MALTEPE UNIVERSITY INTERNATIONAL STUDENT CONGRESS, MUISC 2018

On the design of bubble columns equipped with a fine pore sparger: Effect of gas properties.

Theodosios I. Pavlidis, Aikaterini A. Mouza

Department of Chemical Engineering, Aristotle University of Thessaloniki, Greece
mouza@auth.gr

Abstract: Bubble columns are gas-liquid contactors that are used in a variety of applications, since they offer many advantages due to their simple construction, low operating cost, high-energy efficiency and good mass transfer capabilities. 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 depend on column geometry, operating conditions, physicochemical properties of the two phases and the type of gas sparger. The work conducted in our Lab has led to the development of design equations that can predict with reasonable accuracy the transition point from homogenous to heterogeneous regime, the gas holdup and the mean Sauter diameter at the homogenous regime. In all the experiments the gas phase was atmospheric air. In the present work the effect of gas phase properties is investigated by conducting experiments using various gases (i.e., *air*, CO_2, *He*) that cover a wide range of physical property values. In view of the new experimental data, the correlations were slightly modified to include the effect of gas properties. The new correlations can predict the aforementioned quantities with ±15% accuracy.

Keywords: *bubble column; porous sparger; holdup; bubble size; transition point*

1. Introduction

Bubble columns are gas-liquid contactors that are used in many industrial gas-liquid operations (e.g. gas/liquid reactions, agitation by gas injection, fermentations, waste water treatment, etc.) in chemical and biochemical industries. In all these processes, gas holdup and bubble size distribution are important design parameters, since they define the gas-liquid interfacial area available for mass transfer. In turn, these parameters depend on the operating conditions, the physico-chemical properties of the two phases, the gas sparger type and the column geometry [1,2]. Two main flow regimes are encountered in bubble columns, namely the ***homogeneous*** bubbly flow regime, which is encountered for low gas velocities and is characterized by discrete and uniformly dispersed bubbles and the ***heterogeneous*** regime, which corresponds to higher gas velocities. In the homogeneous regime the bubbles are smaller and thus the interfacial contact area per unit mass of air is larger and thus it is most desirable for practical applications, where a low shear rate environment is desirable (e.g. bioreactors, blood oxygenators). The mechanism of bubble formation, presented in Figure 1 and Table 1, is of crucial importance to bubble column hydrodynamics. A bubble is detached, when the sum of the upward forces outweighs the sum of the downward ones.

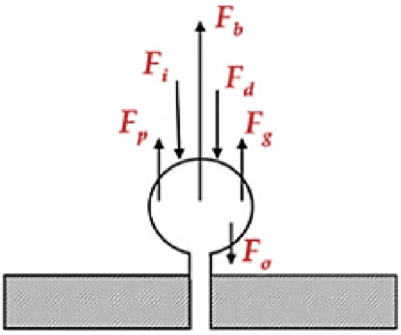


Figure 1. Forces acting on an under-formation bubble (Table 1).

Table 1. Forces acting during bubble formation.

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

In previous works [2,3-5] the effect of the sparger characteristics (i.e. diameter, pore size), the liquid physical properties and the gas flow rate on the performance of a bubble column equipped with a fine pore sparger has been experimentally studied, using Newtonian and non-Newtonian liquids as well as liquids containing surfactants. Based on the data design correlations, which can predict with reasonable uncertainty (better than ±15%) the transition point between the homogeneous and the heterogeneous regime as well as the gas hold-up and the bubble size distribution at the homogeneous regime, were formulated. All these correlations are based on data where the gas phase is air. The purpose of this work is to check the validity of previously proposed correlations, by conducting experiments with several gases and, if necessary, to modify them to incorporate the effect of gas type.

2. Experimental set-up and procedure

The experimental set-up (Figure 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 as the one used at the corresponding experiment was placed around the bubble column to eliminate image distortion caused by light refraction.

The gas phase is introduced to the column through a fine pore sparger, namely a 316 L SS porous disk (Mott Corp.®) with a nominal pore size of 40 μm, that covers the whole bottom plate. The effect of the sparger to column diameter ratio on the bubble column performance has been investigated and discussed in a previous paper [4]. To ensure that the gas phase is evenly distributed over the whole sparger area the gas phase was injected through a 1 cm nozzle to a vessel of 35 cm height placed beneath the bubble column, following the design proposed in a previous paper [4]. 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 measuring the bubble size.

The geometrical characteristics of the bubble columns studied are given in Table 2. The liquid phase was either de-ionized water or an aqueous glycerin solution, while three gases, namely air, CO_2 and He, covering a sufficiently wide range of density values were individually employed. The mentioned fluids and their properties are all given in Table 3. All the experiments were performed with no liquid throughput, at atmospheric pressure and ambient temperature conditions (i.e. around 20 °C).

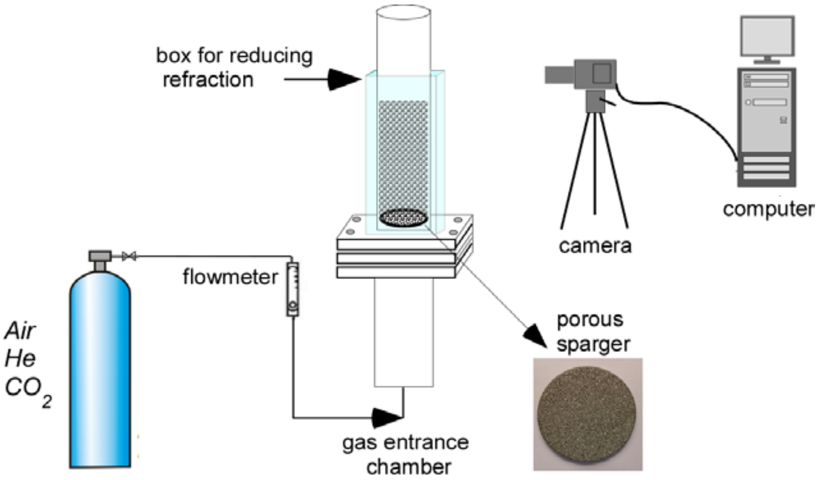


Figure 2. Experimental set-up.

Table 2. Bubble column characteristics.

d_C (cm)	d_S (cm)	d_p (μm)	d_p min (μm)	d_p max (μm)
9	9	40	3	70

Table 3. Fluid properties.

Liquid	ρ_L (Kg/m^3)	μ_L (mPa·s)	σ_L (mN/m)	Gas	ρ_G (Kg/m^3)	μ_G (10^{-5} Pa·s)
water	1000	1.0	72	Air	1.39	1.8
glycerin 40%v/v	1117	5.8	64	CO_2	2.11	1.5
				He	0.19	2.0

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 is 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 $n=50$). The estimated maximum uncertainty of the measurements is less than 15%.

From bubble images taken by the video camera the diameter of a sample of 100 bubbles was measured and the *Sauter* mean diameter (d_{32}), was calculated:

$$d_{32} = \frac{\sum_i^N n_i d_{bi}^3}{\sum_i^N n_i d_{bi}^2} \tag{8}$$

The minimum number of classes required for the construction of the size distributions, k was estimated by the Sturges' rule: $k=1+\log_2 S$. The number of classes used for the construction of the distributions in the present work is 10 equal intervals. Aiming to avoid possible random errors that may be involved in the measuring procedure, we were repeating the same experiment 5 times and we were calculating d_{32} for each experiment.

3. Results and discussion

3.1. Bubble size distribution

Figure 3 illustrates typical bubble size distributions with the 40 μm sparger (d_C=9 cm), for all gases studied and for a constant U_{GS} value. As expected [2], the distributions are log-normal while regardless of the liquid phase only the low density He gas exhibits an observable effect on the bubble distribution curve, due to the lower momentum force exerted by the low density He gas (Table 1). However, the value of mean Sauter diameter is not considerably affected by the type of gas but is mainly affected by the type of liquid phase employed (Table 5).

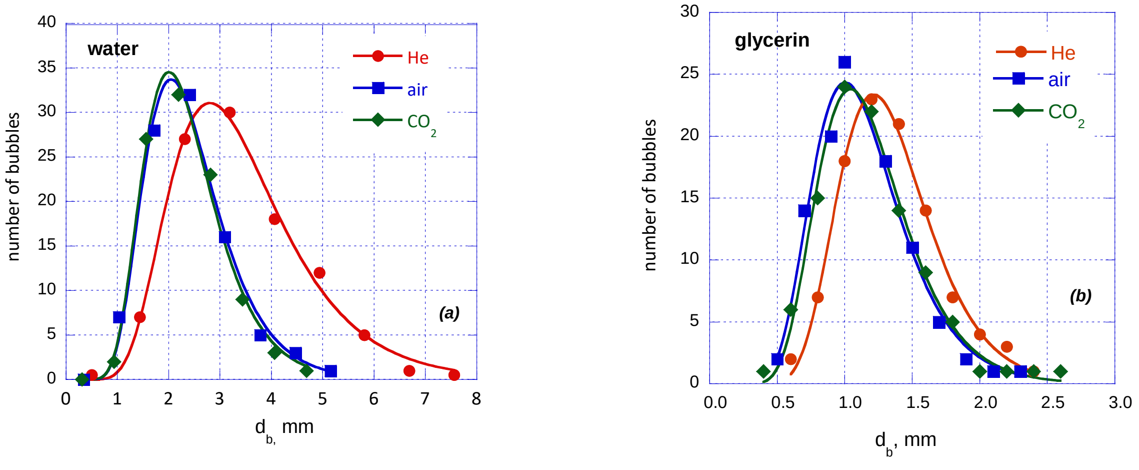


Figure 3. Effect of type of gas on bubble size distribution (U_{GS}=0.01 m/s.)

Table 5. Measured mean Sauter diameter (U_{GS}=0.01 m/s, d_p=40 μm).

Liquid	***Gas***	***d_{32}***	***Liquid***	***Gas***	***d_{32}***
water	Air	1.42	aqueous glycerin solution 40%v/v	Air	1.16
	He	1.50		He	1.24
	CO_2	1.40		CO_2	1.19

In previous works in our lab [2,4] a correlation for predicting the *Sauter* mean diameter (*d_{32}*) based on dimensionless numbers was proposed. The same correlation can be used for predicting the mean Sauter diameter when different gases are employed provided that the constants of the correlation are suitably adjusted (Eq. 9).

$$\frac{d_{32}}{d_s} = 0.9\left[We^{0.95}\, Re^{0.40}\, Fr^{0.47}\left(\frac{d_p}{d_s}\right)^{0.55}\right]^{0.51} \tag{9}$$

where dimensionless numbers are defined as: $We = \frac{\rho_L U_{GS}^2 d_C}{\sigma_L}$, $Re = \frac{U_{GS} d_C \rho_L}{\mu_L}$, $Fr = \frac{U_{GS}^2}{d_C g}$

The proposed correlation (Eq. 9) can be used for predicting d_{32} values with reasonable accuracy (i.e. ±15%) for all the gases employed.

3.2. Regime transition

The transition point from homogeneous to heterogeneous regime is estimated by applying the *drift flux analysis*, which considers the relative motion of the two phases. The basic quantity is the drift flux, *j*, is given by: $j = U_{GS}\left(1-\varepsilon_G\right)$, where ε_G is the gas holdup *and* U_{GS} is the superficial gas velocity defined as $U_{GS} = \frac{Q_G}{A}$. 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 [6].

The effect of the type of gas on regime transition is illustrated in Figure 4. It is obvious that, only when the lower density gas, He, is employed, the homogeneous regime is extended to higher *j* or equally U_{GS} values.

In previous papers [4,7] a correlation was proposed for predicting the transition point that is based on dimensionless numbers and incorporates the physical properties of the liquid phase as well as the geometrical characteristics of the column and the porous sparger. This correlation has the general form: $Fr_{trans} = a_1\left[Eo^{a_2}\left(\frac{d_s}{d_c}\right)^{a_3}\right]^{a_4}$

where Fr_{trans} and Eo based on d_{32} are difined as: $Fr_{trans} = \frac{U_{GS,trans}^2}{d_p g}$, $Eo = \frac{d_{32}^2 \rho_L g}{\sigma_L}$

In view of the new results to incorporate the effect of type of gas, the ratio of gas density to that of air density is added. The new correlation is as follows:

$$Fr_{trans} = 1.2\left[Eo^{0.001}\left(\frac{d_S}{d_C}\right)^{0.02}\left(\frac{\rho_G}{\rho_{air}}\right)^{0.5}\right]^{0.005} \quad (10)$$

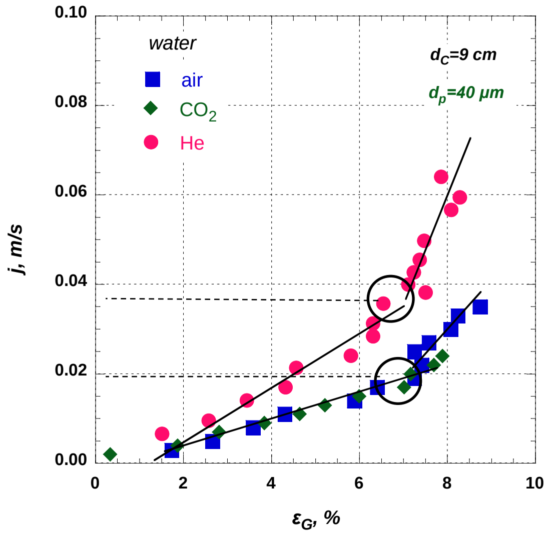
The predicted $U_{GS,\,trans}$ values are in very good agreement, i.e. better than 15%, with the corresponding experimental data. The proposed correlation is suitable for predicting the transition point from homogeneous to heterogeneous regime.

3.3. *Gas holdup*

In this section the effect of the various parameter on the gas hold-up values is investigated. As it is expected, gas holdup increases with the gas velocity. The first part of the curve corresponds to the homogeneous regime, which is followed by a transition regime where the gas holdup slightly decreases. Finally, at the heterogeneous regime the gas holdup continues to increase, but with a lower slope than the homogeneous regime [3].

Figure 5 shows the dependence of gas holdup on corresponding gas superficial velocity for the two bubble columns used. It is obvious from 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. The above works concern bubble columns with diameter larger than 10 cm, where the gas distributor is a perforated plate.

Ruzicka et al. [8] 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 more than 5. On the other hand, some works report that the column diameter affects the gas holdup. The gas holdup increases when the column diameter decreases, whereas Kumar et al. [9] who conducted experiments in bubble columns with diameters larger than 10 cm, state that there is a continuous increase in the gas holdup with increasing column diameter. To the best of our knowledge, there are no experimental results concerning bubble columns with diameter less than 10 cm, equipped with fine porous sparger. Dhotre et al. [10], who have numerically studied the effect of sparger type and height to diameter ratio on radial gas holdup profiles, report that for multipoint spargers, an increase of the column height to column diameter ratio results into marginal decrease of gas holdup. Obviously, when the column diameter decreases the wall effects become more intense.



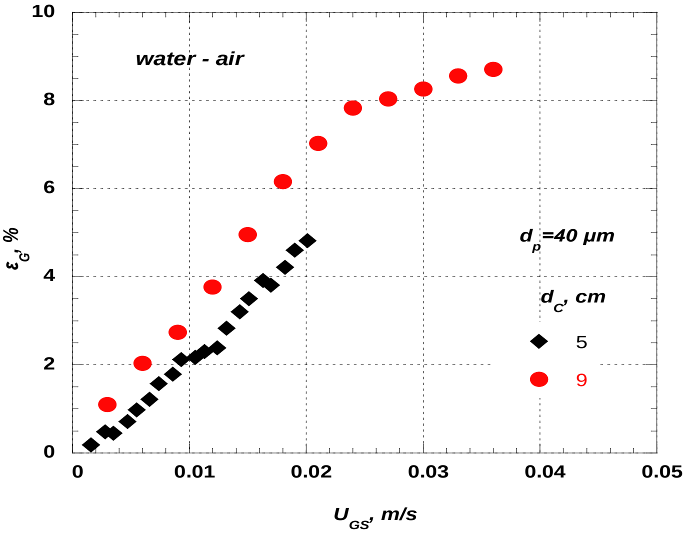


Figure 4. Effect of type of gas on regime transition for water.

ıre 5. Effect of column diameter on gas holdup for the water-air system.

Figure 6 presents typical effect of the type of gas on gas holdup. With increasing gas density gas holdup increases, e.g. helium that has a lower density exhibits lower values of gas holdup than air and CO_2. This behavior is attributed to the fact that, the lower density gas exerts a lower momentum force to an under-formation bubble (Eq. 2). This observation agrees with other researchers 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. However, it is worth noticing that, even though the density of CO_2 is 50% higher than that of atmospheric air, for the lower gas superficial velocities both air and CO_2 exhibit almost the same behavior and only when the density decreases by more than 80% (i.e. for He)) a noticeable change is observed (Figure 6)

In previous studies conducted in our lab [3,4,7] a correlation for predicting the average gas holdup, ε_G, was proposed based on dimensionless numbers. The equation has the general form:

$$\varepsilon_G = c_1 \left[Fr^{c_2} Ar^{c_3} Eo^{c_4} \left(\frac{d_s}{d_c}\right)^{c_5} \left(\frac{d_p}{d_s}\right)^{c_6} \right]^{c_7} \tag{11}$$

where *Fr, Ar* and *Eo* are respectively defined by: $Fr = \frac{U_{GS}^2}{d_C g}$, $Ar = \frac{d_C^3 \rho_L^2 g}{\mu_L^2}$, $Eo = \frac{d_c^2 \rho_L g}{\sigma_L}$.

The values of constants c_1 to c_7 depend on the of liquid phase. It was also proved [3-5,7] that the proposed correlations can predict hold up with reasonable accuracy, i.e. better than 15%.

However, in the ε_G prediction the type of gas is not taken into account, although the gas momentum affects bubble evolution (Table 1). From Figure 6, where the effect of gas type is presented, it is apparent that only the very low density gas He has has a measurable effect on gas hold-up value. In case that the gas phase is other than air, it is necessary to introduce a term that incorporates the properties of the gas phase.

Based on the above, we have modified Eq. 12 by introducing in the gas Reynolds number Re_G defined as: $Re = \frac{U_{GS} d_C \rho_G}{\mu_G}$

The modified form of the proposed correlation is as follows:

$$\varepsilon_G = c_1 \left[Fr^{c_2} Ar^{c_3} Eo^{c_4} Re_G^{c_5} \left(\frac{d_s}{d_c} \right)^{c_6} \left(\frac{d_p}{d_s} \right)^{c_7} \right]^{c_8} \qquad (12)$$

where the constants of the correlation are given in Table 6. Furthermore, Figure 7 shows that the ε_G values predicted by Eq. 12 are in very good agreement (±15%) with the corresponding experimental data.

.

Table 6: Constants value for ε_G prediction equation (Eq. 12).

C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
0.020	0.300	0.015	3.50	0.043	1.10	2.62	1.18

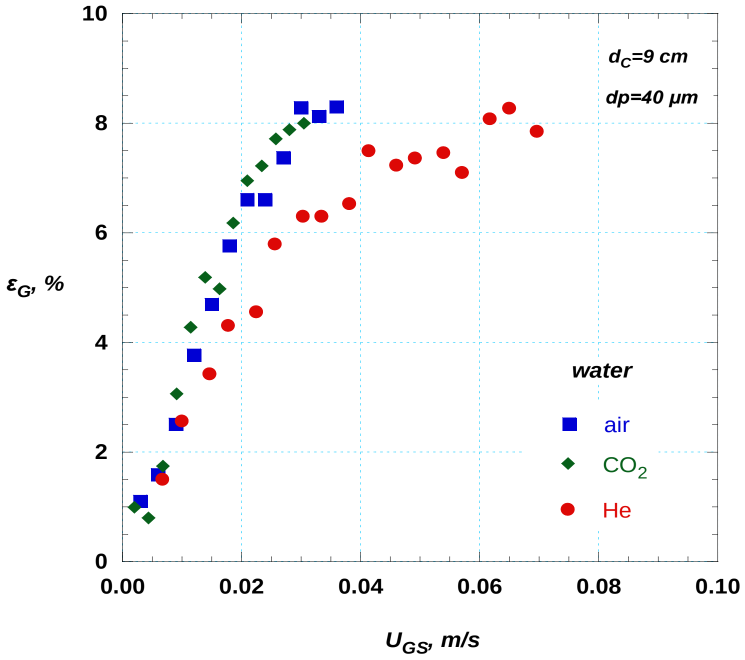


Figure 6. Effect of type of gas on gas holdup (d_p=40 μm, d_c=9 cm).

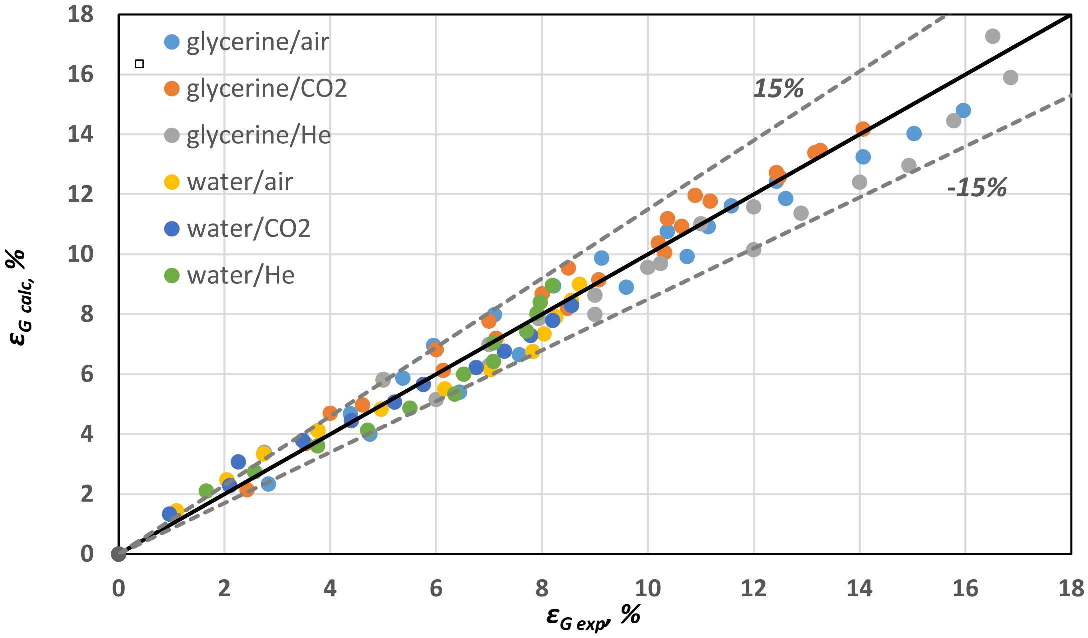


Figure 7. Comparison of the proposed correlation with the experimental data.

4. Concluding remarks

In this work, we have experimentally investigated in what extent the type of gas phase influences the performance of a bubble column reactor by employing gases that cover a wide range of physical properties; namely atmospheric air and CO_2 exhibit almost the same behavior, while the low density He shows a measurable effect on bubble column design quantities. This can be attributed to the fact that the low density He gas exhibits a lower momentum force. 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 effect of the type of gas employed. The new correlations can predict the aforementioned quantities with reasonable accuracy (better than 15%).

Nomenclature

A	column cross section, m^2	*Greek letters*	
d_b	bubble diameter, m	ε_G	average gas holdup, dimensionless
d_{32}	*Sauter* mean diameter, m	μ_G	gas phase viscosity Pa s
d_c	column diameter, m	μ_L	liquid phase viscosity, Pa s
d_p	pore diameter, m	ρ_G	gas density, Kg/m^3
d_s	sparger diameter, m	ρ_L	liquid density, Kg/m^3
F_b	buoyancy force, N	σ_L	surface tension, mN/m
F_d	drag force, N	ε_G	average gas holdup, dimensionless
F_g	gas momentum force, N		
F_i	inertial force, N		

F_p	pressure force, N	*Dimensionless quantities*	
F_σ	surface tension force, N	Ar	Archimedes number
g	acceleration of gravity, m/s^2	Eo	Eotvos number
H_C	column height, m	Fr	Froude number
k	minimum number of classes	Fr_{tans}	Froude number at transition point
j	drift flux, m/s	N	number of classes for the distributions
Q_G	gas flow rate, m^3/s	n_i	number of bubbles of size class i
U_{GS}	superficial gas velocity, m/s	Re	liquid Reynolds number
S	sample size	Re_G	Gas Reynolds number
W_g	bubble formation velocity, m/s	We	Weber number

Acknowledgments: The authors would like to thank Asterios Lekkas for the construction and installation of the experimental setup and Spiros V. Paras for his constructive comments.

References

1. Camarasa, E.; Vial, C. Influence of coalescence behaviour of the liquid and of gas sparging on hydrodynamics and bubble characteristics in a bubble column. Chemical Engineering and Processing: Process Intensification 1999, 38, 329-344.
2. Kazakis, N.A.; Mouza, A.A.; Paras, S.V. Experimental study of bubble formation at metal porous spargers: Effect of liquid properties and sparger characteristics on the initial bubble size distribution. Chemical Engineering Journal 2008, 137, 265-281.
3. Mouza, A.A.; Dalakoglou, G.K.; Paras, S.V. Effect of liquid properties on the performance of bubble column reactors with fine pore spargers. Chemical Engineering Science 2005, 60, 1465-1475, DOI 10.1016/j.ces.2004.10.013.
4. Passos, A.D.; Voulgaropoulos, V.P.; Paras, S.V.; Mouza, A.A. The effect of surfactant addition on the performance of a bubble column containing a non-Newtonian liquid. Chemical Engineering Research and Design 2015, 95, 93-104.
5. Anastasiou, A.D.; Kazakis, N.A.; Mouza, A.A.; Paras, S.V. Effect of organic surfactant additives on gas holdup in the pseudo-homogeneous regime in bubble columns [uipped with fine pore sparger. Chemical Engineering Science 2010, 65, 5872-5880.
6. Shah, Y.T.; Kelkar, B.G. Design parameters estimations for bubble column reactors. AIChE Journal 1982, 28, 353-379, 10.1002/aic.690280302.
7. Kazakis, N.A.; Papadopoulos, I.D.; Mouza, A.A. Bubble columns with fine pore sparger operating in the pseudo-homogeneous regime: Gas hold up prediction and a criterion for the transition to the heterogeneous regime. Chemical Engineering Science 2007, 62, 3092-3103.
8. Ruzicka, M.C.; Drahoš, J. Effect of bubble column dimensions on flow regime transition. Chemical Engineering Science 2001, 56, 6117-6124.
9. Kumar, S.B.; Moslemian, D.; Duduković, M.P. Gas-holdup measurements in bubble columns using computed tomography. AIChE Journal 1997, 43, 1414-1425, 10.1002/aic.690430605.
10. Dhotre, M.T.; Ekambara, K.; Joshi, J.B. CFD simulation of sparger design and height to diameter ratio on gas hold-up profiles in bubble column reactors. Experimental Thermal and Fluid Science 2004, 28, 407-421, https://doi.org/10.1016/j.expthermflusci.2003.06.001.