SLIP VELOCITY AND HYDRODYNAMIC PARAMETERS IN LIQUID-LIQUID SPRAY COLUMNS

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An empirical correlation for the prediction of slip velocity in liquid-liquid spray columns, which includes a dimensionless group containing the interfacial tension, is presented. Good agreement between experimental and predicted values of slip velocity is obtained over a wide range of dispersed phase hold-up (0·97—36·2%) and Reynolds number (58—1 067).

While the liquid-liquid spray column cannot compete with the efficient extractors now used in industry, it provides a suitable standard for checking hypothetical models and theoretical principles. However, the operation of a spray column with a dense packing of drops and high dispersed phase hold-ups might make it attractive for both extraction and heat transfer. Knowledge of hydrodynamic parameters such as drop size, dispersed phase hold-up and axial dispersion coefficient is necessary for the design and scale-up of liquid-liquid columns.

The literature contains a number of empirical and semi-theoretical correlations for the prediction of slip velocity in spray column but no general hydrodynamic equation was found.

Numerous investigators have proposed empirical correlations for the motion of single liquid drops falling down a continuous medium. Kumar[1] has described the mentioned correlations for the terminal velocities of single drops.

In the spray column the basic hydrodynamic parameters for counter-current flow are connected by the general flow equation

$$V_s = V_d/\varepsilon + V_c/(1 - \varepsilon)\,. \qquad (1)$$

On the other hand, the slip velocity is a function of drop size, physical properties of liquid-liquid system and dispersed phase hold-up.

There have been many attempts to relate the slip velocity to the hold-up. Kumar and Hartland[2] described various solutions of the function of slip velocity on hold-up. Pilhofer[3] developed the following equation to correlate the slip velocity in spray column:

$$V_{sd}\varrho_c/\mu_c = 3wq^2\varepsilon/\{(1 - \varepsilon)\, q^3 C_1\}\, [\{C_1 q^3 Ar(1 - \varepsilon)^3/(54(wq^2\varepsilon)^2 + 1)\}^{0.5} - 1]\,. \qquad (2)$$

Kumar, Vohra and Hartland[4] presented a simple equation for the estimation of slip velocity and hold-up in gravity settlers in the following form

$$V_s^2/(dg) = 2{\cdot}725(\Delta\varrho/\varrho_c)\,[(1-\varepsilon)/(1+\varepsilon^{1/3})]^{1.834}\,. \qquad (3)$$

This equation predicts the slip velocity for the dispersed phase hold-up (0·01 to 0·75) and Reynolds number (7 to 2 450).

Kumar and Hartland[2] presented an empirical expression for the prediction of the dispersed phase hold-up and slip velocity in droplet dispersions settled under gravity, as follows:

$$4dg\,\Delta\varrho(1-\varepsilon)/3\varrho_c V_s^2(1+4{\cdot}56\varepsilon^{0.75}) = 0{\cdot}53 + 24\mu_c/(V_s d\varrho_c)\,. \qquad (4)$$

Good agreement between experimental and predicted values of slip velocity is obtained for the dispersed phase hold-up in this range (0·01 to 0·76) and Reynolds number (0·61 to 3 169).

THEORETICAL

The interfacial tension significantly influences the single drop terminal velocities at intermediate and high Reynolds numbers[2]. The purpose of this paper is to investigate the effect of interfacial tension on slip velocity in droplet dispersion in liquid–liquid spray column. In order to improve the correlation for slip velocity developed by Kumar et al.[4], Eq. (3) was redefined by adding a dimensionless group containing the interfacial tension.

Table I gives the physical properties and Table II the operating conditions of 9 liquid–liquid systems from 6 different sources. Marquardt's algorithm[5] was used to calculate the constants in new correlation for the data sources in Table I and II. The final form of the new correlation is

$$V_s^2/(dg) = 4{\cdot}436(\Delta\varrho/\varrho_c)^{1.135}\,[(1-\varepsilon)/(1+\varepsilon^{1/3})]^{2.729}\,(V_d^2 d_N\,\Delta\varrho/\sigma)^{-0.018} \qquad (5)$$

RESULTS AND DISCUSSION

Table III compares the slip velocity values predicted by different correlations in terms of average percentage deviation. It can be seen from Table III that average values of γ for the correlation by Pilhofer[3], Kumar et al.[4] and Kumar and Hartland[2] are 17·3%, 11·9% and 10·8%, respectively, whereas that for Eq. (5) is only 9·6%. Good agreement between experimental and predicted values of slip velocity by Eq. (5) is obtained over a wide range of hold-up (0·0097 to 0·362) and Reynolds number (58 to 1 067).

TABLE I

Physical properties of systems investigated

Source	System	Phases dispersed/continuous	ϱ_d kg/m^3	ϱ_c kg/m^3	μ_d mPa s	μ_c mPa s	σ mN/m
Perrut[6]	1	heptane/water	683·0	1 000·0	0·42	1·00	50·0
	2	DMSO[a]/heptane	1 060·0	722·0	2·20	0·44	6·0
Hupfauf[7]	3	spindle oil/water	804·7—807·2	993·6—995·3	1·658—1·839	0·729—0·814	28·2—29·9
Horvath[8]	4	o-xylene/water	880·2	998·96	0·81	1·00	30·7
Berger[9]	5	*o*-xylene/water	879·6	998·2	0·8235	1·00	40·0
	6	toluene/water	865·8	998·2	0·5829	1·01	34·3
	7	MIBK[b]/water	805·0	995·75	0·615	1·07	10·2
Ugarčić[10]	8	*o*-xylene/water	881·0	1 000·0	0·81	1·00	30·7
Sovilj, Matejašev[11]	9	toluene/water	872·5	998·0	0·615	1·002	36·0

[a] DMSO dimethyl sulfoxide; [b] MIBK methyl isobutyl ketone.

TABLE II
Operating conditions of systems investigated

Source	System	D mm	d_N mm	d mm	ε	V_d mm/s	V_s mm/s	Re_m
Perrut[6]	1	50·0	1·05	1·80—2·35	0·1300—0·3200	8·7—15·9	52·1—72·3	117—154
	2	50·0	1·05	2·00—2·50	0·1850—0·3000	12·4—17·3	68·0—97·8	251—395
Hupfauf[7]	3	100·0	4·00	6·30—6·80	0·0338—0·2027	4·3—16·5	88·5—131·1	764—1 067
Horvath[8]	4	104·4	1·00	2·56—5·28	0·0097—0·2033	1·1—5·5	40·0—172·7	109—745
Berger[9]	5	75·2	1·00	3·00—4·84	0·0188—0·1740	0·8—5·0	45·1—88·8	135—423
	6	75·2	1·00	2·52—4·99	0·0253—0·2265	2·2—9·8	32·7—104·6	105—467
	7	75·2	1·00	2·31—3·08	0·0326—0·2300	2·8—9·4	54·6—103·4	122—266
Urgačić[10]	8	101·5	1·07	2·08—2·73	0·0310—0·3620	2·8—6·6	28·1—101·5	58—277
Sovilj, Matejašev[11]	9	100·0	1·50—2·00	3·05—4·03	0·0497—0·1287	4·4—6·4	49·2—90·4	170—324

Fig. 1 shows the comparison of slip velocity calculated from Eq. (*5*) with experimental data for some of the systems analyzed in this paper. Sixty-five percent of the predicted slip velocities lie within ±10% and 88% within ±20% of the experimentally observed values.

TABLE III

Comparison of different correlations for prediction of slip velocity in terms of average percentage deviation, γ, %

Source	System	No. of data points	Pilhofer[3]	Kumar et al.[4]	Kumar and Hartland[2]	Eq. (*5*)
Perrut[6]	1	7	20·0	16·9	8·2	10·2
	2	5	11·0	12·1	11·2	9·8
Hupfauf[7]	3	18	4·7	8·4	11·2	5·3
Horvath[8]	4	104	18·4	11·6	7·6	7·9
Berger[9]	5	23	31·4	13·1	11·0	12·8
	6	20	23·2	12·2	10·1	10·0
	7	26	12·0	4·7	7·4	4·8
Ugarčić[10]	8	47	11·0	12·6	15·5	11·8
Sovilj, Matejašev[11]	9	36	20·3	17·0	16·7	15·1
Totals or *means*		*286*	*17·3*	*11·9*	*10·8*	*9·6*

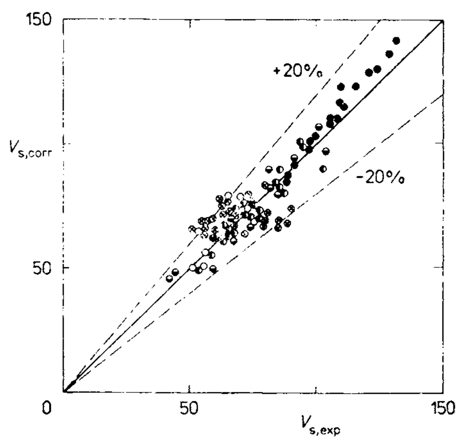

FIG. 1

Comparison of slip velocity calculated from Eq. (*5*) with experimental data for the different systems (V_s, mm s^{-1}). ○ Perrut[6], system 1; ● Hupfauf[7], system 3; ◒ Berger[9], system 6; ◐ Berger[9], system 7; ⊗ Sovilj, Matejašev[11], system 9

LIST OF SYMBOLS

Ar	Archimedes number, $Ar = \Delta\varrho g d^3 \varrho_c/\mu_c^2$
Ar_G	Archimedes number at $C_D We P^{0.15} = 70$, $Ar_G = 371{\cdot}9 P^{0.275}$
C_D	drag coefficient for a single sphere, $C_D = 4\,\Delta\varrho g d/(3\varrho_c U)$
C_I	inertial drag coefficient for a single sphere, $C_I = (1/8)\,(C_D - 24/Re)$; $C_I = (1/8)\,(C_D - 24/Re)\,[1 - \varepsilon^{1.29}\{(Ar - Ar_G)/Ar_G\}^{-1.74}]$ for $\mu_d > \mu_c$ and $C_D We P^{0.15} > 70$
D	column diameter
d	average drop diameter
d_N	nozzle or hole diameter
g	acceleration due to gravity
P	physical property group of Hu and Kintner, $P = \varrho_c^2 \sigma^3/(g\mu_c^4\,\Delta\varrho)$
q	tortuosity factor
Re	Reynolds number, $Re = U d \varrho_c/\mu_c$
Re_m	modified Reynolds number, $Re_m = V_s d \varrho_c/\mu_c$
U	terminal velocity with no wall effect
V_c	superficial velocity of dispersed phase
V_d	superficial velocity of continuous phase
V_s	slip velocity defined by Eq. (*1*)
w	cross section factor
We	Weber number, $We = V_d^2 d \varrho_c/\sigma$
γ	average percentage deviation
$\Delta\varrho$	density difference between phases
ε	dispersed phase hold-up
μ_c, μ_d	continuous and dispersed phase viscosity, respectively
ϱ_c, ϱ_d	continuous and dispersed phase density, respectively
σ	interfacial tension

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