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Prediction of axial liquid velocity profile in bubble columns

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Abstract

The liquid flow and mixing behavior in bubble columns is partially described by means of global liquid recirculation velocity profile. Due to the complex character of the flow in bubble columns, the prediction of the axial liquid circulation is still a difficult task. In this work, the following correlation is proposed for the liquid recirculation profile:

$$\frac{V_L(r)}{V_{LO}} = 1 - 2.65 * n^{0.44} * c\left[\frac{r}{R}\right]^{2.65 * n^{0.44} * c},$$

where n and c are the gas radial holdup profile parameters evaluated by the correlations proposed by Wu, Ong and Al-Dahhan (Chemical Engineering Science, 56 (2001) 1207–1210)

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

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

The predictions of the developed liquid circulation correlation agree well with the experimental data obtained in our laboratory and reported in literature. The model is simple and is easy to use as an engineering tool to assess the liquid recirculation in bubble columns. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Bubble columns; Axial liquid velocity; Correlation

1. Introduction

Bubble column reactors are widely used as gas–liquid and gas–liquid–solid contactors in industrial aerobic fermentations, hydrogenations and other chemical operations because of their simple construction and ease of maintenance. Bubble columns combine efficient gas transfer and mixing with low shear forces. The behavior of these reactors is determined by their hydrodynamic properties. The complex flow and mixing behavior found in bubble columns are often described by means of global parameters such as gas holdup and liquid circulation velocity. Due to the complex character of the flow in bubble columns, their design and scale up are still a difficult task.

Many models have been proposed to analyze and predict liquid circulation. Miyauchi and Shyu (1970) and Joshi and Sharma (1979) predicted liquid velocity in relation to the local gas holdup. However, the local gas holdup must be obtained from experimental data for both of these models. Zehner (1986) introduced a friction factor for liquid velocity prediction, but the value assigned by him to this parameter is not easy to justify. Kumar (1994) developed a one-dimensional momentum balance-based model which requires the holdup profile and eddy viscosity or mixing length profile to which the model is found to be very sensitive. Various attempts have been made at developing functional forms for the eddy viscosity (Ueyama & Miyauchi, 1979) and mixing length (Luo & Svendsen, 1991) which are required for solving the one-dimensional model. However, Kumar (1994) showed that there is truly no universal expression for the mixing length or the eddy viscosity that can be successfully used under wide range of operating conditions, to predict the recirculating liquid velocity profile. In his mixing length correlation there are five parameters which are fitted to experimental data. Recently Krishna,

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Urseanu, van Baten and Ellenberger (1999) proposed a computational fluid dynamics (CFD) based model for prediction of holdup profile and axial velocity profile. CFD based model could be a powerful design and scale-up tool after it has been fully verified. This is not yet the case.

The objective of this work is to develop a simple model based on which axial velocity profile can be predicted in relation to the gas-input rate and the column dimensions without requiring as input the radial gas holdup profiles.

2. Correlation development

A power-law liquid velocity profile is widely accepted in the literature (Montserrat & Garcia-Calvo, 1996, Garcia-Calvo & Leton, 1994). The liquid rises with the bubbles in the central portion of the column and flows downward in the outer annular section. Hence, the liquid velocity distribution in a bubble column may be expressed as

$$\frac{V_L(r)}{V_{LO}} = 1 - 2^{N/2}\left[\frac{r}{R}\right]^N, \tag{1}$$

where N is the exponent of the liquid velocity profile and V_{LO} is the liquid center line velocity. N varies from 2–2.3 or higher based on the work of different investigators (Kawase & Moon-Young, 1986, 1987; Montserrat & Garcia-Calvo, 1996). In fact, liquid circulation is due to the existence of the gas holdup radial profile, and the radial gas holdup profile and liquid circulation are intimately tied together. Both depend on superficial gas velocity, column diameter and the physical properties of the gas–liquid system investigated. The liquid according to the velocity profile of Eq. (1) is in central core region of the bubble column and flows downward in the wall zone.

A correlation of a similar form was proposed for prediction of the radial gas holdup profile (Luo & Svendsen, 1991):

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

In Eq. (2), n is indicative of the steepness of the gas holdup profile, and c determines the value of holdup near the wall. It provides the possibility for both zero and non-zero gas volume fraction values at the wall which may affect the circulation of liquid as well. Possibly exponent N in Eq. (1) also depends on the liquid properties and on the gas flow rates (Wu, Ong & Al-Dahhan, 2000). Hence, it may be necessary to include both n and c in Eq. (1) to predict the axial liquid velocity profile. To establish the needed relationship between the gas and liquid velocity profile, Eq. (1) is modified as

$$\frac{V_L(r)}{V_{LO}} = 1 - f(n,c)\left[\frac{r}{R}\right]^{\xi(n,c)}. \tag{3}$$

Correlations have been developed (Wu et al., 2001) for calculation of parameters n and c as follows:

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

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

where

$$Re_G = \frac{D U_{Sg}(\rho_L - \rho_G)}{\mu_L}, \quad Fr_G = \frac{U_{Sg}^2}{gD},$$

$$Mo_L = \frac{g\mu_L^4}{(\rho_L - \rho_G)\sigma_L^3}.$$

By fitting our computer automated radioactive particle tracking (CARPT) data, it was found that $f(n,c) = \xi(n,c) = 2.65 * n^{0.44} * c$. Therefore, Eq. (3) becomes

$$\frac{V_L(r)}{V_{LO}} = 1 - 2.65 * n^{0.44} * c\left[\frac{r}{R}\right]^{2.65 * n^{0.44} * c}. \tag{6}$$

As mentioned earlier, V_{LO} is the axial liquid velocity in the center of the bubble column and can be obtained from either experiments or correlations reported by Zehner (1986) and Riquarts (1981).

$$V_{LO} = 0.737(U_G D)^{1/3} \quad \text{Zehner (1986)}, \tag{7}$$

$$V_{LO} = 0.21(gD)^{1/2}(U_G^3 \rho_L / g\mu_L)^{1/8} \quad \text{Riquarts (1981)}. \tag{8}$$

From Eqs. (4) and (5), one can see that when the superficial gas velocity increases, c increases and n decreases. However, n decreases with power 0.44 and c increases with power one, so that the overall effect is to render the axial velocity profile steeper with increased superficial gas velocity which is experimentally observed. The value of the term $f(n,c) = 2.65 * n^{0.44} * c$ is between 1.8 and 2.4 with column diameters of 0.1–0.63 m and for superficial gas velocity range of 0.02–0.6 m/s and different gas and liquid physical properties.

A predicted liquid velocity using Eq. (6), with Eqs. (4) and (5), is shown in Fig. 1 and compared with experimental data. From Fig. 1, it can be seen that the model

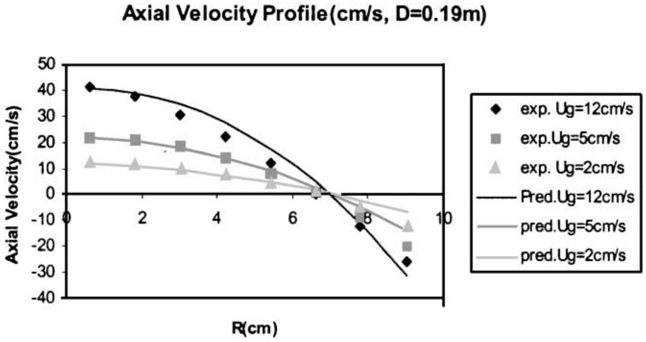

Fig. 1. Comparison of the correlation predictions and experimental data, (CARPT data for air–water system, Degaleesan, 1997).

matches experimental data well at different superficial velocities.

3. Evaluation of the correlation predictions

As mentioned above, Eq. (6) was developed by only using part of our CARPT database, and it is necessary to determine whether Eq. (6) can predict the experimental results from the literature to evaluate the capability of the modified correlation. We have compared the correlation predictions to the experimental data from very different sources reported in the literature and this comparison is illustrated below.

Fig. 2 shows the comparison of the correlation predictions and experimental data for small column diameter. It can be seen that for the column diameter equal to 0.172 m, the model can predict the axial velocity profile at different superficial gas velocity with reasonable accuracy. One can clearly see that the axial liquid velocity becomes steeper with the increase in superficial gas velocity, and the correlation predicts the point of zero velocity well. For the column diameter as big as 0.6 m, the comparison of the correlation predictions and experimental data is plotted in Fig. 3, from which it is evident that the similar predictions, as those represented in Fig. 2, are observed.

Fig. 4 shows the correlation predictions of the data observed by Heat Pulse Anemometry techniques, and the comparison is good.

From Figs. 2–4, it is obvious that the correlation can predict the axial velocity profile of the experimental data within a range of conditions. This establishes that the proposed correlation could be used to predict axial velocity profile.

In order to compare the developed correlation with the one-dimensional model (Kumar, 1994, Luo & Svendsen, 1991), both predictions of the proposed correlation and the 1D model are plotted in Figs. 5 and 6 for comparison with experimental data.

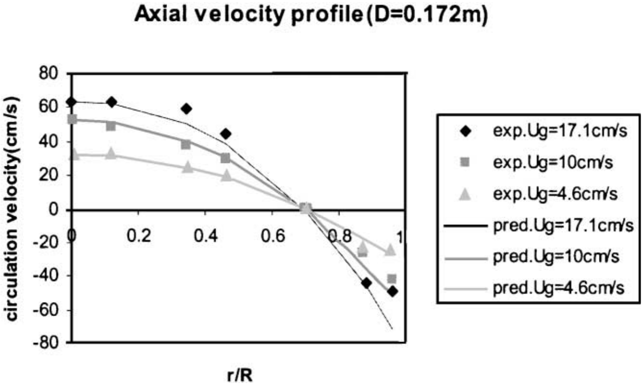

Fig. 2. Comparison of the correlation predictions and data of Pavlov (1965), air–water system.

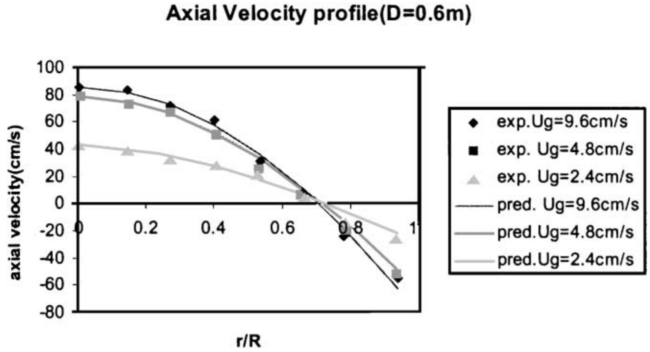

Fig. 3. Comparison of the correlation predictions with the data of Menzel et al. (1990), non-coalescence system.

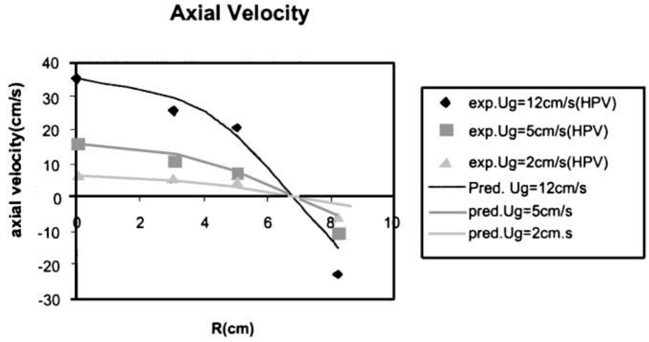

Fig. 4. Comparison of the correlation predictions with the data from HPA (Heat Pulse Anemometry), Degaleesan, 1997.

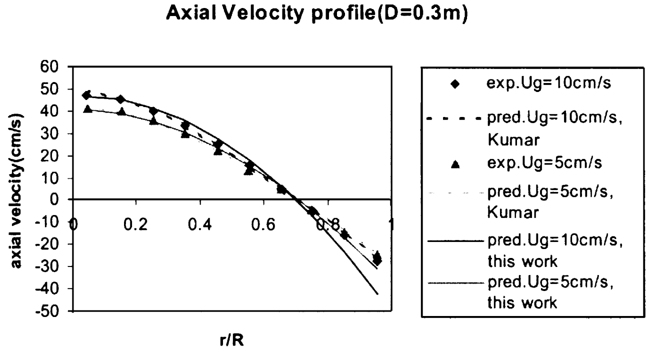

Fig. 5. Comparison of the correlation predictions (this work) with the CARPT data and one-dimensional model (Kumar, 1994).

One can see that the proposed correlation prediction is in reasonable agreement with the one-dimensional model prediction. However, it predicts the time-averaged velocity profile at superficial gas velocity of 0.17 m/s better than the 1D model prediction of Luo and Svendsen (1991).

It should be mentioned that the data in the above figures are not used in developing the correlation. In addition, with *n* and *c* developed under pressurized conditions, it may be possible for the correlation to predict the axial velocity profile in bubble columns operated at pressurized conditions. But this needs to be confirmed.

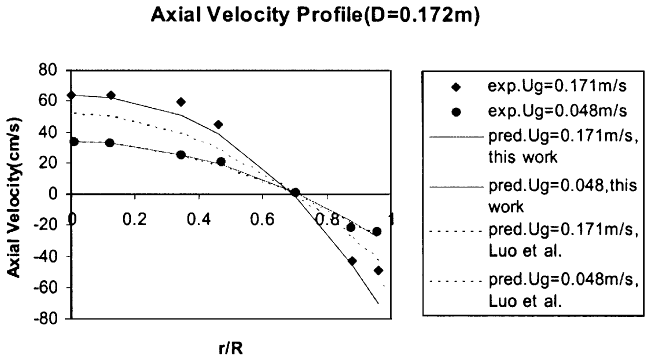

Fig. 6. Comparison of this work and Luo and Svendsen (1991) model with experimental data.

4. Summary

An existing correlation for prediction of the axial velocity profile is modified by using the correlations for the gas holdup n and c developed by Wu et al. (2001). The modified correlation can predict the experimental data reported in the literature well within a range of conditions. The correlation is simple and is easy to use as it requires as input only the superficial gas velocity, physical properties and column dimensions. It can be readily used for prediction of the axial liquid velocity profile over a range of conditions, which should help the process engineers assess convective liquid mixing in bubble column rapidly.

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. (2)
N	parameter in Eq. (1)
r, R	column radius, m
Re_G	gas Reynolds number, dimensionless
U_{Sg}	superficial gas velocity, m/s
V_c	liquid circulation velocity, m/s
$V_L(r)$	axial liquid velocity profile, m/s
V_{LO}	axial liquid velocity in the center of the column, m/s

Greek letters

$\varepsilon(r)$	radial gas holdup profile
$\bar{\varepsilon}_G$	cross-sectional average gas holdup
$\tilde{\varepsilon}_G$	radial 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

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