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A scale up strategy for bubble column slurry reactors

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Abstract

The hydrodynamics of bubble column slurry reactors are strongly influenced by the scale of operation. We suggest a strategy for scaling up reactors from laboratory scale to commercial size that relies on a fundamental understanding of bubble hydrodynamics, which is incorporated into a computational fluid dynamics (CFD) model. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Bubble columns; Churn-turbulent flow regime; Bubble rise velocity; Radial velocity profiles; Column diameter influence; Scale up

1. Introduction

Bubble column slurry reactors are finding increasing application in emerging technologies for conversion of natural gas to liquid fuels. Laboratory scale studies on bubble column slurry reactor hydrodynamics are usually carried out in columns having diameters of about 0.25 m diameter, whereas industrial size reactors are often 6–10 m in diameter. For example, the bubble column slurry reactor for the Fischer–Tropsch synthesis of hydrocarbons from syngas operated by Sasol has a diameter of 5 m and is 22 m in height [1]. The scale up of bubble columns pose considerable problems and have been the subject of comprehensive studies at the University of Amsterdam [1–37]. Furthermore, for reasons of increasing the reactor productivity and throughput, industrial reactors are operated at high slurry concentrations and high superficial gas velocities in the churn-turbulent flow regime [23].

Let us consider, for example, a bubble column operated with air as the gas phase and a paraffin oil slurry containing fine silica particles (silica, d_p = 38 m). With increasing slurry concentrations there is a significant reduction in the gas hold-up, caused by enhanced coalescence of the bubbles; see Fig. 1(a). For the 36 vol.% paraffin oil slurry, the dispersion consists predominantly of "large" bubbles, typically in the 20–50 mm size range [9]. In this paper we use the term "large" bubbles to indicate bubbles for which $E\ddot{o} > 40$. The gas hold-up for 36% slurry is significantly reduced when the column diameter is increased; see Fig. 1(b). The important questions to answer are: (1) why does the gas hold-up decrease with column diameter, and (2) how does one extrapolate to columns of industrial size? The scale up strategy we propose in this paper (see Fig. 2) uses a proper description of bubble hydrodynamics as a function of scale. This information is incorporated into a CFD model, which after verification with laboratory scale data, can be considered to be "tuned" for use as a design and scale up tool for industrial reactors. We now discuss each of the steps in Fig. 2.

2. Bubble hydrodynamics as a function of scale

For slurry bubble columns with fine catalyst particles, there will be no settling of the catalyst particles

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Nomenclature

AF	acceleration factor (dimensionless)
C_D	drag coefficient (dimensionless)
d_b	diameter of either bubble population (m)
D_T	column diameter (m)
$Eö$	Eötvös number, $g(\rho_L - \rho_G)d_b^2/\sigma$
g	acceleration due to gravity, 9.81 m/s^2
M	interphase momentum exchange term
p	pressure (N/m^2)
r	radial coordinate (m)
SF	scale correction factor (dimensionless)
t	time (s)
u	velocity vector (m/s)
U	superficial gas velocity (m/s)
V_b	rise velocity of bubble population (m/s)
$V_L(r)$	radial distribution of liquid velocity (m/s)

Greek letters

α, β	parameters defined by Eq. (3)
ε	volume fraction of gas phase (dimensionless)
μ	viscosity of phase (Pa s)
ν	kinematic viscosity (m^2/s)
ρ	density of phases (kg/m^3)
σ	surface tension of liquid phase (N/m)

Subscripts

b	referring to large bubble population
G	referring to gas phase
k	index referring to either gas or liquid phase
L	referring to liquid phase
trans	referring to regime transition point

Superscripts

0	referring to "single" bubble

during operation at high superficial gas velocities, U. Furthermore, the liquid and the catalyst particles will "move as a whole". This implies that the slurry phase can be considered to be a pseudo-liquid having a high viscosity. To demonstrate this we carried out gas hold-up measurements with the system air–Tellus oil, which has a viscosity 75 times that of water; see Fig. 3(a). The similarity between Figs. 1(b) and 3(a) is striking and both systems appear to exhibit similar scale dependencies. If we perform dynamic gas disengagement experiments with Tellus oil and 36% paraffin oil slurry, we observed nearly the same collapse behaviour, pointing to similar bubble size distributions; see Fig. 3(b). In both cases we have predominantly large sized bubbles. The superficial gas velocity at which we have transition from homogeneous to heterogeneous flow regime is $U_{trans} \approx 0$. The first useful "trick" we shall employ is that the hydrodynamics of concentrated slurries containing fine particles can be mimicked, as regards bubble hydrodynamics, by viscous liquids. Since it is easier to experiment with viscous liquids than with "thick" slurries, this is a useful scale up strategy.

The first task is to model the rise of single bubbles in a liquid. A single "large" bubble forms a spherical cap shape [18,19,22,29] and its rise in a liquid is in the "inviscid" flow regime. This is demonstrated in Fig. 4 which shows that the rise velocity V_b^0 is the same in both water and Tellus oil. In narrow columns, V_b^0 is lower because of "wall" effects; the bubble experiences a downward drag from the liquid and the rise is described by introducing a correction factor into the Davies–Taylor relation:

$$V_b^0 = 0.71\sqrt{g d_b}(\mathrm{SF}) \tag{1}$$

The scale correction factor (SF) accounts for the influence of the column diameter and is taken from the work of Collins [38] to be a function of the ratio of the bubble diameter d_b to the column diameter D_T:

$$\begin{aligned}
&\mathrm{SF} = 1 \text{ for } \frac{d_b}{D_T} < 0.125,\\
&\mathrm{SF} = 1.13\exp\left(-\frac{d_b}{D_T}\right) \text{ for } 0.125 < \frac{d_b}{D_T} < 0.6,\\
&\mathrm{SF} = 0.496\sqrt{\frac{D_T}{d_b}} \text{ for } \frac{d_b}{D_T} > 0.6
\end{aligned} \tag{2}$$

Extensive experiments carried out at the University of Amsterdam in four different columns of diameters 0.051, 0.1, 0.174 and 0.63 m with the air–water system confirm the validity of Davies–Taylor–Collins relations (1) and (2); see Fig. 5(a). The strong influence of the scale factor on the rise velocity is emphasised when we consider the rise of a bubble of 0.038 m diameter as a function of column diameter; see Fig. 5(b). In the 0.051 m diameter column we

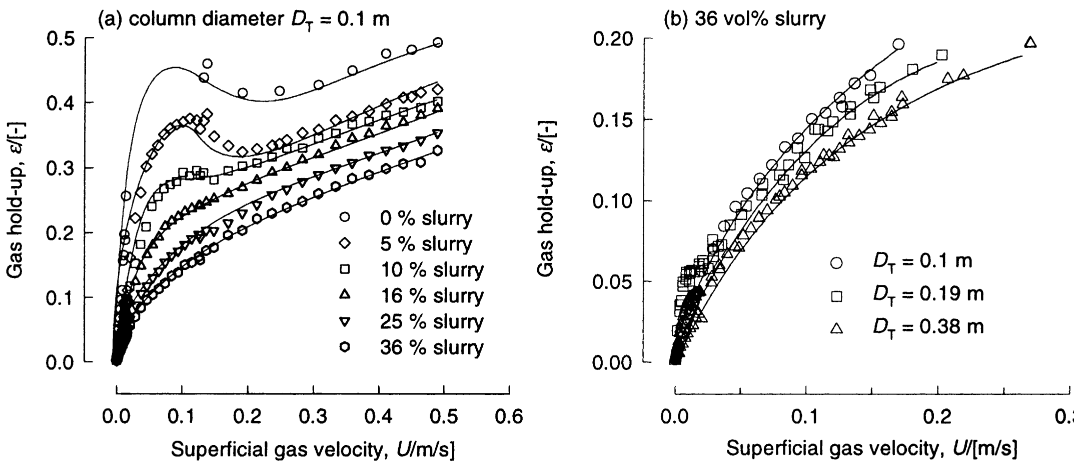

Fig. 1. (a) Influence of increased particles concentration on the total gas hold-up in 0.1 m diameter column operating with air–paraffin oil slurry. (b) Influence of column diameter on the gas hold-up for 36 vol.% paraffin oil slurry. Data from [12].

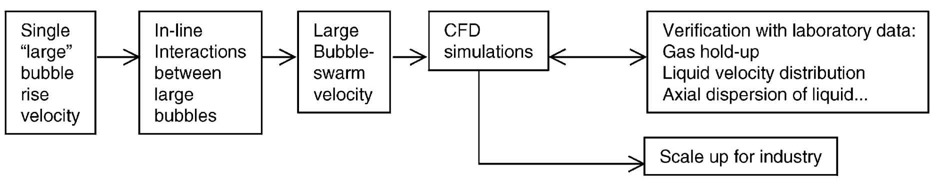

Fig. 2. Scale up strategy with CFD as the predictive tool.

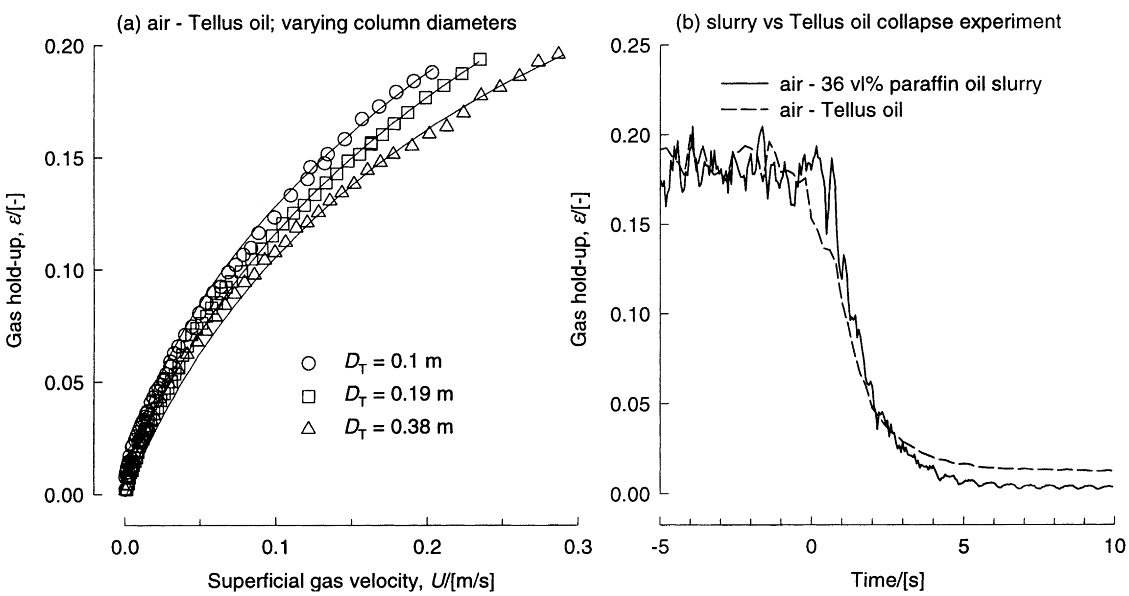

Fig. 3. (a) Influence of column diameter on gas hold-up in air–Tellus oil system. (b) Dynamic gas disengagement experiments with air–Tellus oil and air–36% paraffin oil slurry. Data from [1,12,36].

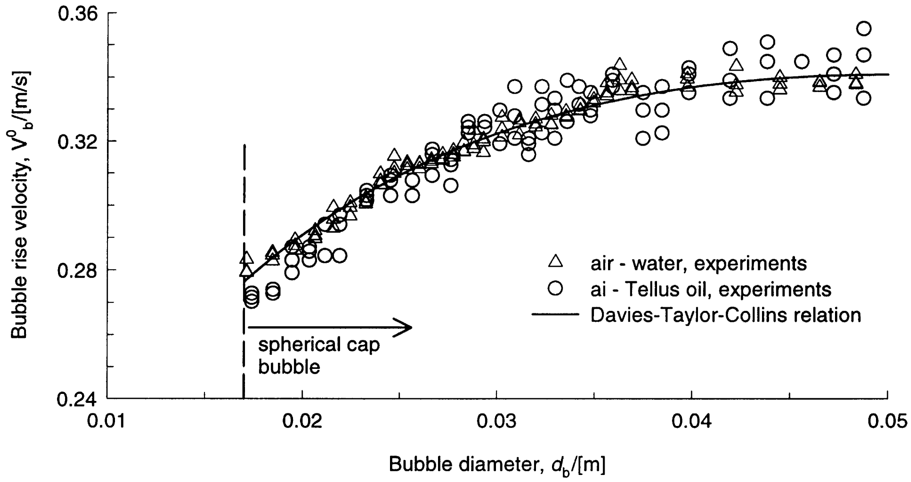

Fig. 4. Rise of single air bubbles in water and Tellus oil. Column diameter = 0.10 m.

have slugging and the rise velocity is 0.25 m/s. For the 0.1 m diameter column the rise velocity is 0.34 m/s, rising to 0.44 m/s in the 0.63 m diameter column.

Let us consider two bubbles of the same size d_b = 31 mm, separated vertically in a 0.051 m diameter column; see Fig. 6. The trailing bubble gets sucked into the wake of the leading bubble and gets accelerated. The slope of the rise trajectory at any instant of time yields the rise velocity. We define an acceleration factor, AF, for the trailing bubble as the ratio of the actual velocity to the velocity it would have were the same bubble uninfluenced by other bubbles; this

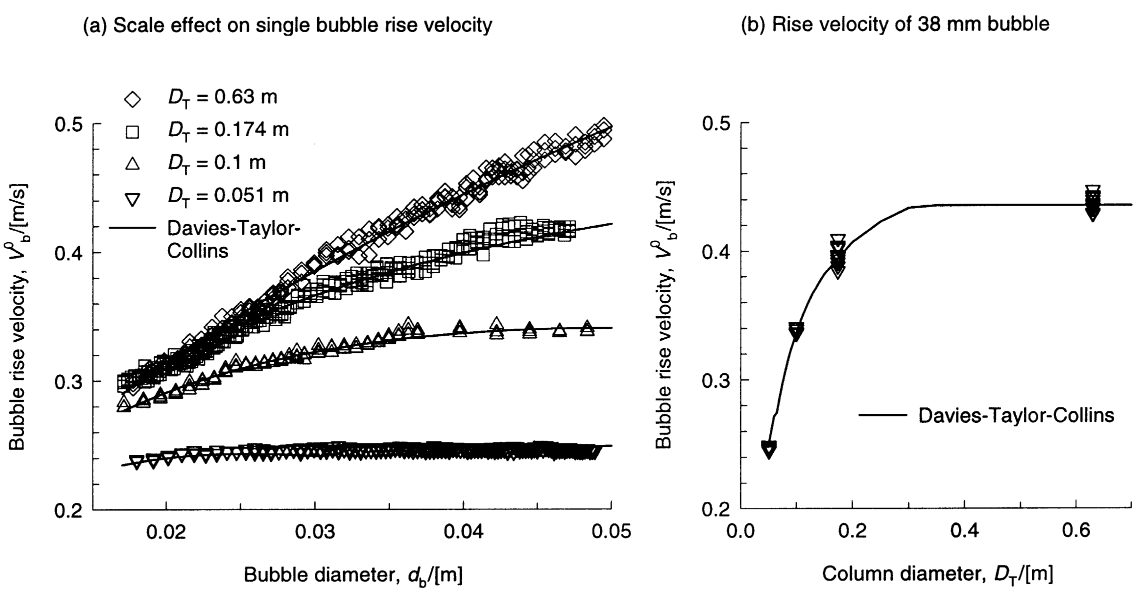

Fig. 5. (a) Rise velocity of air bubbles of varying diameters in columns of 0.051, 0.1, 0.174 and 0.63 m diameter filled with water; comparison of experimental data with the predictions of Davies–Taylor–Collins. (b) Influence of column diameter on the rise velocity of an air bubble of 38 mm diameter in water. Experimental data from [18,28].

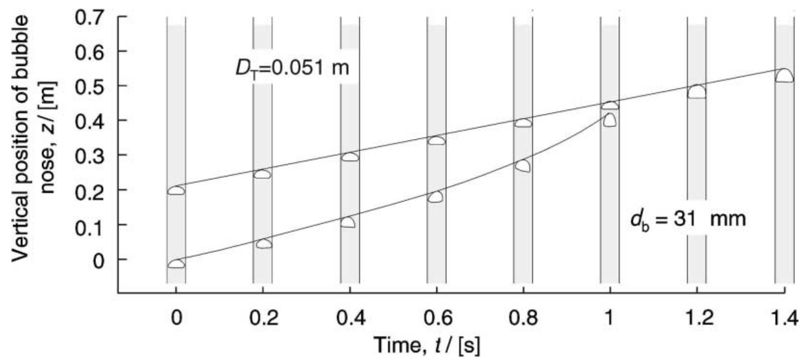

Fig. 6. Retraced video images of in-line interactions of 31 mm diameter bubbles rising in a 0.051 m diameter column filled with water. Experimental data from [18].

latter velocity can be obtained from Eqs. (1) and (2). In Fig. 7(a), the experimentally observed acceleration factor for the trailing bubble is plotted against its distance of separation, Δz, from the leading bubble. The acceleration factor (AF) is seen to increase as Δz decreases in a more or less linear fashion. For a given separation distance, the value of AF decreases with increasing liquid viscosity. For example, when $\Delta z = 0.05$ m, the value of AF for water is about 3. This means that the trailing bubble travels upwards with a velocity which is three times higher than V_b^0. For bubbles rising in Tellus oil, the acceleration factors are significantly lower. When $\Delta z = 0.05$ m, the value of AF for Tellus oil is about 2.5. The wake interaction effects are weaker in highly viscous liquids because the wakes are smaller in size. The same holds for slurries.

The acceleration factor (AF) determined from experiments shown in Fig. 7(a) are valid for a bubble trailing another bubble. To extend the concept to a swarm of “large” bubbles in a bubble column we must realise that every bubble is a “trailing” bubble because there will be a bubble preceding it. The large bubble swarm velocity can therefore be expected to be much

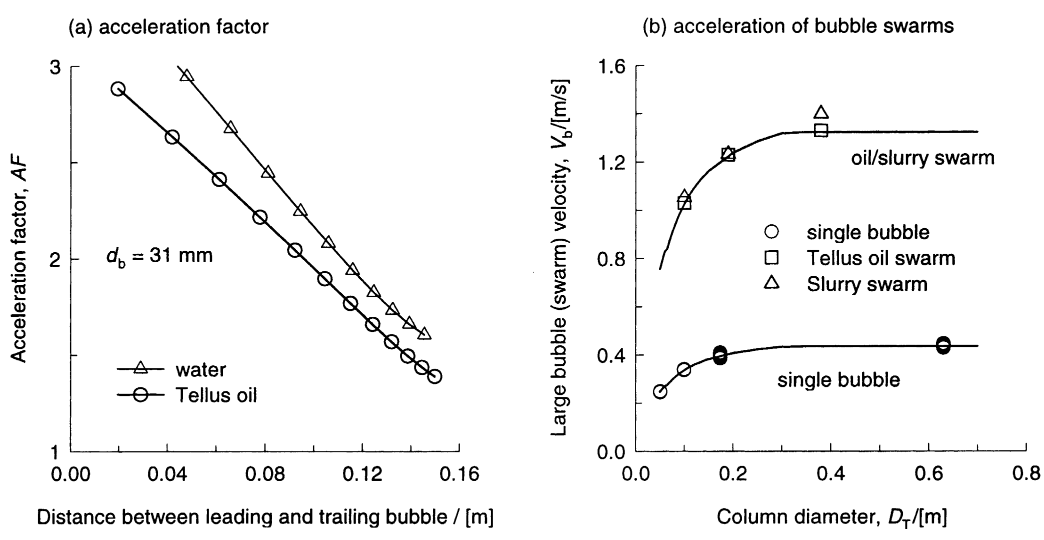

Fig. 7. (a) The acceleration factor vs. separation distance between bubbles. (b) Influence of column diameter on V_b of a swarm with an average diameter of 38 mm. Data compared with Eqs. (1)–(5).

higher than that of a single, isolated bubble, V_b^0. From the foregoing discussion, we should expect the acceleration factor (AF) to increase linearly with decreasing distance of separation of the bubbles. With increasing gas velocity through the large bubbles, $(U - U_{trans})$, we should expect the average distance of separation between the large bubbles to decrease. We therefore assert that

$$V_b = V_b^0(\mathrm{AF}), \quad \mathrm{AF} = \alpha + \beta(U - U_{trans}) \tag{3}$$

From the large bubble swarm velocity measurements made with the system air–Tellus oil, Krishna et al. [18] derived the following empirical relation for AF:

$$\mathrm{AF} = 2.25 + 4.09(U - U_{trans}) \tag{4}$$

and the average large bubble diameter in the swarm:

$$d_b = 0.069(U - U_{trans})^{0.376} \tag{5}$$

The bubble size relationship (5) is in reasonable agreement with bubble size measurements of De Swart et al. [9]. Fig. 7(b) shows the calculations for V_b using Eqs. (1)–(5), taking $U_{trans} \approx 0$, and compares this with experimental data on large bubble swarms in Tellus oil and slurries. A large bubble in a swarm can rise about 3–4 times faster than a single, isolated bubble. We also note that the large bubble swarm velocity in a concentrated slurry is the same as that in Tellus oil; both of these are described well by Eqs. (1)–(5).

3. Eulerian simulation model development and validation

For scale up purposes we adopt the two-phase model for a bubble column slurry reactor, proposed by Krishna et al. [8]; see Fig. 8. The "dilute" phase is to be identified with the fast-rising large bubble population. The "dense" phase is identified with the liquid phase along with the catalyst particles and the entrained "small" bubbles. In the heterogeneous flow regime, the small bubbles have the backmixing characteristics of the liquid or slurry phase. For slurries with concentration higher than 36 vol.%, the small bubble hold-up is virtually destroyed and so $U_{trans} \approx 0$. We develop an Eulerian simulation model for the situation with concentrated slurries, and model the slurry phase as a pseudo-liquid phase with properties of Tellus oil, in view of the remarkable agreement of the hydrodynamics as shown above. For either the large bubble or liquid phase, the volume-averaged mass and momentum conservation equations in the Eulerian framework are

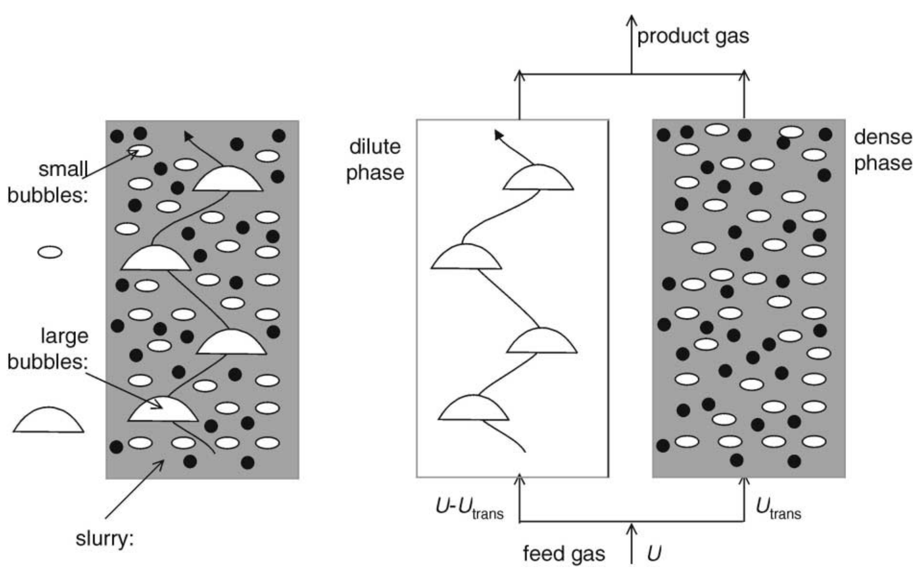

Fig. 8. Two-phase model for slurry reactor.

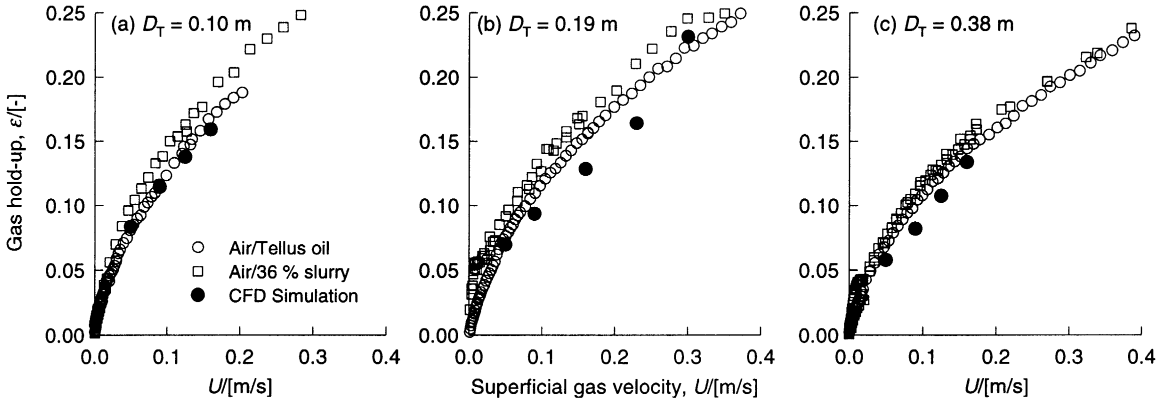

Fig. 9. Comparison of gas hold-up in Tellus oil and concentrated paraffin oil slurries in columns of 0.1, 0.19 and 0.38 m diameter. Also shown are Eulerian simulations of the large bubble hold-up in air–Tellus oil system.

given by

$$\frac{\partial(\varepsilon_k \rho_k)}{\partial t} + \nabla \cdot (\rho_k \varepsilon_k \mathbf{u}_k) = 0 \tag{6}$$

$$\frac{\partial(\rho_k \varepsilon_k \mathbf{u}_k)}{\partial t} + \nabla \cdot (\rho_k \varepsilon_k \mathbf{u}_k \mathbf{u}_k - \mu_k \varepsilon_k (\nabla \mathbf{u}_k + (\nabla \mathbf{u}_k)^{\mathrm{T}})) = -\varepsilon_k \nabla p + \mathbf{M}_{kl} + \rho_k \mathbf{g} \tag{7}$$

The momentum exchange between the large bubble (subscript b) and liquid phase (subscript L) is given by

$$\mathbf{M}_{\mathrm{L,b}} = \frac{3}{4}\rho_{\mathrm{L}}\frac{\varepsilon_{\mathrm{b}}}{d_{\mathrm{b}}}C_{\mathrm{D}}(\mathbf{u}_{\mathrm{b}} - \mathbf{u}_{\mathrm{L}})|\mathbf{u}_{\mathrm{b}} - \mathbf{u}_{\mathrm{L}}| \tag{8}$$

The interphase drag coefficient is calculated from equation

$$C_{\mathrm{D}} = \frac{4}{3}\frac{\rho_{\mathrm{L}} - \rho_{\mathrm{G}}}{\rho_{\mathrm{L}}} g d_{\mathrm{b}} \frac{1}{V_{\mathrm{b}}^2} \tag{9}$$

where V_{b} is the rise velocity of the large bubble phase, calculated according to Eqs. (1)–(5). For the continuous liquid phase, the turbulent contribution to the stress tensor is evaluated by means of k–ε model, using standard single phase parameters. No turbulence model is used for calculating the velocity fields inside the dispersed "large" bubble phase. A commercial CFD package CFX 4.2 of AEA Technology, Harwell, UK was used to solve the equations of continuity and momentum. Further details of the simulations are available in [18,24,32,35] and on our web site: http://ct-cr4.chem.uva.nl/oil-water.

The total gas hold-up determined from Eulerian simulations for air–Tellus oil agree well with the experimental data shown in Figs. 1(b) and 3(a); see Fig. 9. The measured centre-line velocities $V_{\mathrm{L}}(0)$ and radial distribution $V_{\mathrm{L}}(r)$ for the air–Tellus system in the 0.38 m diameter column are compared in Fig. 10 with Eulerian simulations. The agreement is good. The centre-line velocity correlation of Riquarts [39]

$$V_{\mathrm{L}}(0) = 0.21(gD_{\mathrm{T}})^{1/2}\left(\frac{U^3}{g\nu_{\mathrm{L}}}\right)^{1/8} \tag{10}$$

provides a good description provided we take the kinematic viscosity of water ($\nu_{\mathrm{L}} = 10^{-6}\,\mathrm{m^2/s}$) instead of that for Tellus oil. Figs. 9 and 10 show that the Eulerian simulations are reliable and therefore can be used for scale up purposes.

4. Eulerian simulation model as scale up tool

We carried out a series of simulations for air–Tellus oil bubble column operating at $U = 0.3\,\mathrm{m/s}$ for a series of column diameters (details are available in [18,24,32,35]). The results in Fig. 11 show a strong increase in $V_{\mathrm{L}}(0)$ with increasing D_{T} and agree with the square root dependence on column diameter as given by Eq. (10). This strong increase in the liquid circulations with increasing scale leads to a significant reduction in the hold-up of the large bubbles. This decrease in the large bubble hold-up is stronger than anticipated

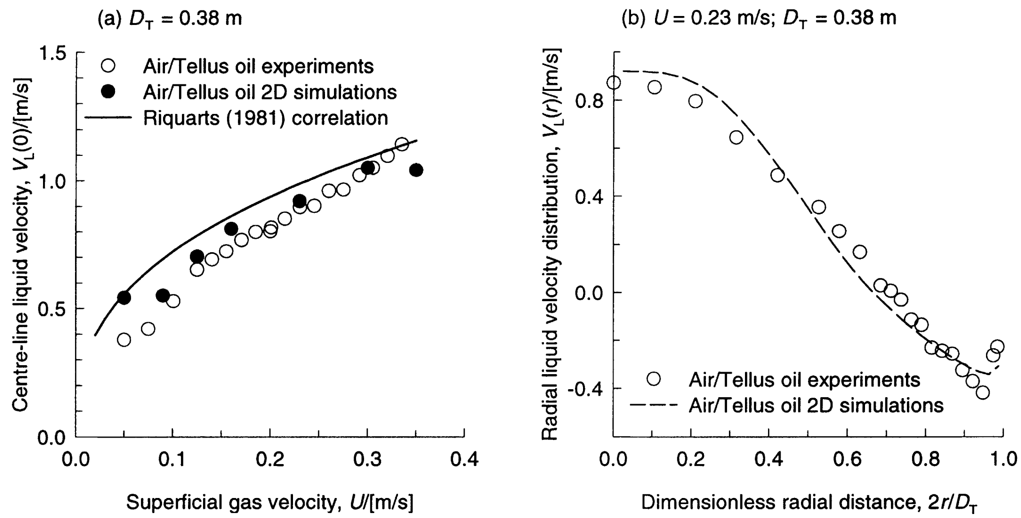

Fig. 10. Comparison of experimental (a) centre-line velocity data $V_L(0)$ and (b) radial distribution $V_L(r)$ of air–Tellus oil systems in 0.38 m diameter column with Eulerian simulations of air–Tellus oil. Experimental data from [18,24,32,35].

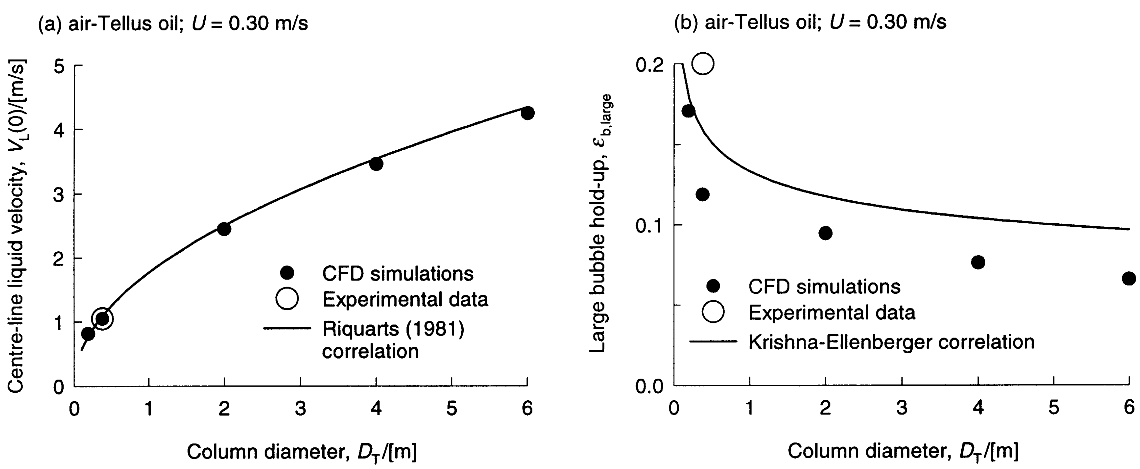

Fig. 11. Eulerian simulations for (a) centre-line liquid velocity and (b) gas hold-up when scaling up to commercial sizes, $U = 0.3$ m/s. Simulation details in [24,32,35].

by any of the published correlations [10,40]. From our previous discussions, it should be clear that the results of Fig. 11 should hold also for concentrated slurries.

5. Concluding remarks

We have demonstrated that the hydrodynamics of concentrated paraffin oil slurries is equivalent to that of a highly viscous oil, such as Tellus oil. The model of Krishna et al. [18] for calculating the large bubble swarm velocity of Tellus oil works equally well for paraffin oil slurries. The Eulerian simulation model developed in this work provides a valuable tool for predicting the hydrodynamics of commercial scale reactors. The simulations show a strong reduction in the large bubble hold-up with increasing column diameter.

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