Effect of gas properties on the characteristics of a bubble column equipped with fine porous sparger.

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Abstract

The purpose of this work is to check the validity of previously proposed correlations concerning the parameters that affect the operation of bubble columns by conducting experiments with various gases. The effect of gas properties on the performance of a bubble column reactor with fine pore sparger is investigated by employing various gases (i.e., air, CO_2, He) that cover a wide range of physical property values, while the liquid phase is de-ionized water. A fast video technique is employed for visual observations and, combined with image processing, is used for collecting data regarding gas holdup and bubble size distribution. Previously proposed correlations for predicting the transition point from the homogeneous to the heterogeneous regime, the gas holdup and the *Sauter* mean bubble diameter are slightly modified to include the effect of gas phase properties. It is found that the new correlations can predict the aforementioned quantities with reasonable accuracy.

Keywords: Bubble column, Porous sparger, Gas properties, Transition point, Gas holdup, Sauter mean diameter

1 Introduction

Bubble columns offer many advantages when used as gas-liquid contactors, due to their simple construction, low operating cost, high-energy efficiency and good mass transfer capabilities. Consequently, they are widely used in many industrial gas-liquid operations (e.g. gas/liquid reactions, agitation by gas injection, fermentations, waste water treatment, etc.) in chemical and bio-chemical process industries. In all these processes gas holdup and bubble size are important design parameters, since they define the gas-liquid interfacial area available for mass transfer. In turn, bubble size distribution and gas holdup in gas-liquid dispersions greatly depend on column geometry, operating conditions, physicochemical properties of the two phases and the type of gas sparger [1]. It has been proved that a fine porous sparger holds advantages over other types of gas distributors, since it produces more numerous and smaller bubbles and, thus, offers a greater gas-liquid contact area [2].

Depending on the gas flow rate, two main flow regimes can be readily observed in bubble columns [3], i.e. the ***homogeneous*** bubbly flow regime encountered at low gas velocities and characterized by a narrow bubble size distribution and radially uniform gas holdup; and the ***heterogeneous*** regime observed at higher gas velocities and characterized by the appearance of large bubbles, formed by coalescence of the small bubbles and bearing a higher rise velocity, hence leading to relatively lower gas holdup values.

The mechanism of bubble formation is of crucial importance to bubble column hydrodynamics. Figure 1 and Table 1 give the forces that act on an under formation bubble (Eqns 1-6). A bubble is detached, when the sum of the upward forces (i.e. buoyancy, gas momentum, pressure) outweigh the sum of the downward ones (i.e. drag, inertial, surface tension).

In previous works conducted in this laboratory [2,3] the effect of the sparger characteristics (i.e. diameter, pore size) and the liquid physical properties on the performance of a bubble column equipped with fine pore sparger, have been experimentally studied. Design correlations applicable in bubble columns equipped with fine porous sparger have been proposed, taking into account the effect of column diameter and pore size [3], as well as the liquid properties (i.e. effect of surfactant additives [4,5]). The aforementioned correlations are based on data where the gas phase is air, although several bubble column applications use other gases, like CO_2. In this case, the difference in gas density affects the ***gas momentum force*** (Eqn. 2).

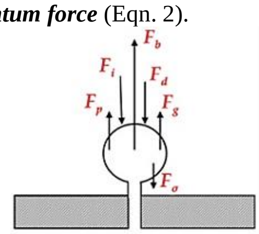

Figure 1: Forces acting on an under-formation bubble

Table 1: Forces acting to bubble formation

Upward Forces	***Downward Forces***
Buoyancy $F_b = (\rho_L - \rho_G) g V_b$ (1)	Drag $F_d = \frac{1}{2}\rho_L W^2 \frac{\pi d_b^2}{4} C_D$ (4)
Gas momentum $F_G = \frac{\pi}{4} d_p^2 \rho_G W_G^2$ (2)	Inertial $F_i = \left(a_i + \frac{\rho_G}{\rho_L}\right)\rho_L V_b \gamma_b$ (5)
Pressure $F_p = \frac{\pi}{4} d_p^2 (P_G - P_L)$ (3)	Surface tension $F_\sigma = \pi d_p \sigma$ (6)

Thus, the purpose of this work is to check the validity of previously proposed correlations, by conducting experiments with various gases.

2 Experimental set-up and procedure

The experimental set-up (Fig. 2) consists of a cylindrical bubble column, equipped with a fine pore sparger for the injection and the uniform distribution of the gas phase, an appropriate flowmeter for gas flow control, a high speed digital video camera (*Redlake MotioScope PCI® 1000S*) for bubble size and gas holdup measurements and a computer for acquiring and processing the data. A *Plexiglas®* rectangular box, filled with the same fluid with the one used at the corresponding experiment was placed out of the bubble column to eliminate image distortion caused by light refraction. A recording rate of 125 frames per second (*fps*) was used for the measurement of gas holdup, while a speed of 500 fps was selected for bubble size measurements.

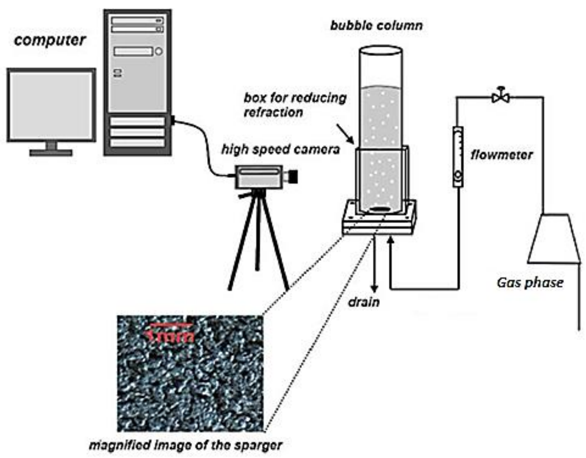

Figure 2: Experimental set-up

For the purpose of the present work, two vertical cylindrical *Plexiglas®* columns of 5 and 9 cm i.d., and 100 cm in height were used. The bubble column dimensions are given in Table 2. The liquid phase was de-ionized water (Table 3), while three gases (i.e. air, CO_2 and He), covering a sufficiently wide range of density values were used (Table 4). All the experiments were performed with no liquid throughput at atmospheric pressure and ambient temperature conditions.

Table 2: Bubble column dimensions

d_C (cm)	H_C (cm)	d_S (cm)	Nominal pore size d_p (μm)	Minimun pore diameter (μm)	Maximumn pore diameter (μm)
5	100	5	100	5	500
9	100	9	40	3	70

The average gas holdup (ε_G) is estimated by calculating the bed expansion as follows:

$$\varepsilon_G = \frac{\sum_{i=1}^{n} \varepsilon_{G,i}}{n} = \frac{\sum_{i=1}^{n} \frac{H_i - H_{0,i}}{H_i}}{n} = \frac{\sum_{i=1}^{n} \frac{\Delta H_i}{H_i}}{n} \quad (7)$$

where H_o and H are the liquid level before and after gas injection respectively, ΔH is the liquid level difference and n is the number of recurrent measurements for each gas flow rate (in this case $n=5$). The maximum uncertainty of the measurements is estimated to be less than 15%.

Table 3: Liquid phase properties at 25 C

Liquid	ρ_L (Kg/m^3)	μ_L (10^{-3} $Pa{\cdot}s$)	σ_L (mN/m)
Water	1000	1.0	72

Table 4: Gas phase properties at 25 C

Gas	ρ_G (Kg/m^3)	μ_G (10^{-5} $Pa{\cdot}s$)
Air	1.39	1.8
CO_2	2.11	1.5
He	0.19	2.0

From bubble images taken by the video camera, the *Sauter* mean diameter (d_{32}), defined as:

$$d_{32} = \frac{\sum_{i}^{N} n_i d_{bi}^3}{\sum_{i}^{N} n_i d_{bi}^2} \quad (8)$$

was calculated, where d_{bi} and n_i are the diameter and the number of the bubbles of size class i respectively and N is the number of classes used for the distribution. The minimum number of classes required for the construction of the size distributions, k was estimated using the Sturges' rule given by:

$$k = 1 + \log_2 S \quad (9)$$

where S is the sample size ($\sim 100\ bubbles$). The number of classes used for the construction of the distributions in the present work is 10 equal interval.

3 Results and discussion

3.1 Regime transition

The transition point from homogeneous to heterogeneous regime is estimated by applying the *drift flux analysis*, which takes into account the relative motion of the two phases [6]. The basic quantity is the drift flux, j, given by:

$$j = U_{GS}\left(1 - \varepsilon_G\right) \quad (10)$$

where U_{GS} is the superficial gas velocity and ε_G is the gas holdup. The gas superficial velocity is defined as:

$$U_{GS} = \frac{Q_G}{A} \quad (11)$$

where Q_G is the gas flow rate and A the column cross section area. When the drift flux is plotted versus the gas holdup, the change in the slope of the curve indicates the transition from homogeneous to heterogeneous regime [7].

Figure 3 presents the effect of column diameter on transition point. It is clear that the transition velocity depends on the column diameter, i.e. for the smaller diameter used, transition occurs at lower gas flow rates. This observation is in agreement with Sarrafi et al. [8], who also noticed that as the column diameter increases, the transitional superficial gas velocity increases sharply.

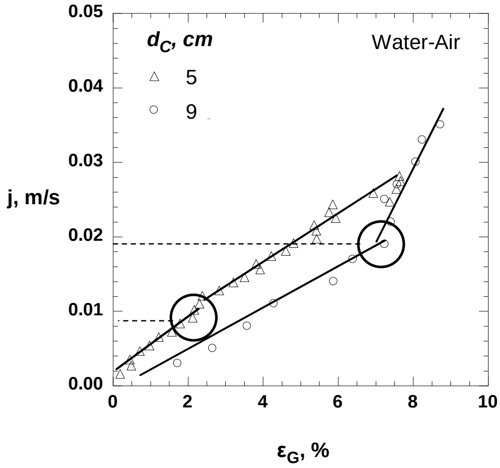

Figure 3: Effect of column diameter on regime transition

The effect of type of gas on regime transition is shown in Fig. 4. It is obvious that as gas density decreases (i.e. He), the homogeneous regime is extended to higher U_{GS} values. This behavior is attributed to the lower value of the gas momentum force acting to bubbles (Eqn 2), due to difference in gas density.

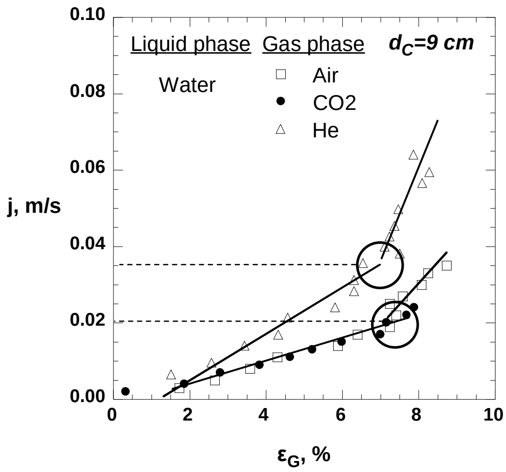

Figure 4: Effect of type of gas on regime transition for water

Prediction of transition point

A general correlation for predicting the transition point based on dimensionless numbers, has been previously proposed [4,9], taking into account the physical properties of the liquid phase, the column diameter, as well as the diameter and the mean pore size of the porous sparger.

To incorporate the effect of type of gas on the transition point, it was found that the ratio of gas to air density (ρ_G/ρ_{air}) and the gas *Reynolds* number, defined as follows:

$$\mathrm{Re}_G = \frac{U_{GS} d_C \rho_G}{\mu_G} \tag{12}$$

should be included. The proposed correlation is suitable for predicting the transition point from homogeneous to heterogeneous regime, taking into account the gas properties:

$$Fr_{trans} = 0.01\left[Eo^{0.58}\,\mathrm{Re}_G^{0.25}\left(\frac{d_S}{d_C}\right)^{2.5}\left(\frac{\rho_G}{\rho_{air}}\right)^{-0.6}\right]^{0.9} \tag{13}$$

where Fr_{trans}, the *Froude* number at the transition point and E_o, the *Eotvos* number, given by:

$$Fr_{trans} = \frac{U_{GS,trans}^2}{d_p g} \tag{14}$$

$$Eo = \frac{d_C^2 \rho_L g}{\sigma_L} \tag{15}$$

In Fig.5 the predicted Fr_{trans} is compared with the experimental data, proving that the correlation accuracy is better than 20 %.

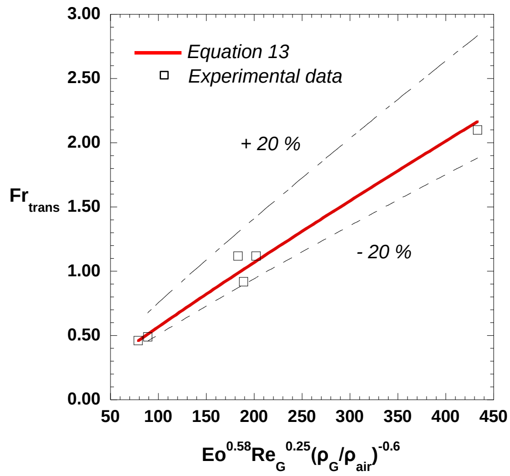

Figure 5: Transition point prediction for all data

3.2 Gas holdup

In this section the measured gas holdup values are given. The flow regimes can be distinguished by plotting the average gas holdup (ε_G) versus the gas flow rate (Q_G). Figure 6 shows the dependence of gas holdup on corresponding gas superficial velocity for the two bubble columns used. As it is expected, gas holdup increases with the gas velocity. The first part of the curve corresponds to the homogeneous regime. A transition regime follows where a slight decrease in gas holdup is observed. Finally, at the heterogeneous regime the gas holdup continues to increase, but with a lower slope than the homogeneous regime [3].

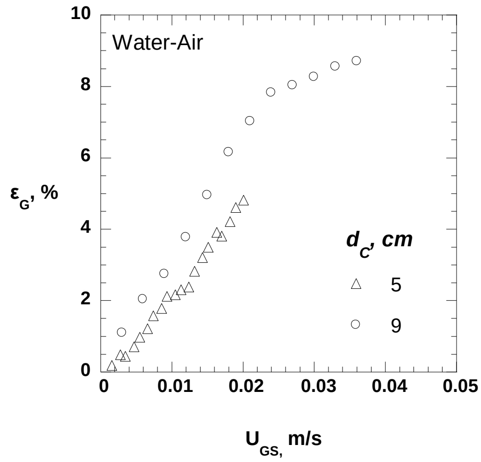

Figure 6: Effect of column diameter on gas holdup for the water-air system

It is obvious from Fig. 6 that by increasing the column diameter the gas holdup increases, especially for higher gas flow rates. However, the literature results concerning the effect of column diameter on gas holdup are contradictory. Some researchers report that the column diameter has no effect on gas holdup [10-13]. The above works concern bubble columns with diameter larger than 10 cm, where the gas distributor is a perforated plate. Ruzicka et al. [14] also state that the gas holdup is independent of column dimensions provided that the column diameter is larger than 10 cm, the column height is larger than 15 cm and the column height to diameter ratio is in excess of 5. On the other hand, some works report that the column diameter affects the gas holdup. Botton et al. [15] report that gas holdup increases when the column diameter decreases, whereas Kumar et al. [16] who conducted experiments in bubble columns with diameter larger than 10 cm, state that there is a continuous increase in the gas holdup with increasing column diameter.

To the author's best knowledge, there are no experimental results concerning bubble columns with diameter less than 10 cm, equipped with fine porous sparger. Dhotre et al. [17] have numerically studied the effect of sparger type and height to diameter ratio on radial gas holdup profiles. The above investigators report that for multipoint spargers, an increase to the H/d_C ratio results into marginal decrease in gas holdup. It is obvious that, by decreasing the column diameter and, thus increasing the H/d_C ratio, the wall effects become more intense.

Figure 7 presents the effect of the type of gas on gas holdup when the bubble column is filled with water. With increasing gas density gas holdup increases, e.g. helium that has lower density exhibits lower values of gas holdup than air and CO_2. This is expected, if we take into account the forces that influence an under formation bubble (Table 1). The only force that is affected by gas density is the gas momentum force (Eqn 2). The gas momentum force is greater in gases of higher density (e.g. CO_2) and therefore, the formation of smaller bubbles is more pronounced. This observation is in agreement with other researchers [18,19] who also reported that gases of higher density produce higher gas holdup values, attributing this behavior on phenomena occurring during bubbles formation on the sparger.

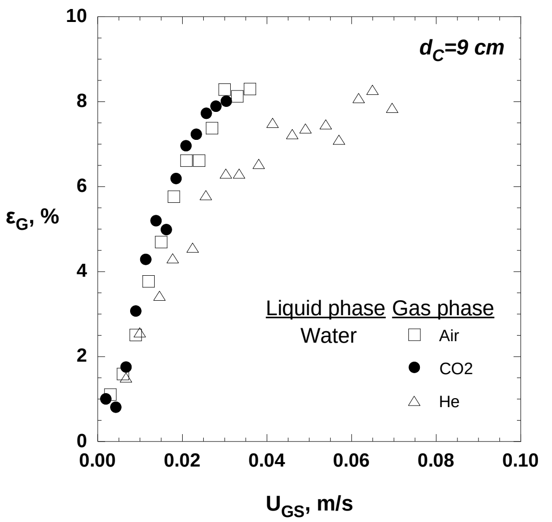

Figure 7: Effect of type of gas on gas holdup

Prediction of gas holdup

In previous studies conducted in this lab [3,4,9] a correlation for predicting the average gas holdup, ε_G, was proposed based on dimensionless numbers. In the case that the gas phase is other than air, it is necessary to introduce a term that incorporates the properties of the gas phase. For that purpose, the ratio of gas to liquid viscosity (μ_G/μ_L) and the gas *Reynolds* number (Eqn 12) , were introduced. The proposed correlation is appropriate for predicting the gas holdup, including the gas phase properties:

$$\varepsilon_G = 0.2\left[FrAr^{0.1}Eo^{1.6}\,\mathrm{Re}_G^{0.18}\left(\frac{d_p}{d_s}\right)^{0.05}\left(\frac{d_S}{d_C}\right)^{0.9}\left(\frac{\mu_G}{\mu_L}\right)^{-0.6}\right]^{0.4} \quad (16)$$

where ε_G (%) is the gas holdup and *Froude* (Fr), *Archimedes* (Ar) and *Eotvos* (Eo) are defined as:

$$Fr = \frac{U_{GS}^2}{d_C g} \quad (17)$$

$$Ar = \frac{d_C^3 \rho_L^2 g}{\mu_L^2} \quad (18)$$

$$Eo = \frac{d_C^2 \rho_L g}{\sigma_L} \quad (19)$$

This correlation is plotted in Fig. 8 and is in fairly good agreement (i.e.±20%) with the experimental data.

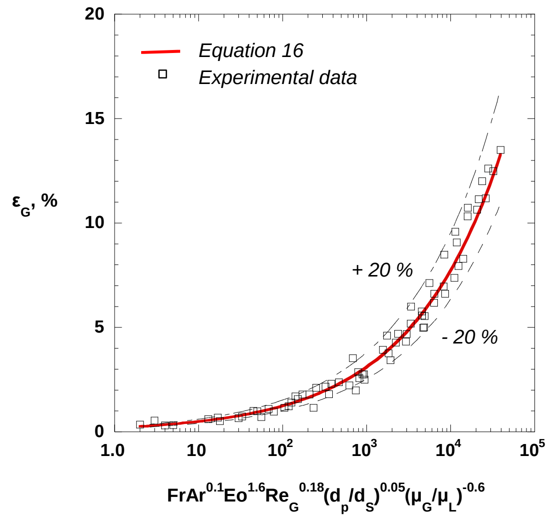

Figure 8: Prediction of gas holdup

3.3 Bubble size distribution

Figure 9 illustrates typical bubble size distributions when the sparger of 40 μm was used (d_C=*9 cm*), for all gases studied in the present work and for a constant U_{GS} value. It is obvious that the distributions are log-normal, while it seems that as the gas density decreases (i.e. He), the size distribution curve shifts to higher values.

Figure 10 presents bubble size distributions for the water-air system, for a constant U_{GS} value when the two spargers of different mean pore diameter were used. It is obvious that as the sparger mean pore diameter increases, the size distribution curve is bimodal and shifts to higher values. This is in accordance with Kazakis et al. [2], who ascribed this difference to the pore size range of the two spargers. The two peaks shown in the distribution of 100 μm sparger, can be attributed to the broad size range of this sparger, whereas for the sparger of 40 μm the pore size range is much narrower and as a result there are not large deviations in bubble size.

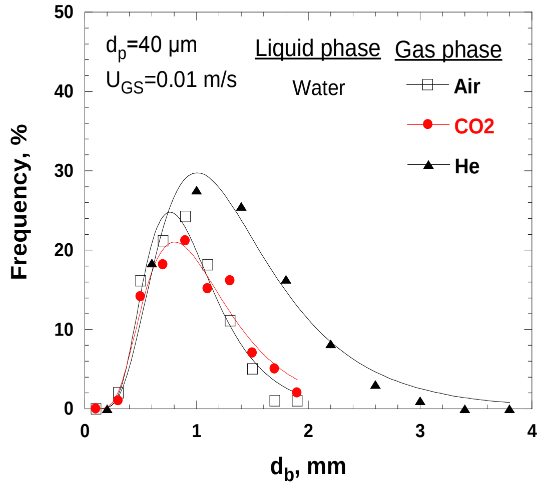

Figure 9: Effect of type of gas on bubble size distribution

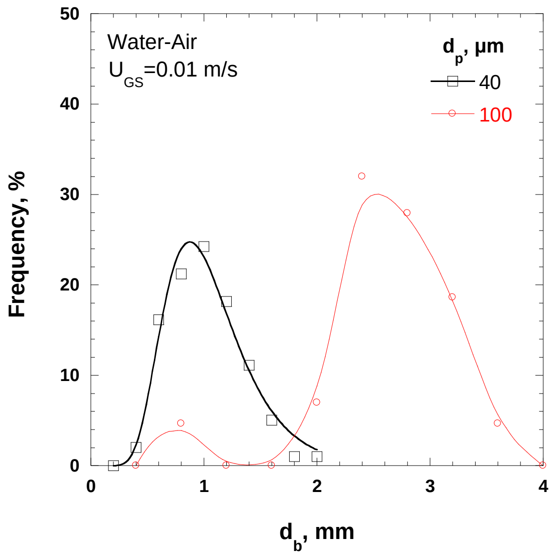

Figure 10: Effect of sparger mean pore diameter on bubble size distribution

Table 5 contains the calculated *Sauter* mean diameter d_{32} values for all gases and for both column diameters used. It is clear that d_{32} is unaffected by the gas flow rate and it increases as the column diameter decreases. Regarding the effect of gas density on *Sauter* mean diameter, it is obvious that as the gas density decreases (i.e. He), d_{32} obtains higher values for water regardless of the bubble column

Table 5: *Sauter* mean diameter, d_{32}

		U_{GS}=0.005 m/s		U_{GS}=0.01 m/s	
Liquid	Gas	d_C=9 cm	d_C=5 cm	d_C=9 cm	d_C=5 cm
Water	Air	1.19	2.69	1.28	2.66
	CO_2	1.29	2.73	1.35	2.79
	He	1.89	4.87	1.80	4.50

Prediction of mean bubble size

In previous works in our lab [2,4] a correlation for predicting the *Sauter* mean diameter (d_{32}) based on dimensionless numbers, was proposed. In the present work, a term was introduced to account for the different gas type (i.e. gas *Reynolds number*, Eqn 12). The new equation is as follows:

$$\frac{d_{32}}{d_S} = 0.68\left[We^{-2}\mathrm{Fr}\,\mathrm{Re}^{0.6}\,\mathrm{Re}_G^{-0.1}\left(\frac{d_p}{d_S}\right)^{2.2}\right]^{0.2} \quad (20)$$

where We is the *Weber*, Re the *Reynolds* and Fr the *Froude* number respectively, defined as:

$$We = \frac{\rho_L U_{GS}^2 d_C}{\sigma_L} \quad (21)$$

$$\mathrm{Re} = \frac{U_{GS} d_C \rho_L}{\mu_L} \quad (22)$$

$$Fr = \frac{U_{GS}^2}{d_C g} \quad (23)$$

This correlation is plotted in Fig. 11 and is in good agreement with the experimental data (± 20 %).

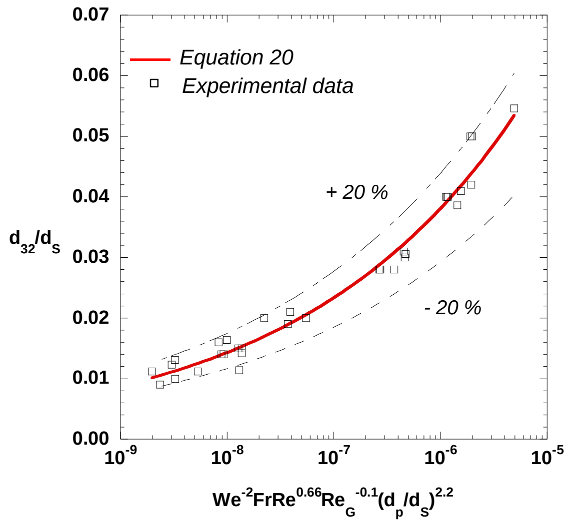

Figure 11: Comparison of the *Sauter* mean diameter prediction with experimental data

4 Concluding remarks

In this work we have experimentally investigated in what extent the column diameter and the type of gas phase influence the performance of a bubble column reactor. The experiments revealed that, as gas density increases, the transition point shifts to lower gas flow rates and the gas holdup increases. This can be attributed to the increased gas momentum force when gas of higher density is employed. Thus, the previously proposed correlations for predicting the transition point from the homogeneous to the heterogeneous regime, the gas holdup and the *Sauter* mean diameter are slightly modified to include the gas phase properties. The new correlations were tested with date from the current as well as from previous works and are found that can predict the aforementioned quantities with reasonable accuracy.

More work is currently in progress in an effort to investigate the wall effects on the operation of small bubble columns (e.g.

d_C<10 cm) when various fluids are employed as liquid and gas phases.

Nomenclature

A	column cross section, (m^2)
d_b	bubble diameter, (m)
d_{32}	*Sauter* mean diameter, (m)
d_C	column diameter, (m)
d_p	pore diameter, (m)
d_S	sparger diameter, (m)
F_b	buoyancy force, (N)
F_d	drag force, (N)
F_g	gas momentum force, (N)
F_i	inertial force, (N)
F_p	pressure force, (N)
F_σ	surface tension force
g	acceleration of gravity, (m/s^2)
H_C	column height, (m)
j	drift flux, (m/s)
Q_G	gas flow rate, (m^3/s)
U_{GS}	superficial gas velocity, (m/s)
W_g	bubble formation velocity, (m/s)
Greek letters	
ε_G	average gas holdup, (dimensionless)
μ_G	gas phase viscosity (Pa s)
μ_L	liquid phase viscosity, (Pa s)
ρ_G	gas density, (Kg/m^3)
ρ_L	liquid density, (Kg/m^3)
σ_G	gas interfacial tension, (mN/m)
σ_L	liquid surface tension, (mN/m)
Dimensionless	
Ar	Archimedes number
Eo	Eotvos number
Fr	Froude number
Fr_{tans}	Froude number at transition point
k	minimum number of classes
N	number of classes used for the distributions
n_i	number of bubbles of size class i
Re	Reynolds number
Re_G	gas Reynolds number
S	sample size
We	Weber number

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