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Dependence of slip velocity on operating parameters of air-lift bioreactors

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Abstract

In this study we analyzed the quality of local mixing in external loop air-lift bioreactors for two hydrodynamic regimes in terms of slip velocity. In particular, the effects of design and operating parameters (e.g., reactor geometry, superficial gas velocity and flow regime) on the slip velocity were determined. Several correlations found in the literature based on theoretical models of fluid flow and several semi-empirical and empirical correlations were examined and the applicability of all the proposed correlations was tested on available experimental data. The most accurate correlations for the prediction of the slip velocity in each bioreactor operating regime were identified. New correlations for homogeneous and heterogeneous flow regimes were developed. These correlations are among the most accurate and have increasing accuracy with increase of superficial gas velocity. They also give insight into how the change in geometry properties or gas flow will alter the slip velocity. This is very important in the design and optimization of air-lift bioreactors.

Keywords: Air-lift bioreactors; Hydrodynamics; Slip velocity correlations

1. Introduction

Biotechnology is currently a rapidly expanding field of interdisciplinary research. This is evident from the development of a number of new types of bioreactors. The traditional stirred-tank reactor is no longer *a priori* the standard bioreactor, mainly because of economic considerations and the intrinsic properties of the bio-phase used [1–6]. Air-lift bioreactors (ALR) are a relatively new type of fermentor, offering several advantages for large-scale aerobic bioprocesses, for animal and cell culture in particular. In many cases immobilized biocatalysts or microorganisms are used [16–18]. However, bio-phase could form complex aggregates in microcarrier matrixs [19]. The optimization of cell growth includes the optimization of micro-environmental conditions, i.e., saturated oxygen concentration and pH, as well as substrate concentration, and mass transfer. The quality of the local mixing pattern is an estimate of the optimal mass transfer conditions. Numerous investigations have been carried out on the mass transfer capability of air-lift contactors but the results so far do not yield much more than empirical correlations [1,2].

The principal goal of this study was to examine the influence of the reactor geometry on the mixing quality for two-phase systems. Slip velocity was used as a measure of local mixing quality. The various correlations proposed in the literature were considered for two-phase systems [4,7–9], which could be further modified and applied for three-phase systems, where often the third phase is immobilized biocatalysts or microorganisms. The main goal was to clarify which operation parameters and geometrical characteristics are of special importance for the ALR optimization.

2. Description of the system and equations

Hydrodynamics of two-phase, water–air systems have been examined in various geometries of ALR with external recirculation in laminar (homogenous) and heterogeneous flow regime. The set of geometrical characteristics of ALR are shown in Table 1.

Surface gas velocity is the major independent hydrodynamic parameter and is correlated with slip velocity. Experimentally obtained values of hydrodynamic parameters are shown in Table 2.

Experimental data were examined in order to determine the most accurate correlations for the prediction of slip velocity. The method of theoretical analysis includes determi-

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nation of hydrodynamic parameters from the experimental data [10–15].

Slip velocity prediction, for various flow regimes, is of major importance for better mass transfer realization and ALR optimization and could be used as a quantification of local mixing quality. Correlation of slip velocity with reactor geometry as well as hydrodynamic parameters would be useful.

Various slip velocity based models have been considered [4,7–9]. A general treatment of dispersed flow systems has been introduced [8], in which the relative velocity between phases is the essential parameter, as there is a difference between the real local relative velocity and that defined by

$$V_s = \frac{V_g}{\varepsilon} - \frac{V_l}{1-\varepsilon} \tag{1}$$

where V_s is the slip velocity, V_g the superficial gas velocity, V_l the superficial liquid velocity, and ε is the gas hold-up.

Correlations from the literature given in Table 3 were used for prediction of values of slip velocity. Predicted values were compared with the experimental data. Experimental data covered a wide range of hydrodynamic conditions and geometrical characteristics of reactors.

Slip velocity depends on flow regime, namely: (1) slowly decreases with increase of gas velocity, in the homogeneous regime (for gas velocity below 0.05 m/s); (2) increases with increase of gas velocity, in the heterogeneous regime (for gas

Nomenclature

A	cross-section (m^2)
C_1	parameter defined in drift flux model (m/s)
d	diameter (m)
H	height of reactor (m)
k	reactor parameter, Eq. (4) (s^2/m^2)
K_f	total friction coefficient
V	velocity (m/s)

Greek letters

ε	gas hold-up
ρ	phase density (kg/m^3)
σ	surface tension (kg/s^2)
υ	reactor volume (m^3)

Subscripts

b∞	single bubble terminal
d	downcomer
g	gas phase
l	liquid phase
M	gas liquid mixture
o	orifice
r	riser
s	slip

Table 1
Geometrical characteristics of experimental air-lift reactors

No.	References	υ (m^3)	H (m)	d_r (m)	d_d (m)	A_r/A_d	K_f	k (s^2/m^2)	Gas sparger
1	Merchuk and Stein [12]	0.3	4.05	0.14	0.14	1	11.2	0.143	Perforated plate $d_o = 0.025$ m
2	Bugarski [14]	0.3×10^{-3}	0.224	0.022	0.022	1	4.98	1.47	Sintered plate $d_o = 100–160$ μm
3	Bugarski [14]	1.0×10^{-3}	0.3	0.05	0.05	1	5.21	0.734	Sintered plate $d_o = 100–160$ μm
4	Milivojevic [13]	0.3×10^{-3}	0.224	0.022	0.022	1	4.98	1.47	Sintered plate $d_o = 100–160$ μm
5	Sajc et al. [15]	0.25×10^{-3}	0.27	0.027	0.017	2.25	3.22	3.86	Sintered plate $d_o = 100–160$ μm
6	Glennon et al. [11]	0.3	3.13	0.225	0.15	2.25	3.5	0.291	–
7	Glennon et al. [11]	0.055	4	0.1	0.05	4	4	0.818	–
8	Verlaan [16]	0.165	3.23	0.2	0.1	4	4.62	1.148	–
9	Verlaan [16]	0.165	3.23	0.2	0.1	4	1.82	0.469	–
10	Verlaan [16]	0.6	10.5	0.225	0.1	5.06	4.43	0.570	–
11	Garcia Calvo and Leton [10]	0.042	2.1	0.1	0.1	1	17.6	0.427	Sintered plate $d_o = 175$ μm
12	Garcia Calvo and Leton [10]	0.042	2.1	0.1	0.1	1	32	0.777	Sintered plate $d_o = 175$ μm

Table 2
Hydrodynamic regimes in experimental air-lift reactors

No.	References	V_g (m/s)	V_l (m/s)	ε_{gr}	$V_{b\infty}$ (m/s)	d_b (m)
1	Merchuk and Stein [12]	0.02–0.18	0.426–0.957	0.03–0.131	–	–
2	Bugarski [14]	0.0003–0.006	0.0397–0.1411	0.0025–0.0285	≈0.20	≈0.001
3	Bugarski [14]	0.0003–0.006	0.0607–0.2321	0.0027–0.0378	≈0.20	≈0.001
4	Milivojevic [13]	0.001–0.007	0.092–0.22	0.0122–0.0278	≈0.20	≈0.001
5	Sajc et al. [15]	0.002–0.012	0.0407–0.1052	0.0089–0.034	≈0.23	≈0.0025
6	Glennon et al. [11]	0.04–0.1	0.451–0.606	0.0583–0.1021	–	–
7	Glennon et al. [11]	0.04–0.1	0.313–0.402	0.0854–0.1333	–	–
8	Verlaan [16]	0.04–0.16	0.223–0.35	0.0607–0.1327	0.235	≈0.006
9	Verlaan [16]	0.02–0.175	0.283–0.538	0.075–0.1435	0.235	≈0.006
10	Verlaan [16]	0.02–0.1	0.247–0.379	0.0331–0.0959	0.235	≈0.006
11	Garcia Calvo and Leton [10]	0.015–0.045	0.293–0.387	0.0265–0.0387	–	–
12	Garcia Calvo and Leton [10]	0.015–0.045	0.201–0.280	0.0353–0.0858	–	–

Table 3
Various correlations proposed for slip velocity prediction in air-lift reactors

No.	Authors	Equations	Comments
1	van der Lans [8]	$V_s = V_{b\infty} + 0.2\frac{V_{lr}}{1-\varepsilon} + \frac{V_{gr}}{2}$	
2	Towell et al. [8]	$V_s = V_{b\infty} + 2V_{gr}$	
3	Wallis [8]	$V_s = V_{b\infty}(1 - \varepsilon)$	Homogenous flow
4	Gomezplata et al. [8]	$V_s = V_{b\infty}[1 - 0.73(1 - \varepsilon^{2.8})]$	Homogenous flow
5	van der Lans [8]	$V_s = V_{b\infty}\left[1 + \frac{\varepsilon}{1-\varepsilon}\right] + 0.2\frac{V_M}{1-\varepsilon}$	
6	Zuber and Findlay [9]	$V_s = 1.53\left(\frac{\sigma g \Delta\rho}{\rho_l^2}\right)^{1/4}$	Homogenous flow
		$V_s = 0.35\left(\frac{g\Delta\rho d_r}{\rho_l}\right)^{1/2}$	Bubble slug flow
7	Locktett and Kirkpatric [4]	$V_s = V_{b\infty}(1 - \varepsilon)^{1.39}(1 + 2.55\varepsilon^3)$	
8	Joshi et al. [4]	$V_s \approx C_l$	C_1 given graphically maximum error 17%
9	Garcia Calvo [7]	$V_s = 0.25$ m/s	
10	Turner [8]	$V_s = V_{b\infty}$	

velocity over 0.05 m/s). Garcia Calvo [7] used a constant value of slip velocity of 0.25 m/s for liquid–gas systems. Zuber and Findlay [9] proposed the value of 0.30 m/s for homogeneous flow regime independent of surface gas velocity. For heterogeneous flow regime, slip velocity depends on reactor geometry. The value of 0.40 m/s is proposed for reactor diameter of 0.14 m [9].

3. Results

Proposed correlations for slip velocity prediction were compared with experimental data in various flow regimes in order to determine the most accurate equation in each regime. Our model equation is based on Eq. (1) which for low gas hold-ups can be simplified to

$$V_s = \frac{V_g}{\varepsilon} - V_l \tag{2}$$

In this equation gas hold-up and liquid superficial velocity can be correlated with equations from the literature that we found in a previous work to be among the most accurate [13]. For gas hold-up this is the well-known balance equation:

$$\varepsilon = \frac{K_f V_l^2}{2gH}\left(\frac{A_r}{A_d}\right)^2 = kV_l^2 \tag{3}$$

with

$$k = \frac{K_f}{2gH}\left(\frac{A_r}{A_d}\right)^2 \tag{4}$$

For prediction of the superficial liquid velocity Glennon et al. [11] proposed an equation that we have found to give good results for different regimes and geometries [13]:

$$V_l = ak^{-b}V_g^c \tag{5}$$

where $a = 1.017$, $b = 0.409$, $c = 0.42$ for $V_g < 0.05$ m/s and $a = 0.375$, $b = 0.427$, $c = 0.315$ for $V_g > 0.05$ m/s.

Based on Eqs. (1)–(5) our model equation has two different expressions:

(1) for $V_g < 0.05$ m/s (homogeneous flow):

$$V_s = V_g^{0.16}\left(\frac{0.967}{k^{0.182}} - 1.017k^{-0.409}V_g^{0.26}\right) \tag{6}$$

(2) for $V_g \geq 0.05$ m/s (heterogeneous flow):

$$V_s = V_g^{0.315}\left(\frac{1.851V_g^{0.055}}{k^{0.146}} - 0.735k^{-0.427}\right) \tag{7}$$

where V_g is the superficial gas velocity and the k parameter is a function of reactor geometry as defined by Eq. (4).

Slip velocity is dependent on two parameters, superficial gas velocity and the k parameter, which incorporates geometrical characteristics of the reactor. Calculated slip velocity as a function of V_g in the homogeneous regime, for various values of k is shown in Fig. 1.

Fig. 1 shows that the slip velocity for constant value of the parameter k first increases, reaches maximum and further slowly

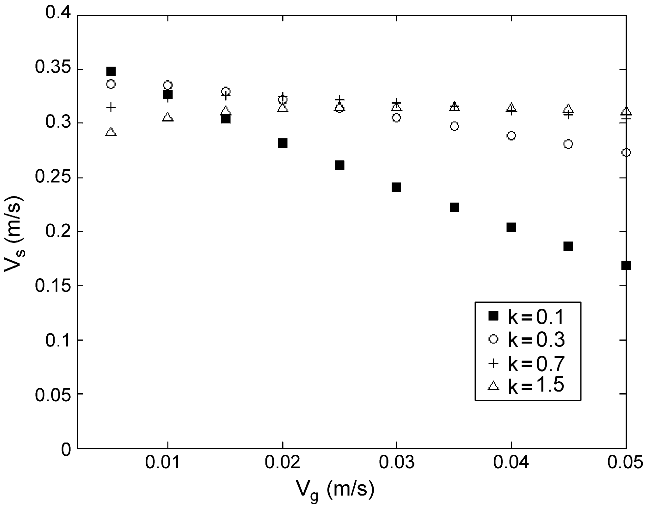

Fig. 1. Slip velocity as a function of the superficial gas velocity for various values of the parameter k in the homogeneous regime.

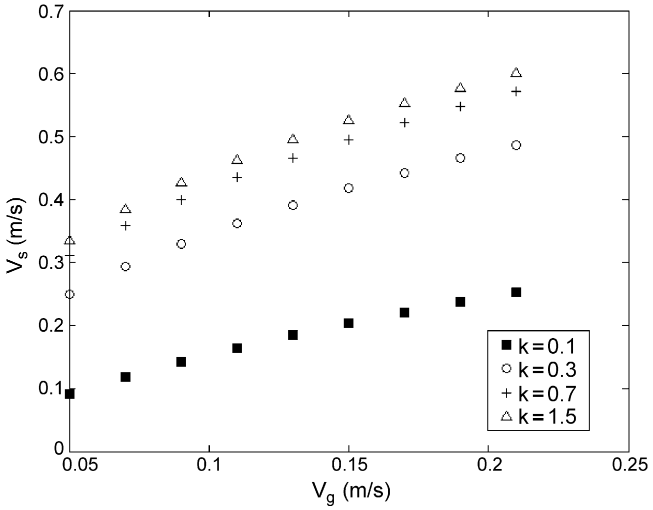

Fig. 2. Slip velocity as a function of the superficial gas velocity for various values of the parameter *k* in the heterogeneous regime.

decreases. This behavior is more pronounced at lower values of the parameter *k*, where the slip velocity reaches a maximum for lower gas velocities. Also it can be seen that, for *k* larger than 0.3, slip velocity is almost constant with a value around 0.3 m/s. This is in good agreement with the value of 0.25 m/s Garcia Calvo [7] recommended for slip velocity in the homogeneous regime, and the value of 0.3 m/s Zuber and Findlay [9] found in air-weather systems. Slip velocity decreases with increase of the superficial gas velocity, which is in accordance with the findings of Joshi at al. [4], and Merchuk and Stein [12]. Analyzing Eq. (6) we also found that slip velocity is less sensitive to superficial gas velocity change for values of *k* higher than about 1.

Table 4
Comparison of the predictions of the various models with experimental data

Flow regime	Most accurate equations	Relative error (%)
$V_g < 0.01$ m/s	(1) Towell et al. [8]	0.6
	(2) van der Lans (Eq. (1)) [8]	6.2
	(3) van der Lans (Eq. (5)) [8]	6.3
	(4) Joshi et al. [4]	11.6
	(5) Wallis [8]	13.8
	(6) Lockett and Kirkpatric [4]	14.6
0.01 m/s $< V_g <$ 0.05 m/s	(1) Lockett and Kirkpatric [4]	33.0
	(2) Wallis [8]	33.3
	(3) Our correlation (Eqs. (6) and (7))	35.0
	(4) Joshi et al. [4]	35.1
	(5) Garcia Calvo [7]	36.4
0.05 m/s $< V_g <$ 0.10 m/s	(1) Garcia Calvo [7]	30.6
	(2) Our correlation (Eqs. (6) and (7))	30.8
	(3) Joshi et al. [4]	32.3
	(4) Zuber and Findlay (slug flow) [9]	37.8
	(5) Wallis [8]	37.9
$V_g >$ 0.10 m/s	(1) Our correlation (Eqs. (6) and (7))	25.1
	(2) Zuber and Findlay (slug flow) [9]	34.4
	(3) Joshi et al. [4]	44.1
	(4) Garcia Calvo [7]	44.9

Calculated slip velocity as a function of V_g in the heterogeneous regime, for various values of *k* is shown in Fig. 2.

Slip velocity increases with increase of the superficial gas velocity, which is also in accordance with the results of Joshi at al. [4], and Merchuk and Stein [12]. Slip velocity increases with increase of the parameter *k* with constant V_g and this increase is more pronounced for *k* lower than 0.5.

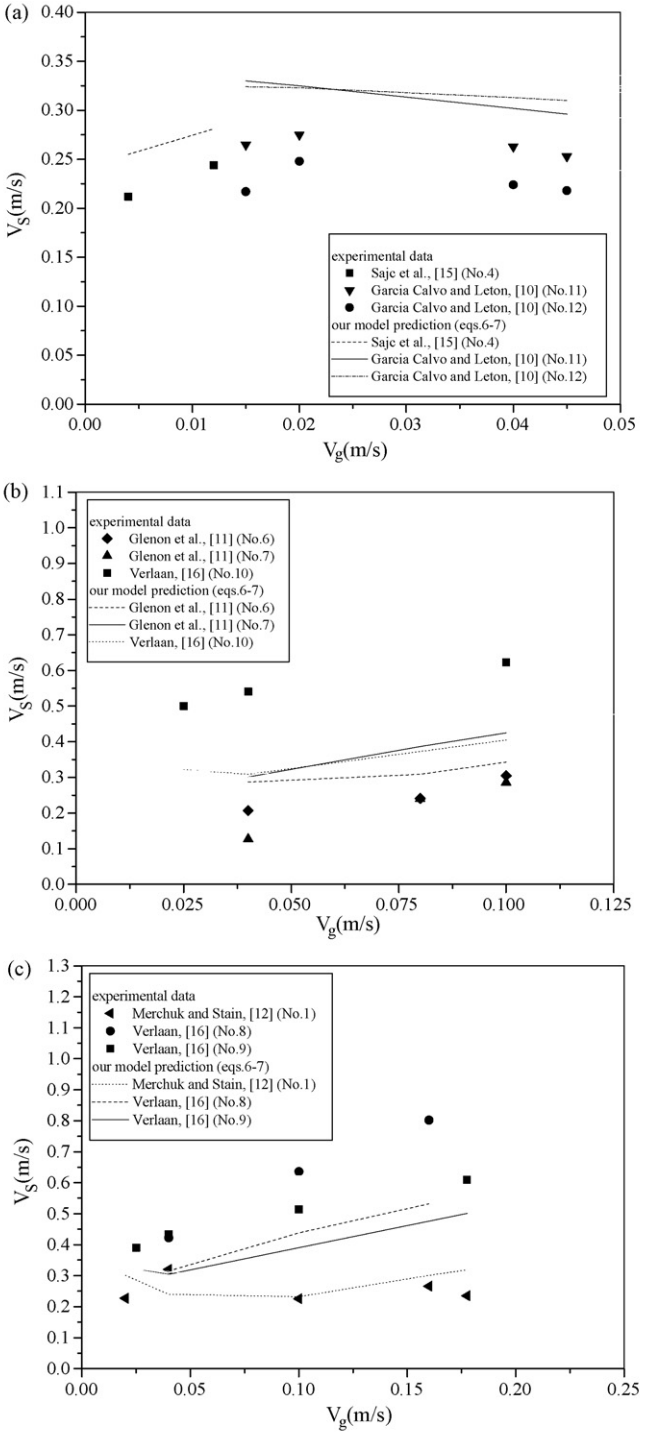

Fig. 3. (a) The data for which the maximal superficial gas velocity is $V_g = 0.05$ m/s. (b) The data with the maximal $V_g = 0.1$ m/s. (c) The data with the maximal $V_g = 0.2$ m/s.

It should be noted that there is a discontinuity in the calculated values of slip velocity with the change of the flow regime. For the same values of k and for gas velocity of 0.05 m/s we get different values of slip velocity with Eqs. (6) and (7). This discontinuity is due to the equations of Glennon et al. [11]. incorporated in our model equations.

The correlations for slip velocity presented in Table 3, as well as our correlations were tested with the experimental data. The listed correlations and the corresponding mean relative errors at different regimes are given in Table 4.

Analysis of the results listed in Table 4 shows that in the homogenous regime a number of correlations could be used for slip velocity prediction. The main reason for this is the fact that in the homogenous regime slip velocity has a value of about 0.25 m/s (±20%). Also, for the heterogeneous regime and reactors with diameters less than 0.14 m slip velocity does not vary much from this value. Larger deviations from this value are found only for reactors that operate in the heterogeneous regime and have diameter greater than 0.14 m or ratio of riser to down-comer area greater than 2.5. For this reason, slip velocity prediction is complicated and less accurate for these reactors, especially if they operate in the heterogeneous regime with larger gas superficial velocities. In this case the predicted values could be used only at the lower limit of slip velocity.

Fig. 3 shows experimental values of slip velocities for different reactor geometries and gas velocities. It can be seen that it is

Table 5
Comparison of slip velocities calculated by our correlations with experimentally measured ones

Experimental data and geometrical characteristics of reactors	V_g (m/s)	V_s^{exp} (m/s)	V_s^{mod} (m/s)	Relative error (%)
(1) Merchuk and Stein [12], $d_r = d_d = 0.14$ m, $H = 4.05$ m, $\upsilon = 0.3$ m^3, $K_f = 11.2$, $A_r/A_d = 1$, $k = 0.143$	0.02	0.227	0.301	+32.6
	0.04	0.320	0.240	−25.0
	0.1	0.225	0.232	+3.1
	0.16	0.266	0.301	+13.2
	0.18	0.235	0.319	+35.7
(2) Bugarski [14], $d_r = d_d = 0.022$ m, $H = 0.224$ m, $\upsilon = 0.3$ dm^3, $K_f = 4.98$, $A_r/A_d = 1$, $k = 1.47$	0.0003	0.080	0.241	+201.3
	0.003	0.102	0.303	+197.1
	0.006	0.065	0.317	+387.7
(3) Bugarski [14], $d_r = d_d = 0.05$ m, $H = 0.3$ m, $\upsilon = 1.0$ dm^3, $K_f = 5.23$, $A_r/A_d = 1$, $k = 0.734$	0.0003	0.050	0.217	+334
	0.003	0.042	0.280	+567
	0.006	−0.086	0.296	+444
(4) Milivojevic [13], $d_r = d_d = 0.022$ m, $H = 0.224$ m, $\upsilon = 0.3$ dm^3, $K_f = 4.98$, $A_r/A_d = 1$, $k = 1.47$	0.001	−0.010	0.275	+2850
	0.004	0.015	0.309	+1960
	0.007	0.032	0.319	+1100
(5) Sajc et al. [15], $d_r = 0.027$ m, $d_d = 0.017$ m, $H = 0.27$ m, $\upsilon = 0.25$ dm^3, $K_f = 3.22$, $A_r/A_d = 2.52$, $k = 3.86$	0.004	0.212	0.255	+6.1
	0.008	0.244	0.281	+15.2
(6) Glennon et al. [11], $d_r = 0.225$ m, $d_d = 0.15$ m, $H = 3.13$ m, $\upsilon = 0.3$ m^3, $K_f = 3.5$, $A_r/A_d = 2.25$, $k = 0.291$	0.04	0.207	0.287	+38.6
	0.08	0.241	0.309	+28.2
	0.1	0.305	0.343	+12.5
(7) Glennon et al. [11], $d_r = 0.1$ m, $d_d = 0.05$ m, $H = 4.0$ m, $\upsilon = 0.055$ m^3, $K_f = 4$, $A_r/A_d = 4$, $k = 0.818$	0.04	0.127	0.314	+147
	0.08	0.240	0.387	6+1.3
	0.1	0.286	0.425	+48.6
(8) Verlaan [16], $d_r = 0.2$ m, $d_d = 0.1$ m, $H = 3.23$ m, $\upsilon = 0.165$ m^3, $K_f = 4.62$, $A_r/A_d = 4$, $k = 1.148$	0.04	0.422	0.315	−22.4
	0.1	0.636	0.438	−31.1
	0.16	0.802	0.532	−33.7
(9) Verlaan [16], $d_r = 0.2$ m, $d_d = 0.1$ m, $H = 3.23$ m, $\upsilon = 0.165$ m^3, $K_f = 1.82$, $A_r/A_d = 4$, $k = 0.469$	0.025	0.390	0.321	−17.7
	0.04	0.433	0.304	−29.8
	0.1	0.514	0.390	−24.1
	0.18	0.609	0.501	−17.7
(10) Verlaan [16], $d_r = 0.225$ m, $d_d = 0.1$ m, $H = 10.5$ m, $\upsilon = 0.6$ m^3, $K_f = 4.43$, $A_r/A_d = 5.06$, $k = 0.570$	0.025	0.500	0.322	−35.6
	0.04	0.541	0.309	−42.9
	0.1	0.632	0.405	−35.9
(11) Garcia Calvo and Leton [10], $d_r = d_d = 0.1$ m, $H = 2.1$ m, $\upsilon = 0.042$ m^3, $K_f = 17.6$, $A_r/A_d = 1$, $k = 0.427$	0.015	0.265	0.330	+24.5
	0.02	0.275	0.325	+18.2
	0.04	0.263	0.302	+14.8
	0.045	0.253	0.296	+17.0
(12) Garcia Calvo and Leton [10], $d_r = d_d = 0.1$ m, $H = 2.1$ m, $\upsilon = 0.042$ m^3, $K_f = 32$, $A_r/A_d = 1$, $k = 0.777$	0.015	0.217	0.324	+49.3
	0.02	0.248	0.323	+30.2
	0.04	0.224	0.313	+39.7
	0.045	0.218	0.310	+42.2

impossible to correlate slip velocity with a one-parameter model. Lines represent values of slip velocity predicted by our model. Results of Bugarski [3] and Milivojevic [13] were not included in Fig. 3 because these experiments were carried out with very low values of gas velocities. This regime of gas velocities gives slip velocities below 0.1 m/s and could not be predicted by our or other correlations except by the correlation of Gomezplata et al. [8], which was originally developed for similar working conditions.

In Table 5 the experimental slip velocity values are compared with those predicted by our model. These values were used in Fig. 3. Also, the values of the reactor geometry characteristics are given.

Detailed analysis of the data presented in Fig. 3 and listed in Table 5 shows that the data of Glennon et al. [11] for a 0.055 m^3 reactor are markedly lower than predicted. This is probably due to the low value of reactor diameter ($d_r < 0.14$ m). Also the results of Verlaan are all markedly higher than the predicted values. This could be explained by the large values of both, reactor diameter ($d_r > 0.14$ m) and riser to downcomer area ratio ($A_r/A_d \geq 4$). This combination enhances bubble coalescence and homogeneous regime could not be achieved even at low gas velocities. Also, Verlaan's data confirm that in the heterogeneous regime larger values of k give larger slip velocities. The results of Garcia Calvo and Leton [10] and Glennon et al. [11] confirm that in the homogeneous regime lower values of k give larger slip velocities for lower V_g.

Generally, the choice of the correlation for slip velocity predictions depends on the regime. There is no particular correlation suitable for all regimes. The most accurate ones are Joshi et al. [4], Garcia Calvo [7], Wallis [8] and our correlations (Eqs. (2)–(4)). For reactors with riser diameter larger than 0.14 m, and riser to downcomer area ratio larger than 4, the correlation of Towell et al. [8] gives good results, since it was developed for reactors with larger riser diameters. Our correlation also give good results for those cases.

4. Discussion and conclusions

Slip velocity plays the major role in bioreactor optimization. Higher value of slip velocity ensures better mixing quality and mass transfer conditions. Effects of design and operating parameters (i.e., reactor geometry, design of the gas sparger, superficial gas velocity and flow regime) on the slip velocity were analyzed. Higher value of slip velocity could be realized with:

(1) higher values of superficial gas velocity in the heterogeneous regime,
(2) downcomer to riser cross-section ratio higher than 4,
(3) reactor diameter larger than 0.14 m,
(4) lower values of k parameter in the homogeneous regime.

From Figs. 1 and 2, it can be seen that in the homogeneous regime it is better to work with lower values of V_g, if we can achieve values of k less than say, 0.3, and if not it is better to work with higher V_g and k. In the homogeneous regime, for values of k lower than 0.5, it is easier to achieve large slip velocities by increasing k than with increasing V_g. For values of k larger than 1, further increase of k would not give significant increase in slip velocity.

Several correlations found in the literature based on theoretical models of fluid flow, and several semi-empirical and empirical correlations were tested and the applicability of all the proposed correlations was tested with available experimental data. The most accurate correlations for the prediction of the slip velocity in each bioreactor operating regime were pointed out.

We developed the model equations for homogeneous and heterogeneous flow regimes based on superficial gas velocity and geometrical parameters of the reactor. Our correlations are among the most accurate and have increasing accuracy with increase of superficial gas velocity. They also give insight in how the change in the geometrical characteristics or gas flow will alter the slip velocity. This is very important for the design and optimization of ALR.

The proposed model could be further used for prediction of the slip velocity in three-phase systems. It could be extended for three-phase systems by correlating the total friction coefficient K_f and the coefficients a, b and c in Eq. (5) with solid phase hold-up.

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