Pergamon

Chemical Engineering Science, Vol. 53, No. 24, pp. 4151–4154, 1998
© 1998 Elsevier Science Ltd. All rights reserved
Printed in Great Britain
0009–2509/98/$–See front matter

PII: S0009–2509(98)00230–9

A reassesment of relationship between riser and downcomer gas holdups in airlift reactors

(Received 14 April 1998; accepted 15 July 1998)

INTRODUCTION

Gas holdup and liquid circulation velocity are amongst the most widely studied parameters in airlift reactors. This emphasis attests to their significance. The difference in gas holdup between the riser and the downcomer in an airlift reactor determines the magnitude of the induced liquid circulation velocity which in turn influences the bubble rise velocity, and the gas holdup. The holdup and the liquid velocity together affect the mixing behaviour, mass and heat transfer, the prevailing shear rate, and the ability of the reactor to suspended solids. Clearly, all aspects of performance of airlift systems are influenced by gas holdup and liquid circulation. Because of its significance, the relationship between the gas holdups in the riser and the downcomer has received some attention in the published literature. Almost all existing relationships between the riser and the downcomer gas holdups in airlift devices were purely empirically derived (Chisti, 1989, 1998; Chisti *et al.*, 1995). These relations are influenced by geometric and operational factors, but the nature of this dependence is unclear. This paper provides a mechanistic reinterpretation of empirical observations relating riser and downcomer gas holdups in airlift reactors. Some of the existing empirical correlations are shown to be especial cases of a general equation based in the continuity principle.

THEORY AND DISCUSSION

The volumetric flow rate of liquid in the riser of an airlift reactor can be expressed in terms of the superficial liquid velocity in the riser and it's cross-sectional area; thus,

$$Q_{Lr} = U_{Lr} A_r \tag{1}$$

where Q_{Lr} is the liquid flow rate, U_{Lr} is the superficial liquid velocity in the riser, and A_r is the riser cross-sectional area. Similarly, for the downcomer we have

$$Q_{Ld} = U_{Ld} A_d \tag{2}$$

where U_{Ld} is the superficial liquid velocity in the downcomer and A_d is the downcomer cross-sectional area. Because all the liquid exiting the downcomer circulates through the riser, i.e., $Q_{Lr} = Q_{Ld}$, from eqs (1) and (2), we have

$$U_{Lr} A_r = U_{Ld} A_d. \tag{3}$$

Equation (3) can be written in terms of the linear liquid velocities in the various zones:

$$V_{Lr} A_r (1 - \varepsilon_r) = V_{Ld} A_d (1 - \varepsilon_d) \tag{4}$$

where V_{Lr} and V_{Ld} are the linear liquid velocities in the riser and downcomer, respectively, and ε_r and ε_d are the respective gas holdups. Rearrangement of eq. (4) leads to

$$\varepsilon_d = \frac{V_{Lr} A_r}{V_{Ld} A_d}\, \varepsilon_r - \left(\frac{V_{Lr} A_r}{V_{Ld} A_d} - 1 \right). \tag{5}$$

Equation (5) is an explicit relationship between the riser and downcomer holdups. The equation is quite general and it applies to any airlift reactor, irrespective of the liquid and the gas phases used. Equation (5) may be written as

$$\varepsilon_d = \alpha \varepsilon_r - \beta, \tag{6}$$

where

$$\alpha = \frac{V_{Lr} A_r}{V_{Ld} A_d} \tag{7}$$

and

$$\beta = \alpha - 1. \tag{8}$$

Equation (6) has the same form as many empirical correlations found in the literature (Table 1). Frequently, β has been neglected as being negligibly small, and eq. (6) has been simplified to

$$\varepsilon_d = \alpha \varepsilon_r. \tag{9}$$

Equation (9) is fundamentally flawed because a zero value of β implies an α-value of unity—an impossible situation because for $\varepsilon_d = \varepsilon_r$, the airlift reactor will cease to circulate and all the gas will disappear from the downcomer. Equation (9) is also inconsistent with the observation that the downcomer remains free of gas (that is, $\varepsilon_d = 0$) until some gas holdup has been built-up in the riser (Chisti *et al.*, 1995; Ganzeveld *et al.*, 1995). Indeed, a close inspection of some of the data expressed in the form of eq. (9) confirms that β does not equal zero as claimed. One clear example of this occurrence is the work of Bakker *et al.* (1993). A multitude of correlations such as eqs (6) and (9) are available as summarized in Table 1; however, most of those equations differ on the values of the parameters α and β. The only exception to the above forms of correlations was reported by Miyahara *et al.* (1986), who worked with draft-tube sparged concentric tube reactors of modest size. In all cases, the equations obtained by Miyahara *et al.* (1986) could be reduced to the general form

$$\varepsilon_d = \chi \varepsilon_r^n \tag{10}$$

where the parameter χ depended on the properties of the fluid and the geometry of the reactor, and n varied over the approximate range 0.8–4.2.

Table 1. Interrelationship between the riser and the downcomer gas holdups in airlift reactors

Reactor	Equation	System and Geometry	Reference
1. Annulus sparged concentric draft-tube reactors	$\varepsilon_d = 0.89\ \varepsilon_r$	Air–water $A_d/A_r = 0.13, 0.35$, or 0.56	Bello (1981)
2. Split-cylinder device	$\varepsilon_d = 0.997\ \varepsilon_r$	Air–water and air–salt solution (0.15 M sodium chloride) $A_d/A_r = 0.411$	Chisti (1989)
3. Draft-tube sparged internal-loop	$\varepsilon_d = (0.863 \pm 0.004)\varepsilon_r$	Air–salt solution (0.02 M potassium chloride) $A_d/A_r = 0.78$	Bakker *et al.* (1993)
4. Multiple internal-loop airlift	$\varepsilon_d = (0.875 \pm 0.006)\ \varepsilon_r$	Air–salt solution (0.02 M potassium chloride) $A_d/A_r = 0.31, 0.43, 0.91$	Bakker *et al.* (1993)
5. Draft-tube sparged internal-loop	$\varepsilon_d = 0.8\ \varepsilon_r(1 + 20d_p)\left(1 + \frac{W_S}{W_L}\right)^{-0.46}$	Suspensions of calcium alginate beads $\rho_S = 1030\ \mathrm{kg\,m^{-3}}$; $d_p = 1 - 3.6$ mm; loading $= 0$–30% vol.	Lu *et al.* (1995)
6. Split-cylinder internal-loop	$\varepsilon_d = 0.63\ \varepsilon_r - 0.0008$ $\varepsilon_d \geqslant 8 \times 10^{-4}$	Animal cell microcarriers in 0.1 M aqueous sodium chloride $\rho_S = 1030$–$1050\ \mathrm{kg\,m^{-3}}$; $d_p = 150$–$300\ \mu$m; 0–30 $\mathrm{kg\,m^{-3}}$ solids loading; $A_r/A_d = 1$; $U_{Gr} = (0$–$6.7) \times 10^{-3}\ \mathrm{m\,s^{-1}}$	Ganzeveld *et al.* (1995)
7. Draft-tube sparged internal-loop	$\varepsilon_d = c\varepsilon_r$ c depended on sparger hole diameter $0.770 \leqslant c \leqslant 0.798$ for $30 \leqslant \delta\ (\mu\mathrm{m}) \leqslant 1000$	Sea water. Sintered glass and perforated pipe spargers $A_d/A_r = 1$	Contreras (1996)
8. Split-cylinder internal-loop (liquid level below upper edge of baffle)	$\varepsilon_d = (0.889 + 2.972h_c)\varepsilon_r - 0.642h_c$ $h_c = \frac{h_b - h_L}{h_b}, \quad h_L < h_b$	Air–water $A_r/A_d = 2.44$ $h_c = 0.029 - 0.120$	Wenge *et al.* (1996)
9. External-loop reactors	$\varepsilon_d = 0.79\ \varepsilon_r - 0.057$	Air–water and aqueous salt solutions $A_r/A_d = 2.273, 4.000, 9.091$	Bello (1981)
10. External-loop reactors	$\varepsilon_d = 0.460\varepsilon_r - 0.024$	Air–water, air–salt solution (0.15 M sodium chloride), 1 and 2% (wt/vol) slurries of cellulose fibers in aqueous sodium chloride (0.15 M) $A_d/A_r = 0.25, 0.44$	Chisti (1989)

The parameters α and β supposedly depend on the geometry of the reactor (internal or external loop), the liquid and gas phases used, and the regime of operation. The α-values have normally ranged over 0.8–0.9 (Chisti, 1989). Lower values of α have been reported, but values equalling unity or higher have never been observed. As demonstrated below, an α value that is greater than unity is the only value that is theoretically correct.

Note that a constant value of α in a given reactor implies that the ratio V_{Lr}/V_{Ld} is not sensitive to the gas flow rate or the gas holdup in the riser. This appears to be the case over much of the operational range for internal-loop type of airlift reactors without especial gas–liquid separators. However, a constant V_{Lr}/V_{Ld} cannot be assumed generally; hence, in some cases the linear equation (6) could breakdown. This would happen mostly in airlift devices with gas–liquid separators. With an effective gas–liquid separator, the downcomer gas holdup will be nil, and eq. (6) will take the form

$$\varepsilon_r = 1 - \frac{1}{\alpha}. \tag{11}$$

Because the riser gas holdup must increase with increasing gas flow rate, the α value must increase, i.e., the V_{Lr}/V_{Ld} ratio will increase. In a reactor with no gas in the downcomer, the bounds of variation of α can be shown to be $0 \leqslant 1/\alpha \leqslant 1$.

When the V_{Lr}/V_{Ld} ratio varies little with gas flow rate, eq. (5) may be approximated as the solid straight line shown in Figure 1. This line has negative y-intercept. Note that the y-intercept can never be a positive number because this would imply a downcomer gas holdup value that is higher than the riser holdup. Therefore, the slope of the line, or the parameter α in eq. (6), must always be greater than unity albeit slightly. This is inconsistent with all the empirically determined correlations (Table 1) because they all yield α-values that are below one. Normally, the y-intercept has a low absolute value (in the order of 10^{-3}–10^{-4}). This means that α in eq. (6) can be very close to 1; however, the α value should not be less than one. In fact, eq. (9), with a α equal to 1 (which is the only theoretically possible value in this equation), is the upper limit of eq. (5). The lines representing eqs (9) and (5) will cross at the hypothetical extreme where $\varepsilon_r = \varepsilon_d = 1$ (A in Fig. 1). Therefore, any linear correlation relating ε_d and ε_r must have a slope greater than unity and a y-intercept lower than zero.

At ε_r-values just greater than at point B in Fig. 1 the gas begins to recirculate in the downcomer. At point B $\varepsilon_d = 0$, and from eq. (5), the riser gas holdup is given by

$$\varepsilon_r = 1 - \frac{V_{Ld}A_d}{V_{Lr}A_r}. \tag{12}$$

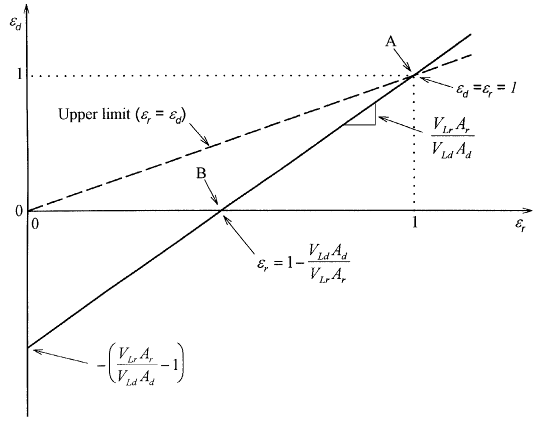

Fig. 1. Schematic representation of eq. (5).

Equation (12) provides the minimum value of the riser holdup that needs to be exceeded to obtain recirculation of gas into the downcomer. That a minimum or 'critical' value of ε_r should exist is consistent with the observations of Ganzeveld *et al.* (1995) and Wenge *et al.* (1996). With a higher value of riser holdup at point B, higher is the slope of the line and higher is the rate of increase of downcomer holdup. As seen in eq. (12), the value of the riser holdup needed to obtain recirculation of gas in the downcomer depends on the liquid velocity in the downcomer and the riser.

CONCLUSIONS

Based on the continuity principle, the gas holdups in the riser and downcomer of airlift reactors are related by the equation:

$$\varepsilon_d = \alpha\varepsilon_r - \beta.$$

In many cases α and β do not vary with gas flow rate; hence, a linear dependence is observed. The holdup in the downcomer is always lower than the value in the riser. The α-value is unity or greater and β is always lower than zero. Expressions of the form

$$\varepsilon_d = \alpha\varepsilon_r$$

are theoretically incorrect, but are often reported in the literature.

A. CONTRERAS
Y. CHISTI*
E. MOLINA

Department of Chemical Engineering
University of Almería
E-04071 Almería, Spain

NOTATION

A_d	cross-sectional area of the downcomer, m^2
A_r	cross-sectional area of the riser, m^2
c	dimensionless parameter
d_p	diameter of particle, m
g	gravitational acceleration, m s^{-2}
h_b	height of upper edge of baffle in split-cylinder airlift reactor, m
h_c	dimensionless baffle clearance above liquid level
h_L	height of gas-free liquid, m
n	parameter in eq. (10)
Q_{Lr}	liquid flow rate in the riser, m^3 s^{-1}
Q_{Ld}	liquid flow rate in the downcomer, m^3 s^{-1}
U_{Gr}	superficial gas velocity in the riser, m s^{-1}
U_{Ld}	superficial liquid velocity in the downcomer, m s^{-1}
U_{Lr}	superficial liquid velocity in the riser, m s^{-1}
V_{Ld}	linear liquid velocity in the downcomer, m s^{-1}
V_{Lr}	linear liquid velocity in the riser, m s^{-1}
W_L	total weight of liquid in the slurry, kg
W_S	total weight of solids in the slurry, kg

Greek letters

α	parameter in eq. (6)
β	parameter in eq. (6)
δ	sparger hole diameter, μm
ε_d	fractional gas holdup in the downcomer
ε_r	fractional gas holdup in the riser
χ	parameter in eq. (10)
ρ_S	density of solids, kg m^{-3}

REFERENCES

Bakker, W. A. M., van Can, H. J. L., Tramper, J. and de Gooijer, C. D. (1993) Hydrodynamics and mixing in a multiple airlift loop reactor. *Biotechnol. Bioengng* **42**, 994–1001.

---

*Corresponding author. Tel.: 34-950-215566; fax: 34-950-215484; e-mail: ychisti@ualm.es.

Bello, R. A. (1981) A characterization study of airlift contactors for application to fermentations. Ph.D. Thesis, University of Waterloo, Ontario, Canada.

Chisti, Y. (1989) *Airlift Bioreactors*, Elsevier, London.

Chisti, Y., Wenge, F. and Moo-Young, M. (1995) Relationship between riser and downcomer gas holdup in internal-loop airlift reactors without gas–liquid separators. *Chem. Engng J.* **57**, B7–B13.

Chisti, Y. (1998) Pneumatically agitated bioreactors in industrial and environmental bioprocessing: hydrodynamics, hydraulics and transport phenomena. *Appl. Mech. Rev.* **51**, 33–112.

Contreras, A. (1996) Caracterización de una columna de burbujeo con recirculación interna. Aplicación al cultivo de *Phaeodactylum tricornutum.* Ph.D. Thesis, University of Almería, Almería, Spain.

Ganzeveld, K. J., Chisti, Y. and Moo-Young, M. (1995) Hydrodynamic behaviour of animal cell microcarrier suspensions in split-cylinder airlift bioreactors. *Bioprocess Engng* **12**, 239–247.

Lu, W. J., Hwang, S. J. and Chang, C. M. (1995) Liquid velocity and gas holdup in three-phase internal loop airlift reactors with low-density particles. *Chem. Engng Sci.* **30**, 1301–1310.

Miyahara, T., Hamaguchi, M., Sukeda Y. and Takehashi, T. (1986) Size of bubbles and liquid circulation in a bubble column with draught tube and sieve plate. *Can. J. Chem. Engng* **64**, 718–725.

Wenge, F., Chisti, Y. and Moo-Young, M. (1996) Split-cylinder airlift reactors: hydraulics and hydrodynamics of a new mode of operation. *Chem. Engng Commun.* **155**, 19–44.