As can be observed in Figure 2, CMC solutions exhibited shear-thinning behavior. The variation of the apparent viscosity with the shear rate can be described by the power-law model [16]

$$\mu = K\dot{\gamma}^{n-1}. \quad (2)$$

Here, K is the consistency index and n is the flow index. The shear rate $\dot{\gamma}$ is obtained as follows [17]:

$$\dot{\gamma} = 5000U_s. \quad (3)$$

Here, U_s is the superficial gas velocity.

Table 1: Rheological and physical properties of different fluids.

Solutions	K/mPa·s^n	n	Surface tension/mN·m^{-1}	ρ/kg·m^{-3}
0.20 wt% CMC	33	0.92	61	998
0.20 wt% CMC + 10 mg·L^{-1} SDS	33	0.92	53	998
0.20 wt% CMC + 20 mg·L^{-1} SDS	33	0.92	44	998
0.20 wt% CMC + 30 mg·L^{-1} SDS	33	0.92	37	998
0.60 wt% CMC	422	0.68	65	1001
0.60 wt% CMC + 10 mg·L^{-1} SDS	422	0.68	54	1001
0.60 wt% CMC + 20 mg·L^{-1} SDS	422	0.68	45	1001
0.60 wt% CMC + 30 mg·L^{-1} SDS	422	0.68	36	1001
1.0 wt% CMC	1115	0.56	62	1005
1.0 wt% CMC + 10 mg·L^{-1} SDS	1115	0.56	53	1005
1.0 wt% CMC + 20 mg·L^{-1} SDS	1115	0.56	45	1005
1.0 wt% CMC + 30 mg·L^{-1} SDS	1115	0.56	37	1005

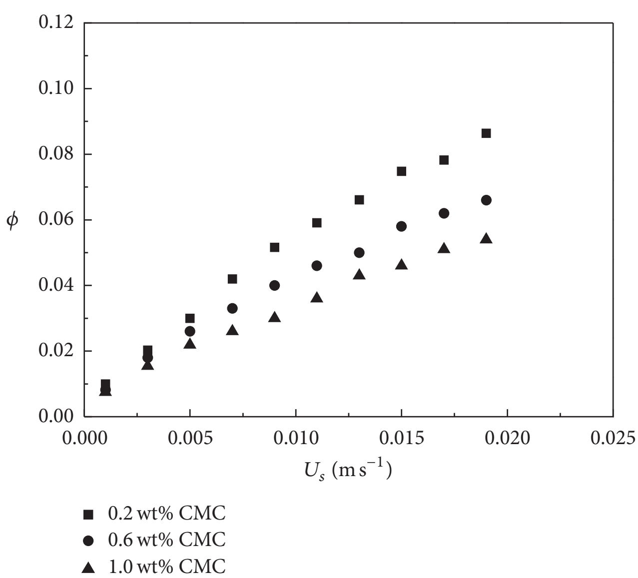

Figure 3: Effects of superficial gas velocity and CMC concentration on gas holdup.

Table 1 summarizes the physical and rheological properties of experimental fluids. As can be observed in Table 1, the SDS concentration did not exhibit any effect on the rheological property of CMC solutions.

3. Results and Discussion

Figure 3 shows the variation of gas holdup with gas superficial gas velocity at different CMC solution concentrations. As can be observed in Figure 3, the gas holdup increased with superficial gas velocity and decreased with the CMC solution concentration under the same superficial gas velocity. The effect of the CMC solution concentration was attributed to the viscosity variation of different CMC solutions. As can be seen from Figure 2, the apparent viscosity increased with increasing CMC concentration because of two opposing effects: on the one hand, the bubble rise velocity decreased with increasing liquid-phase viscosity, leading to a long bubble residence time and a high gas holdup; on the other hand, Fan et al. [18] have reported that the generated bubble volume increases with increasing liquid-phase viscosity: big bubbles exhibited high rise velocity, leading to a less bubble residence time and a low gas holdup. Moreover, Sousa et al. [19] have reported that the viscosity of liquids of bubble wake exhibits thinning caused by the shear-thinning effect, which decreases the drag force of the next bubble and accelerates it such that it approaches the leading bubble until final coalescence and becomes large bubbles. Thus, the larger the shear-thinning effect of the liquid phase, the smaller the gas holdup. From the positive and negative effects of CMC concentration mentioned above, the negative effects were dominant; consequently, the gas holdup decreases with increasing CMC concentration. These results are in agreement with those reported previously [3, 20, 21].

Figure 4 shows the effect of SDS concentration on the gas holdup in 0.60 wt% CMC solutions. As can be observed from Figure 4, the gas holdup increased with increasing SDS concentration in CMC solutions. Fan et al. [18] have reported that the diameter of the bubbles decreases with increasing surfactant concentration at the same gas superficial gas velocity in the liquid phase. Small bubbles have a low rise velocity and long residence time in the bubble column, thereby possibly increasing gas holdup. On the other hand, when bubbles rise in a solution containing a surfactant, the surfactant molecules will accumulate on the bubble surface and decrease the bubble velocity, and as the surfactant concentration increases, the terminal velocity decreases [10]. Moreover, surfactants can prevent bubbles from undergoing coalescence [7, 22]. Three effects simultaneously play a role in gas holdup, leading to the increase of gas holdup with increasing SDS concentration. This conclusion is consistent with previously reported results [8, 23].

For a thorough analysis of the gas holdup based on the comparison of the predictions from various proposed correlations and experimental values, typical correlations for gas holdup from other studies were utilized. Schumpe and Deckwer [12] have investigated the hydrodynamics of the

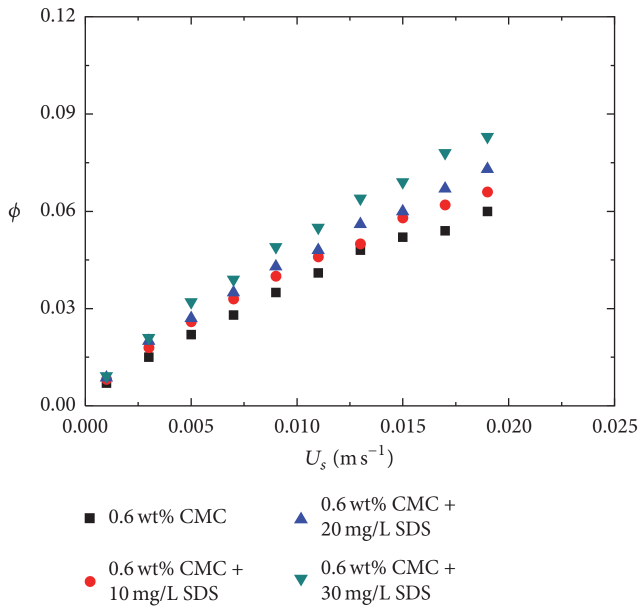

Figure 4: Effects of superficial gas velocity and SDS concentration on gas holdup in 0.60 wt% CMC.

bubble column with the highly viscous pseudoplastic solutions of CMC and proposed a simple correlation to calculate the gas holdup for CMC solutions in bubble columns as follows:

$$\phi = 0.725 U_s^{0.627}. \quad (4)$$

Kawase and Moo-Young [13] have experimentally investigated the gas holdup in shear-thinning power-law fluids and proposed a semiempirical correlation based on experimental data

$$\phi = 1.07 n^{2/3} \mathrm{Fr}^{1/3}. \quad (5)$$

Here, n is the flow index of power-law fluids. The Froude number Fr is defined as

$$\mathrm{Fr} = \frac{U_s^2}{D_c g}. \quad (6)$$

Here, D_c is the diameter of the bubble column.

Moreover, Fransolet et al. [14] have proposed a gas holdup correlation based on experimental data in power-law fluids by introducing superficial gas velocity and the apparent liquid-phase viscosity:

$$\phi = 0.26 U_s^{0.54} \mu^{-0.147}. \quad (7)$$

Figure 5 shows the comparison of three gas holdup correlations with experimental data. Figures 5(a), 5(b), and 5(c) show the comparisons of experimental data with the calculated value predicted by (4), (5), and (7), respectively. From Figure 5(a), the prediction of (4) exhibits a large deviation caused by only considering the effect of the superficial gas velocity and neglecting the effect of the liquid-phase viscosity and rheological property, surface tension, and the diameter of the bubble column. Thus, the calculated data of (5) is more accurate than that expressed in (4) because of the introduction of the effect of the gas superficial velocity, diameter of bubble column, and flow index (it characterizes the rheological property of the liquid phase). However, the deviation between the calculated and measured values increased with increasing gas superficial velocity as the effects of the surface tension and viscosity of liquid phase were not considered. Figure 5(c) shows the predicted gas holdup by (7) as a function of the measured gas holdup; similarly, because of considering only the effect of superficial gas velocity and viscosity, the error of experimental data and predicted data increased with increasing gas holdup.

From the comparisons of our experimental values for gas holdup with those obtained from classical correlations in previously reported studies, comparison is skewed. Hence, a new correlation for the gas holdup of bubbles in power-law liquids in bubble columns is necessary and highly useful for design purposes in the industrial application of power-law liquids. The new correlation should completely consider all factors. For the bubble swarms rise in shear-thinning fluids, the influence factors include superficial gas holdup, physical properties of the liquid phase (density, viscosity, and surface tension), rheological properties of the liquid phase, and diameter of the bubble column. Thus, the Archimedes number (Ar) and Eotvos number (Eo) should be considered apart from the Froude number and flow index. Ar and Eo are, respectively, defined as follows:

$$\mathrm{Ar} = \frac{{D_C}^3 {\rho_l}^2 g}{{\mu_L}^2}, \qquad \mathrm{Eo} = \frac{{D_C}^2 \rho_l g}{\sigma}. \quad (8)$$

Here, ρ_l is the density of the liquid phase and g is the acceleration by gravity.

In the mathematical form, a general function f of the effect factors is required, which satisfies

$$\phi = f(\mathrm{Fr}, \mathrm{Ar}, \mathrm{Eo}, n). \quad (9)$$

Using a least-squares method, based on the experimental data, a new correlation for the gas holdup of bubble swarms in non-Newtonian liquids is proposed as follows:

$$\phi = 0.85 \mathrm{Fr}^{0.33} \mathrm{Ar}^{0.09} \mathrm{Eo}^{0.16} n^{0.7}. \quad (10)$$

The validity of (10) can be represented by the relative deviation, which could be calculated as follows:

$$\delta = \left(\frac{\left| \phi_{\mathrm{cal}} - \phi_{\mathrm{exp}} \right|}{\phi_{\mathrm{exp}}} \right) \times 100\%, \quad (11)$$

where ϕ_{cal} and ϕ_{exp} are the calculated and measured gas holdup, respectively.

The average relative deviation between the gas holdup predicted by (10) and the measured gas holdup was approximately 6.2%, which is acceptable for the intricate rheological

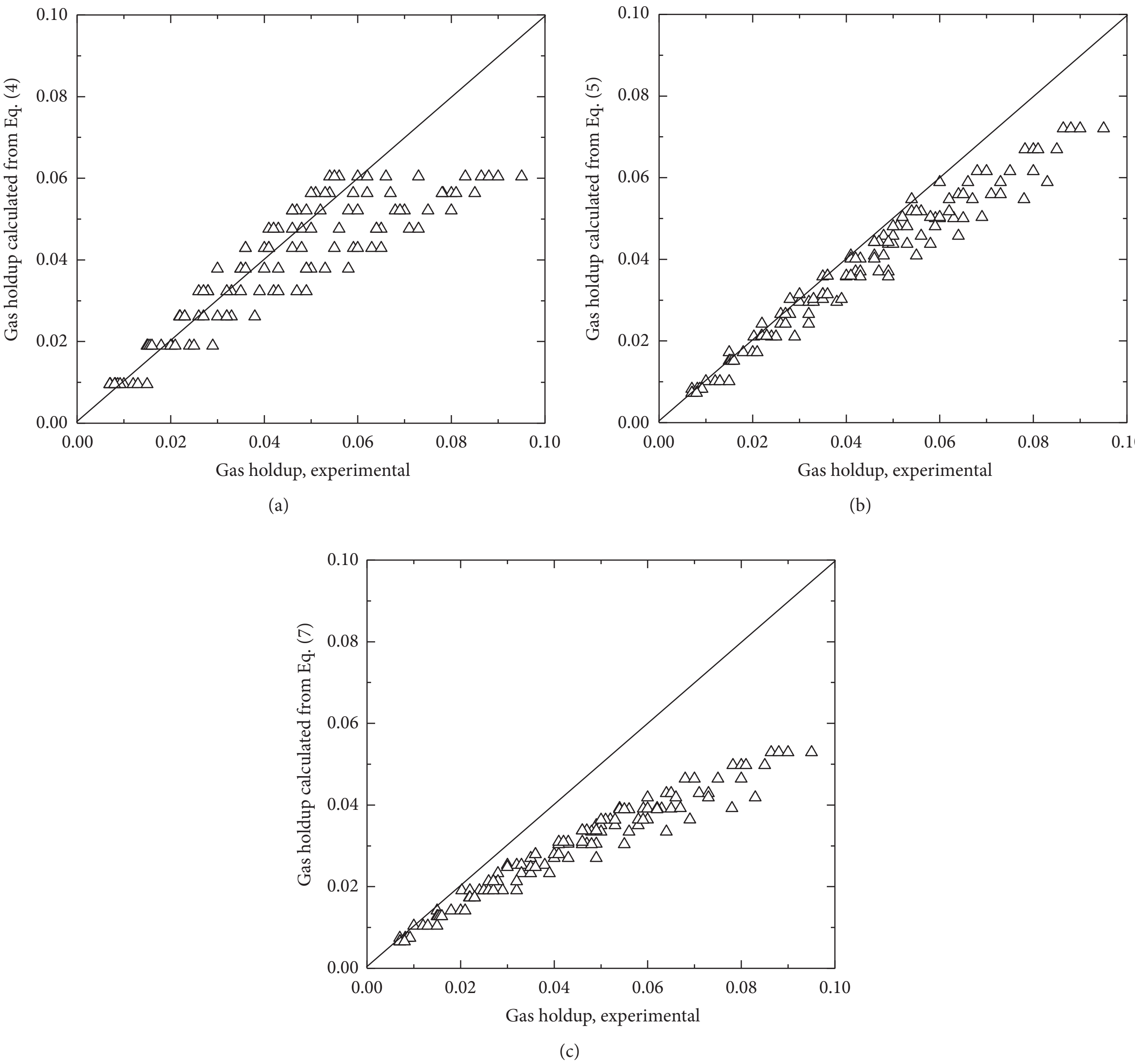

Figure 5: Comparison of three gas holdup correlations with experimental data. (a) Schumpe [12] correlation; (b) Kawase [13] correlation; (c) Fransolet [14] correlation.

properties of fluid and the destabilization of the external factors involved in the experiments. Good agreement can also be observed in Figure 6. This demonstrates that (10) is suitable for shear-thinning fluids with different surfactant concentrations. However, further studies need to be conducted on other types of non-Newtonian fluids.

4. Conclusions

In this study, the gas holdup in bubble columns using shear-thinning fluids as the liquid phase was investigated. The effect of different operating variables (surfactant concentration, superficial gas velocity, concentration, and rheological properties of the liquid phase) was studied. The gas holdup increased with increasing superficial gas velocity and decreasing liquid-phase concentration. The effect of liquid-phase concentration is attributed to two results: increasing viscosity and the shear-thinning effect. Moreover, the addition of SDS in CMC solutions could increase gas holdup, and the degree increases with the surfactant concentration.

On the basis of experimental data, an empirical correlation was proposed to predict the gas holdup for shear-thinning fluids with different surfactant concentrations by introducing physical and rheological properties of the liquid phase, surface tension, superficial gas velocity, and diameter of the bubble column. The correlation is in good agreement with experimental measurements.

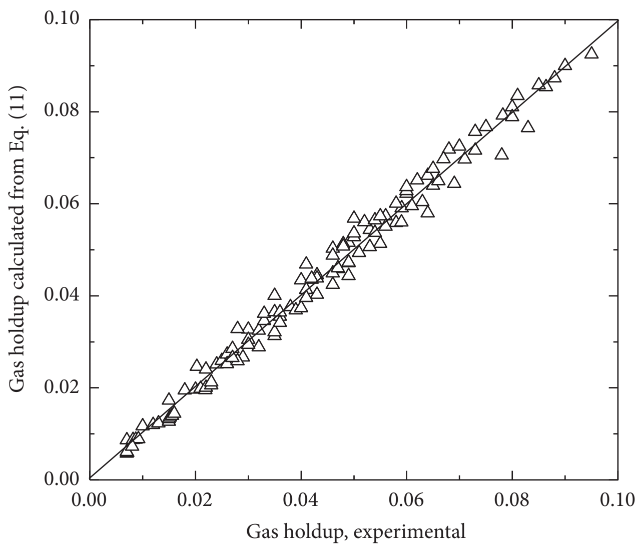

FIGURE 6: Measured gas holdup versus calculated gas holdup from (10) in shear-thinning liquids.

Nomenclature

Ar: Archimedes number
D_c: Diameter of the bubble column, m
Eo: Eotvos number
Fr: Froude number
g: Gravitational acceleration, m·s^{-2}
K: Consistency index, mPa·s^n
n: Flow index
U_s: Superficial gas velocity, m·s^{-1}
$\dot{\gamma}$: Shear rate, s^{-1}
δ: Relative deviation
μ: Viscosity of the liquid phase, Pa·s
ρ: Density of liquid phase, kg·m^{-3}
σ: Surface tension, mN·m^{-1}
ϕ: Gas holdup.

Subscripts

C: Bubble column
cal: Calculated
exp: Experimental
l: Liquid phase.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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