Fluid Dynamics of Airlift Reactors: Two-Phase Friction Factors

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Airlift loop reactors (ALR) are useful equipment in biotechnology in a wide range of uses, however their design is not a simple task since prediction of fluid dynamics in these reactors is difficult.

Most of the different strategies found in the literature in order to predict two main parameters, namely, gas holdup and liquid velocity, are based on energy or momentum balances. The balances include frictional effects, and it is not yet clear how to predict these effects.

Literature shows a great controversy about the value of friction coefficients and how they have to be calculated (Joshi et al., 1990; Young et al., 1991). The question is whether the values corresponding to one-phase flow are useful (Wallis, 1969), or the friction coefficient in the riser is quite different from that corresponding to single-phase flow.

Recently Young et al. (1991) have conducted one of the most complete studies, both theoretical and experimental, to appear in the literature. Their model uses only an empirical parameter, the frictional factor, f, in the riser and the downcomer. The values of this parameter are not easy to justify, not only for two-phase flow in the riser but also for one-phase flow in the downcomer. The experimental error is decisive in calculations used by the authors to determine f. As examples, they calculated the two-phase friction factor in the riser using a momentum balance (Their Eq. 70). One of the terms introduce the experimental gas holdup. The mean error in gas holdup determination is around 8.3%, while the term from which the friction factor is calculated never reaches a value of 5% of the gas holdup term. Hence small errors in the gas holdup determination have a decisive influence on the observed values of fictional factors. The liquid phase mechanical energy balance in the downcomer, their Eq. 80, contains five terms. The term from which the downcomer friction coefficient is obtained have a value lesser than 5% of the pressure difference term in any case. A small error in pressure determination introduces a high error in the friction coefficient.

Young et al. (1991) remark that there is substantial dependence of liquid velocity on radial coordinate of the riser. The influence of such dependence should be taken into account in order to obtain the frictional effects. Hsu and Dudukovic (1980) found two-phase friction factors for laminar flow close similar to one-phase liquid flow, whereas, the experimental values under turbulent flow were approximately twofold the single-phase values. Differences between experimental two-phase friction factors and calculated one-phase factors may be justified taking into account the liquid velocity profiles in the riser. Assuming a parabolic liquid velocity distribution ($n = \alpha = 2$), the kinetic energy term of the Bernouilli equation in a given section of the riser would be twofold higher than the value corresponding to flat profile. The frictional losses are expressed in linear dependence of the kinetic energy. If the kinetic energy is calculated in relation to the liquid or mixture mean average velocity and the α parameter is not introduced (flat profile), the calculated value is half of the true one and, hence, the observed friction factor is twofold higher than the true factor. Therefore, the friction factors obtained from the experimental data of Hsu and Dudukovic would be similar to the one-phase liquid flow if the liquid velocity profile is taken into account.

The objective of this article is to show how criteria corresponding to one-phase flow may be used in order to predict the frictional effects in ALRs. Based on a model proposed by García-Calvo (1989, 1991), we simulated experimental data of liquid velocity profiles and gas holdup obtained by Young et al. in an ALR with two different configurations.

Experimental data obtained in other three external ALRs with different shapes and sizes are also simulated.

Theory

The model proposed by García-Calvo (1989, 1991) contains the following energy balance:

$$\left|\begin{array}{c}\text{Energy input}\\ \text{due to isothermal}\\ \text{gas expansion, } E\end{array}\right| = \left|\begin{array}{c}\text{Energy dissipated}\\ \text{due to the net}\\ \text{liquid flow, } F\end{array}\right| + \left|\begin{array}{c}\text{Turbulent energy}\\ \text{dissipation due to}\\ \text{internal liquid}\\ \text{recirculation within}\\ \text{the riser, } W\end{array}\right| + \left|\begin{array}{c}\text{Friction losses}\\ \text{in the gas liquid}\\ \text{interface, } S\end{array}\right| \quad (1)$$

Table 1. Geometrical Details and Parameters for Simulation of Young et al. Data

Geometrical Parameters (m)	0.14-m Downcomer	0.089-m Downcomer
$H_r(H_d)$	1.94α (1.94)	1.94α (1.94)
D_r	0.19	0.19
D_d	0.14	0.089
Equivalent Lengths of Fittings (m)		
Riser entrance (standard tee, $90D_r$)	17.1	17.1
Enlargement at the bottom connection, $[(D_r/D_d)^2-1]^2\cdot 50\cdot D_r$	6.7	120.2
Riser-separator connection: standard tee, $90D_r$	17.1α	17.1α
Separator-downcomer connection: standard tee, $90D_d$	12.6	8.0
Square elbow in the downcomer	8.4	5.34
n[Eq. 2] dimensionless	1.72	2.18
α [Eq. 9] dimensionless	2.13	1.93
v_s ($m\cdot s^{-1}$)	0.20	0.20

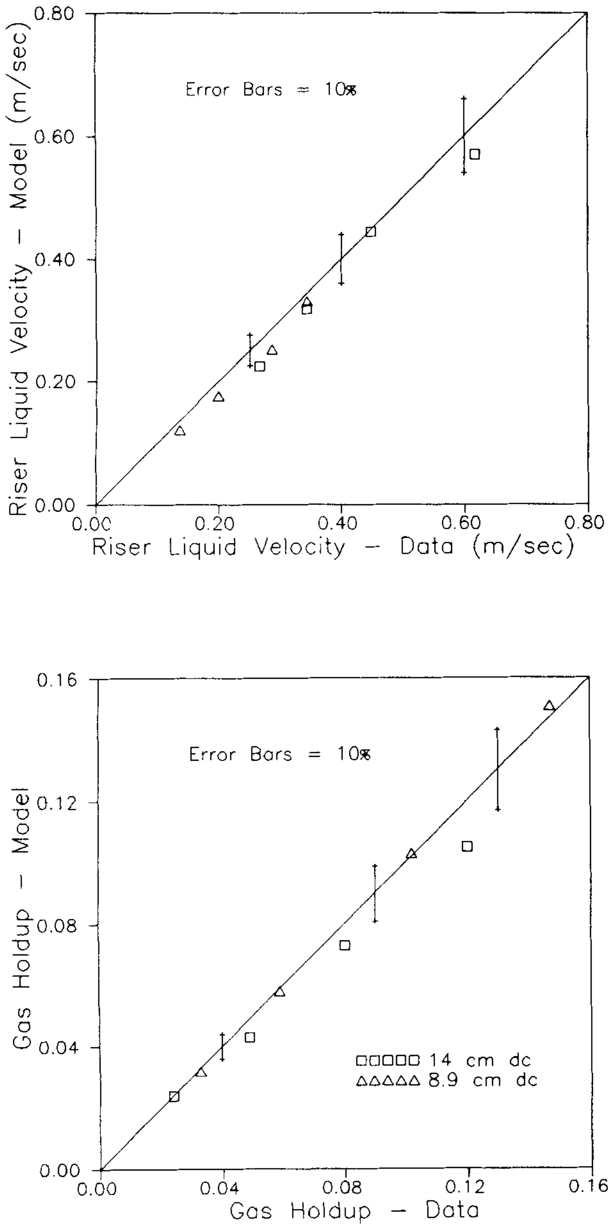

Figure 1. Measurements of Young et al. (1991) vs. model predictions.

The liquid velocity in a given point of the riser is calculated as an addition of the mean average velocity $\overline{V}_{Lr}$ and the local velocity coresponding to bubble column behavior (no net liquid flow) with parabolic profile. Most times, the profile parameter n is assumed as 2, however, Young et al. (1991) have found n values of 1.72 and 2.18. In order to take into account the different values of n, Eq. 2 is used:

$$\frac{V_{Lr}-\overline{V}_{Lr}}{V_{Lo}-\overline{V}_{Lr}}=1-2^{n/2}\left(\frac{r}{R}\right)^n \qquad (2)$$

Following the steps already commented (García Calvo, 1989, 1991), the following equations are then obtained:

$$PJ_G\ln\left(1+\frac{\rho_L g H_o}{P_a}\right)$$

$$=\frac{0.64(2)^{3n/2}n^3\rho_L H(V_{Lo}-\overline{V}_{Lr})^3}{D}\left(\frac{1}{2(3n-1)}+\frac{1}{3n+1}-\frac{2^{1/2}}{3n}\right)$$

$$+\frac{1}{2}K_{ft}\left(\frac{A_d}{A_r}\right)\rho_L J_{Ld}^3+v_s\rho_L g H_r\epsilon \qquad (3)$$

$$\epsilon_r=\frac{J_{Gp}}{\overline{V}_{Lr}+\frac{V_{Lo}-\overline{V}_{Lr}}{2(1-\epsilon)}\left(1-\frac{2}{n+2}\right)+v_s} \qquad (4)$$

$$\epsilon_r=\frac{K_{ft}J_{Ld}^2}{2gH_o} \qquad (5)$$

Introducing the friction losses in the separator and bottom connection as equivalent lengths of straight pipe in the riser or downcomer:

$$K_{ft}=K_{fr}\left(\frac{A_d}{A_r}\right)^2+K_{fd} \qquad (6)$$

where

$$K_f=4f\frac{L+\Sigma L_e}{D} \qquad (7)$$

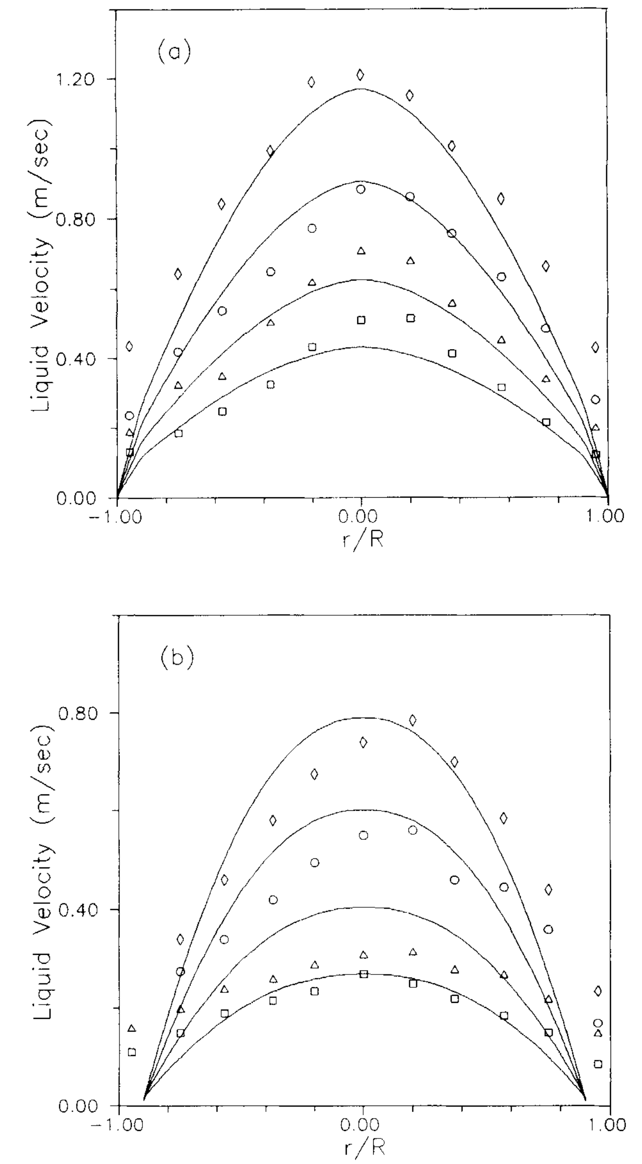

Figure 2. Riser liquid velocity profiles. Measurements of Young et al. (1991) vs. model predictions.

a) 0.14-m downcomer; b) 0.089-m downcomer.
Parameter is superficial velocity with values of 0.082/0.084, 0.047, 0.021, and 0.0097 $m\cdot s^{-1}$ from the top curve down.

Since the friction losses are calculated as a number of the kinetic energy K_f lost and Eqs. 3 and 5 contain the mean average liquid velocity, the radial variation of liquid velocity is taken into account multiplying the friction coefficient by the α parameter corresponding to the kinetic term of the Bernouilli equation. This is defined as:

$$\alpha = \frac{2\int_o^R [V_L(r)]^3 r dr}{(\overline{V}_{Lr})^3 R^2} \tag{8}$$

Liquid velocity profiles are different for one-phase flow (usually flat profile) and for two-phase flow (a parabolic profile is assumed). Clearly, the friction losses corresponding to fittings (enlargements and elbows, and so on) with two-phase flow as the separator entrance have to be calculated taken also into account the velocity profile.

For flat profile ($n=0$) the α value is 1. Most times the n value for parabolic profile is assumed 2, then $\alpha=2$. Generalizing:

$$\alpha = \frac{3(n+2)^3}{(n+1)[3(n+1)^2+2(n+1)-1]} \quad \text{for } n \neq 0 \tag{9}$$

Values of friction factors for both the riser, f_r, and downcomer, f_d, are calculated from the Blasius equation for one-phase flow:

$$f = 0.0791 Re^{-0.25} \tag{10}$$

Comparison With Experiment

We test the theory in detail by comparing with the data obtained by Young et al. (1991) for two ALR configurations. The mean gas holdup, the superficial velocity and velocity profiles of liquid in the riser are simulated taking into account the one-phase equivalent lengths of fittings. In order to simplify the calculation of equivalent length, the riser entrance, riser-separator and the separator-downcomer connections are assumed as standard tees with flow through the side ($L_e/D=90$). Other fittings are the enlargement in the riser entrance and a square elbow in the downcomer.

Table 2. Geometrical Details and Parameters for Simulation

Geometrical Parameters (m)	Verlaan et al.	Akita et al.	Onken and Weiland
$H_r(H_d)$	3.23α (3.23)	8.02α (8.02)	8.5α (8.5)
D_r	0.2	0.148	0.1
D_d	0.1	0.148	0.05
Equivalent Length of Fittings (m)			
Riser entrance (standard tee, 90 D_r)	18.0	13.3	9
Enlargement at the bottom connection	90.0	--	45.0
Riser-separator connection (standard tee)	18α	13.3α	9α
Separator-downcomer connection (standard tee)	9.0	13.3	4.5
Square elbow(s) in the downcomer	6.0	8.9	
$n=\alpha=2$ in any case			
$v_s=0.20\ m\cdot s^{-1}$			

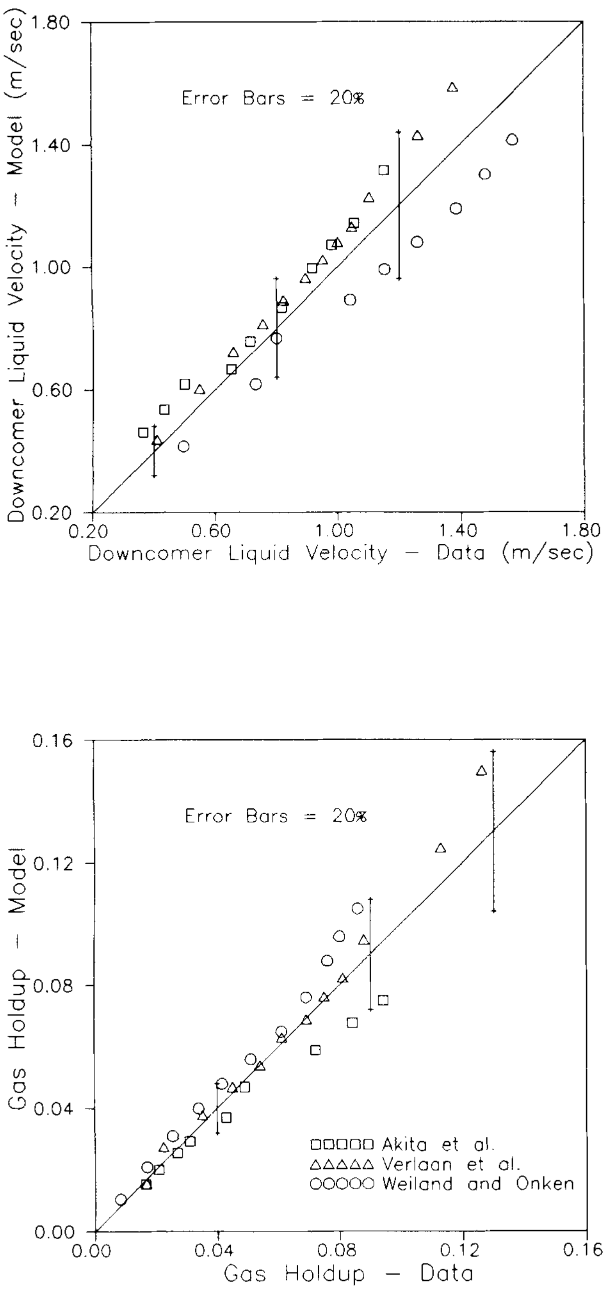

Figure 3. Experimental data vs. model predictions.

Parabolic profile of liquid velocity is assumed in the straight pipe of the riser and the riser-separator tee connection.

The authors have found a gas slip velocity roughly constant at approximately 0.20 $m \cdot s^{-1}$. This value is used in calculations.

Equations 3 to 7, 9 and 10 along with data of Table 1 are used to determine the gas holdup, the superficial liquid velocity and the liquid velocity in the center of the riser. Later Eq. 2 is used to simulate the liquid velocity profiles.

Figure 1 shows the agreement between computed values of gas holdup or riser liquid velocity and the experimental values obtained by Young et al. (1991). The model predicts experimental data with an error up to 12.5%.

Figure 2 shows the agreement between simulated and experimental liquid velocity profiles. Experimental values are the average of the lower and upper 0° port portals, they may be assumed as a mean value along the riser.

Liquid velocity profiles with 0.14m-downcomer are simulated with accuracy despite the complexity of the liquid movement. Differences between simulated and experimental values are higher for the ALR with 0.089 m-downcomer. Young et al. determined the accumulated measurement error using mass balances. They calculated the liquid flux through the riser by integration of the local velocities and comparing with the experimental values in the downcomer. The error is the deviation of the riser measurement from the dowcomer values. The error range for the large downcomer configuration was 4.5 to 10%, whereas the analogous result for the 0.089 m downcomer was 8.9 to 21%. This may explain the differences between experimental and simulated liquid velocity profiles.

Table 2 shows some parameters to introduce in the model equations for simulation of experimental data obtained in other three external loop reactors. In these cases, Eq. 2 is used with $n=2$ to calculate the liquid velocity profiles in the riser. This value is a good assumption for BC behavior (Kawase and Moo-Young, 1986).

In order to simplify the assumptions, the gas slip velocity was assumed to be 0.20$m \cdot s^{-1}$ in the three reactors, as Young et al. had found. Values between 0.20 and 0.25 $m \cdot s^{-1}$ are widely asssumed in literature. Provided that details about geometrical configuration of ALR are not widely described, we assume the same configuration for the three reactors and similar to that of Young et al. Again the riser entrance, riser-separator and separator-downcomer connections are assumed as standard tees with flow through the side. A standard elbow in the downcomer, and an enlargement in the bottom if the riser and downcomer diameters are different, are also assumed.

Table 2 shows the values of the main parameters to introduce in the model equations.

Figure 3 shows good agreement between experimental and simulated data despite the high number of simplifying assumptions used in the calculations.

Conclusions

This article shows how liquid velocity profiles and gas holdup may be simulated in a wide range of external ALR shape and sizes by the means of a fluid dynamic model (Garcia Calvo, 1989, 1991) based on an energy balance in which one-phase friction factors corrected to take into account the velocity profiles are introduced.

The present work also justifies, in contrast with the opinion of Young et al. (1991), the equivalent length of 92 m obtained by Merchuk and Stein (1981) from measures of pressure drop and the values of friction factors obtained by Hsu and Dudokovic (1981). Friction factors obtained by Young et al. and Akita et al. (1988) seem to be influenced by errors of pressure measurement.

Acknowledgment

The author gratefully acknowledges financial support from CJCYT and CAM.

Notation

A = cross-sectional area of flow channel, m^2
D = diameter, m

E = energy input rate, $W \cdot m^{-2}$
F = friction losses due to net liquid flow, $W \cdot m^{-2}$
f = frictional factor, dimensionless
g = gravitational acceleration, $m \cdot s^{-2}$
H = height, m
J = superficial velocity, $m \cdot s^{-1}$
K_f = frictional coefficient, dimensionless
L = length, m
n = exponent in Eq. 2, dimensionless
P = pressure, Pa
R = radius, m
r = radial coordinate, m
S = energy dissipation rate at the gas-liquid interface, $W \cdot m^{-2}$
$\underline{V}$ = linear velocity, $m \cdot s^{-1}$
$\bar{V}$ = mean average linear velocity, $m \cdot s^{-1}$
v_s = terminal bubble velocity, $m \cdot s^{-1}$
W = energy dissipation rate due to liquid recirculations in the riser, $W \cdot m^{-2}$

Greek letters

α = parameter in the kinetic term of Bernouilli equation, dimensionless
ϵ = gas holdup, dimensionless
ρ = density, $kg \cdot m^{-3}$

Subscripts

a = atmospheric
d = downcomer
e = equivalent
G = gas
L = liquid
p = middle point of the riser
r = riser
t = total
0 = at $r=0$

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Manuscript received Oct. 18, 1991, and revision received May 18, 1992.