01 Feb 2001

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Recommended Citation

Y. Wu et al., "Predictions of Radial Gas Holdup Profiles in Bubble Column Reactors," *Chemical Engineering Science*, vol. 56, no. 3, pp. 1207 - 1210, Elsevier, Feb 2001.
The definitive version is available at https://doi.org/10.1016/S0009-2509(00)00341-9

PERGAMON

Chemical Engineering Science 56 (2001) 1207–1210

Chemical
Engineering Science

www.elsevier.nl/locate/ces

Predictions of radial gas holdup profiles in bubble column reactors

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Abstract

Gas holdup and its profile are important parameters to be characterized in bubble column reactors. Proper prediction of the radial gas holdup profiles is necessary for determining liquid mixing, flow regime transition, heat and mass transfer. In this study, the following gas holdup profile form, which can be fitted to the observed holdup profiles, is proposed:

$$\varepsilon_G = \bar{\varepsilon}_G\left(\frac{n+2}{n+2-2c}\right)[1 - c(r/R)^n].$$

The parameters n and c needed to describe the gas holdup profile are correlated with appropriate dimensionless groups.

$$n = 2.188 \times 10^3\, Re_G^{-0.598}\, Fr_g^{0.146}\, Mo_L^{-0.004},$$

$$c = 4.32 \times 10^{-2}\, Re_G^{0.2492}.$$

However, the cross-sectional average gas holdup, $\bar{\varepsilon}_G$, can be estimated using the available correlations for overall gas holdup. The agreement between the correlation predictions and experimental data is reasonable over wide range of operating conditions. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Bubble columns; Gas holdup profiles; Correlation

1. Introduction

Gas holdup profile is one of the most important parameters in bubble column reactors. The spatial variation of gas holdup gives rise to pressure variation, which results in liquid recirculation in the bubble column. This liquid recirculation governs the rate of mixing, heat transfer and mass transfer. The ability to predict radial gas holdup profiles in bubble column reactors would help us in determining the flow regimes, liquid mixing, heat and mass transfer better. This should make bubble column scale-up more reliable.

The existence of a pronounced radial holdup profile is the characteristic of the heterogeneous regime of flow in bubble column which generates strong liquid recirculation. The magnitude of gas holdup radial gradients and the magnitude of liquid velocity driven by the gas depend on superficial gas velocity, column diameter, the nature of the gas–liquid system and the operating conditions (pressure and temperature of the reactor).

During the past three decades, a number of experimental measurements of gas holdup and gas holdup profile have been reported in the literature and have been summarized by Joshi et al. (1998). A variety of techniques, such as optical fiber probes, gamma-ray densitometry, particle image velocimetry, and gamma-ray and X-ray attenuation together with computer tomography have been employed for the local gas holdup measurements. Due to the complexity of the system, no fundamental equation is available at present for prediction of the gas holdup profiles in bubble columns. There are a number of empirical equations, similar in form, that can be fitted to the observed holdup profiles.

Nassos and Bankoff (1967) proposed the following equation for the radial holdup profile

$$\varepsilon_G = \tilde{\varepsilon}_G\left(\frac{n+2}{n}\right)[1 - (r/R)^n]. \tag{1}$$

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PII: S0009-2509(00)00341-9

In Eq. (1), $\tilde{\varepsilon}_G$, which is the radial chordal average gas holdup along the column diameter, and the exponent n are parameters and r/R is the dimensionless radial position. The value of parameter n is indicative of the steepness of the holdup profile. When n is large the profile is flat, for small n the profile is steep. The steepness of the holdup profile is reflected in the intensity of liquid circulation. Ueyama and Miyauchi (1979) reviewed the published literature and modified the above equation as follows to include the possibility of finite gas holdup close to the wall.

$$\varepsilon_G = \tilde{\varepsilon}_G\left(\frac{n+2}{n}\right)[1 - c(r/R)^n]. \tag{2}$$

In Eq. (2), c is an additional parameter which is indicative of the value of gas holdup near the wall. If $c = 1$ there is zero holdup close to wall, if $c = 0$ holdup is constant with changing r/R.

Luo and Svendsen (1991) used Eq. (2) rewritten in terms of mean cross-sectional holdup, $\bar{\varepsilon}_G$, as given below:

$$\varepsilon_G = \bar{\varepsilon}_G\left(\frac{n+2}{n+2-2c}\right)[1 - c(r/R)^n]. \tag{3}$$

By applying Eq. (3) to data, n was found to vary from 1.4 to 11, and c from 0.5 to 1 according to different authors (Joshi et al., 1998) and based on different systems investigated. In the absence of a firm theoretical prediction of the radial gas holdup profile correlations are needed for evaluating n and c based on the knowledge of the general operating variables and physical properties of the system in order to estimate the gas holdup profile by Eq. (3). In this work, such correlations have been developed as discussed below.

2. Correlations development

Extensive gas holdup and gas holdup profile data have been acquired in the Chemical Reaction Engineering Laboratory (CREL) over the years under DOE contract DE2295PC95051 on the bubble column hydrodynamics, by employing gamma ray Computed Tomography (CT) over a range of superficial gas velocities (from 2 cm/s to 60 cm/s), at different pressures (0.1–1.0 MPa) with five different gas distributors and in columns ranging in diameter from 0.19–0.44 m. The majority of the gas holdup profiles were measured in air–water system. However, air–drakeoil (light mineral oil) and air-propanol systems were also used at different operating conditions. The reproducibility of the measured gas holdup profiles was within ± 3%. By analyzing the experimental results carefully, it was found that the shape of holdup profiles changes most significantly with superficial gas velocities. However, pressure affects the shapes of holdup profiles but it has less effect compared to superficial gas velocity within the range of pressure and superficial gas velocity that was examined. Gas distributor does affect holdup in a certain range of gas velocities but it has a minor effect on gas holdup profiles particularly in the fully developed region and at high gas velocity. The shape of the gas holdup profile at different column heights seems to be unchanged at a given gas velocity once the measurement has been taken at a certain distance from the distributor (2 L/D or higher). Column diameter has been reported to have an effect on gas holdup profile (Kumar, Moslemain & Dudukovic, 1997).

Based on the experimental observations and dimensional analysis, the following functional dependence was proposed for parameters n and c:

$$n = af(Re_G, Mo_L, Fr_G), \quad c = \beta\zeta(Re_G).$$

The above dimensionless groups, Re_G, Mo_L, Fr_G, which are defined below reflect the effect of velocity and pressure, which change the density of the gas and has an effect on gas holdup profile, and the effect of gas and liquid physical properties. By fitting about two thirds of the available experimental data from the database consisting of our experiments mentioned above and those in the literature (the remaining of the experimental data set is used to evaluate the developed correlations), the correlations listed below are generated for n and c

$$n = 2.188 \times 10^3\, Re_G^{-0.598}\, Fr_g^{0.146}\, Mo_L^{-0.004}, \tag{4}$$

$$c = 4.32 \times 10^{-2}\, Re_G^{0.2492}, \tag{5}$$

where

$$Re_G = \frac{DU_{Sg}(\rho_L - \rho_G)}{\mu_L}, \quad Fr_G = \frac{U_{sg}^2}{gD}, \quad Mo_L = \frac{g\mu_L^4}{(\rho_L - \rho_G)\sigma_L^3}.$$

Eqs. (4) and (5) along with Eq. (3) are utilized for estimation of the gas holdup profiles for the whole set of the experiment data available. The cross sectional mean gas holdup, $\bar{\varepsilon}_G$, values used in this study were evaluated from the experimental data. However, a favorite correlation for the overall gas holdup can be used to estimate $\bar{\varepsilon}_G$ (Kemoun, Ong, Gupta, Al-Dahhan & Dudukovic, 2000).

As mentioned above, the majority of experimental data used were obtained by using an air–water system. Hence, based on the fitting performed in this study, n is almost independent of Mo_L($n \propto Mo_L^{-0.004}$). However, it was found that the liquid physical properties affect the overall gas holdup (Luo, Lee, Lau, Yang & Fan, 1999) and the holdup profile (Chen et al., 1998; Joshi et al., 1998). Therefore, at this stage, Mo_L is included in the correlation to be examined for any future necessary modification as gas holdup profiles become available for a wide enough range of liquid physical properties.

Due to the fact that most of the holdup profiles used were for air–water system, c was found to be only a function of Re_G. Liquid physical properties would affect the parameter c which needs to be examined further.

3. Comparison between the predicted and experimentally measured gas holdup profiles

3.1. *Effect of superficial gas velocity*

As mentioned earlier, gas holdup profiles vary significantly with gas velocity. The results are shown in Fig. 1.

One can see from Fig. 1 that gas holdup profiles become steeper with increased gas velocity (n changes from 3.73 at 8 cm/s to 2.02 at 60 cm/s). The steeper holdup profile is, the faster liquid recirculation rate is, hence liquid mixing, heat transfer and mass transfer rate will be improved accordingly. From Fig. 1, one can observe that the developed correlations predict the experimental results reasonably well (mean relative error is within 15%).

3.2. *Effect of reactor pressure*

It is shown that pressure not only changes the gas holdup but also changes the gas holdup profile as well (Joshi et al., 1998).

At higher pressure smaller bubbles are formed at the sparger due to high gas density (Luo et al., 1999). Small bubble size increases the overall gas holdup, and as pressure increases, gas bubble size distribution becomes narrow which results in a slightly flatter hold up profile due to the uniform distribution of small bubbles. As shown in Fig. 2, at $U_g = 14$ cm/s as pressure varies from 0.4 MPa to 1 MPa there is no major difference in the shape of gas hold up profile (n values varies from 3.146 to 3.168). Unfortunately, currently there is no gas holdup profile available at higher pressure and higher gas velocity. For the operating condition studied, the developed correlations also predict the experimental results reasonably well (mean relative error is within 14%).

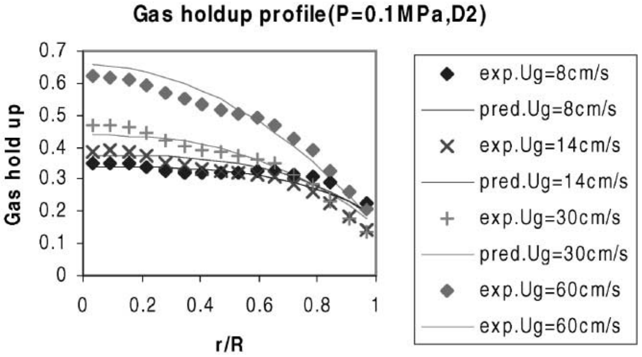

Fig. 1. Effect of velocity on gas holdup profile. (diameter of column: 0.15 m, distributor D2: perforated plate, hole diameter: 0.5 mm, number of holes:163, open area: 0.15%; P = 0.1 MPa; air–water system).

3.3. *Effect of physical properties*

As mentioned earlier, both holdup distribution and liquid recirculation depend on liquid physical properties. A noncoalescing system and a coalescing systems have different overall gas holdup and gas holdup profiles as well. Fig. 3 illustrates that the proposed correlations predict the experimental results reasonably well for liquids of different physical properties.

It is noteworthy that two sets of the data presented in Fig. 3 are taken from the literature (Menzel et al., 1990; Chen et al., 1998), and are predicted well by the developed correlations (mean relative error is within 17%). However, larger errors in the correlations predictions are obtained in the region near the wall for the data obtained from Menzel et al. (1990). This would be due to, as mentioned above, the majority of the measured holdup profiles used for the developed correlations (Eqs. (4) and (5)) were obtained for air–water system which affect the dependency of the parameters n and c on the liquid physical properties.

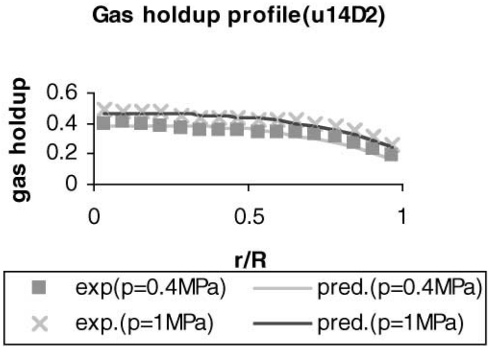

Fig. 2. Effect of pressure on gas holdup profile in 0.15 m reactor diameter. ($U_g = 14$ cm/s, distributor D2: perforated plate, hole diameter: 0.5 mm, number of holes: 163, open area: 0.15%, water–air system).

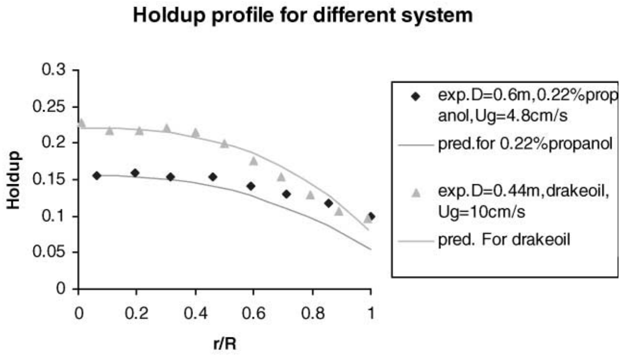

Fig. 3. Effect of liquid physical properties on holdup profile. ($U_g = 4.8$ cm/s, $D = 0.6$ m, air–0.22% propanol in water: Menzel, Thomas der, Staudacher, Wein & Onken, 1990; $U_g = 10$ cm/s, $D = 0.44$ m, air–drakeoil: Chen et al., 1998).

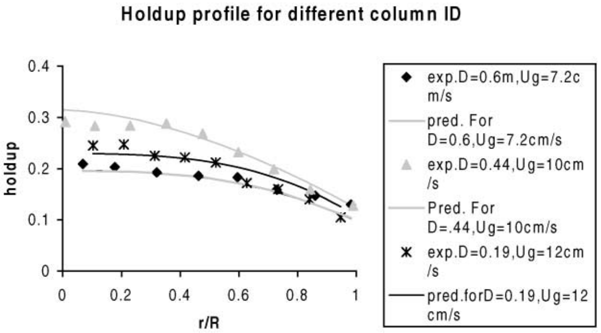

Fig. 4. Effect of column diameter on the holdup profile. ($U_g = 7.2$ cm/s, $D = 0.6$ m: Menzel et al., 1990; $U_g = 10$ cm/s, $D = 0.44$ m: Chen et al., 1998; $U_g = 12$ cm/s, $D = 0.19$ m: Kumar et al., 1997).

3.4. *Effect of column diameter*

As reported in the literature (Joshi et al., 1998) with increase in column diameter D, the liquid recirculation velocity increases as $V_c \alpha D^{0.3-0.4}$. Hence, one would expect a steeper holdup profile in larger column diameter. This is not obvious from Fig. 4 due to different superficial gas velocities used in columns of different diameter and this is the only available data at the moment.

Fig. 4 shows the comparison of the correlations prediction and the experimental data at different column diameters. One can see that the prediction agrees with our experimental results and literature experimental data (mean relative error is within 15%).

4. Summary

It should be pointed out that in all the data presented here the cross-sectional mean holdup $\bar{\varepsilon}_G$ was known. In a design situation, that would not be the case. Then a favorite correlation for the overall gas holdup can be used (Kemoun et al., 2000) to determine the mean holdup $\bar{\varepsilon}_G$ and the accuracy for our suggested radial holdup profile would naturally be affected by the accuracy of the correlation used to estimate $\bar{\varepsilon}_G$. A correlation is proposed for prediction of radial gas holdup profiles, which are important in driving liquid recirculation in bubble column. As Figs. 1–4 illustrate the agreement between the correlations predictions and the experimental data is reasonable over a range of operating conditions (mean relative error is less than 17%). Further work considering gas–liquid–solid slurry system is still in progress.

Notation

c	parameter in Eq. (2)
D	column diameter, m
Fr_g	gas Froude number, dimensionless
g	acceleration due to gravity, m/s^2
Mo_L	liquid Morton number, dimensionless
n	parameter in Eq. (1)
r, R	Column radius, m
Re_G	Reynolds number, dimensionless
U_{Sg}	superficial gas velocity, m/s
V_c	liquid circulation velocity, m/s

Greek letters

$\varepsilon(r)$	radial gas hold up profile
$\bar{\varepsilon}_G$	cross-sectional average gas holdup
$\tilde{\varepsilon}_G$	radial chordal average gas holdup
μ_L	liquid viscosity, Pa s
ρ_G	gas density, kg/m^3
ρ_L	liquid density, kg/m^3
σ_L	liquid surface tension, N/m

Acknowledgements

The authors are thankful for the UCR-DOE grant (DE-FG26-99FT40594) which made this work possible. The support of CREL industrial sponsors and the Department of Energy via contract DE2295PC95051 is gratefully acknowledged as it made creation of the CREL database on holdup profiles possible.

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