BACK FLOW BETWEEN STAGES IN BUBBLE-TYPE REACTORS*

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A relation is derived for the back flow in bubble-type sieve plate, multistage reactors with downcomers. The derivation is based on the character of bubbled bed in the stage and has been verified experimentally on a three-stage column 297 mm in diameter with the water–air system.

An important parameter for the flooded bubbled multistage flow reactor is the coefficient of liquid backmixing between stages in the column. The backmixing intensity affects directly the liquid residence time distribution in the reactor and thus the resulting conversion of the chemical reaction. As a small attention has been paid until now to flooded bubble-type plate reactors, neither theoretical relations nor empirical correlations exist for the intensity of liquid backmixing between individual stages. It is obvious that the considered operation, as far as driving force and mechanism are concerned, considerably differs from the liquid entrainment from the free liquid surface which takes place in distillation and absorption plate columns with a low bed of foam on plates. For flooded, bubble-type reactors is characteristic a high liquid content in the bed while gas velocities usually attained are relatively low. Under such conditions, due to the momentum ratio of both phases, the back flow of liquid between stages cannot be expected to result from its entrainment by the gas stream as it is usual at high gas velocities and low beds with small content of liquid. This has been verified also by our preliminary measurements in experimental units where in the measured velocity ranges of both phases usually used in bubble-type reactors[1], the values of back flow varied in a wide range while the liquid entrainment from the surface in the top stage was nill.

From considerations on the character of bubbling in flooded bubble-type reactors the assumption resulted that the mechanism of liquid back flow between the stages is analogous to the flow of liquid inside individual stages and that both types of flow are closely related and are the result of existence of pressure differences in the bed. Backmixing between stages thus depends in general on a whole number of factors affecting the motion and mixing of the liquid phase in the reactor. Flow rates of both phases, design parameters of the reactor and derivation of theoretical relations for the intensity of backmixing should be based on the model of liquid flow in the system.

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THEORETICAL

Flow patterns of both phases in the reactor are given in Fig. 1 and derivation of relations for backmixing has been based on the following assumptions: *1*) In the considered interstage space for the given liquid and gas flow-rates and the used plates is the mean value of gas porosity ε_{Gi}, which can in general be different in individual stages. *2*) Negligible quantity of gas is entrained into the downcomer pipe so that the pipe can be considered to be fully filled with liquid. *3*) In the case of the considered type of downcomer pipes (without outlet weirs-caps) the space below the pipe is filled with liquid with negligible gas holdup regardless of the length of the downcomer pipe. *4*) Liquid does not weep through the plate holes but it flows only through the downcomer pipe to the next lower stage. Validity of assumptions (*2*)–(*4*) has been verified by preliminary experiments. In general cases when circulation of liquid phase takes place in the stage due to bubbling, assumption (*1*) isn ot fulfilled since circula-

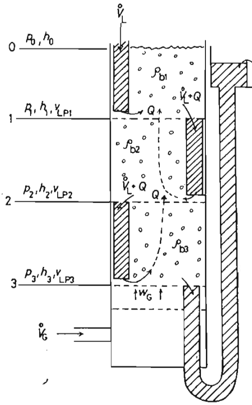

FIG. 1

Model of Liquid and Gas Flow Patterns in a Flooded Bubble-Type Plate Reactor with Downcomers

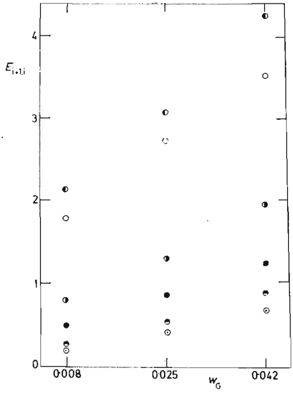

FIG. 2

Coefficient of Liquid Backmixing in Dependence on Linear Gas Velocity w_G (m/s)
Plate $\varphi = 4\%$, $d_0 = 5$ mm; E_{32}: ○ $W_L = 2 \cdot 5 \cdot 10^{-3}$ m/s; ● $W_L = 5 \cdot 0 \cdot 10^{-3}$ m/s; ⊙ $W_L = 7 \cdot 5 \cdot 10^{-3}$ m/s; E_{21}: ◐ $W_L = 2 \cdot 5 \cdot 10^{-3}$ m/s; ◑ $W_L = 5 \cdot 0 \cdot 10^{-3}$ m/s; ◓ $W_L = 7 \cdot 5 \cdot 10^{-3}$ m/s.

tion loops form, having a different porosity in downward and upward regions and thus the porosity on the cross-section is not constant. But it can be assumed, that porosities in both regions are approaching each other with increasing gas flow rate and since the backmixing is important especially at higher gas velocities, also the assumption *1*) can be considered to be reasonable. Deviations of local porosities in vertical direction from the constant mean value ε_{Gi} can be neglected in this derivation. Assumptions (*1*)–(*4*) thus correspond to such a state in the column when backmixing is not affected by internal circulation.

It is obvious from Fig. 1 that a pressure difference originates at an arbitrary level of the plate h_i which results from different hydrostatic pressures of the bed of clear liquid in the downcomer pipe and the bubbled bed. This pressure difference originates the liquid flow while the difference in potential energies of gas–liquid columns with differrent density is balanced by kinetic energy of the flowing liquid and by the corresponding energy losses in local resistances. Circulation of liquid thus occurs between two stages when the liquid flows upwards through holes of the perforated plate and downwards through the downcomer pipe. Thus in general both the liquid feed rate $\dot{V}_L$ and the back flow Q are passing through the downcomer pipe. For example, if the stage between the plates 1 and 2 is considered then in the plate plane 2 holds

$$p_2 - p'_2 = \Delta p_2 \,, \tag{1}$$

where

$$p_2 = p_0 + (h_0 - h_1)\,\varrho_{b1}g + (h_1 - h_2)\,\varrho_L g \,, \tag{2}$$

$$p'_2 = p_0 + (h_0 - h_1)\,\varrho_{b1}g + (h_1 - h_2)\,\varrho_{b2}g \,, \tag{3}$$

$$\Delta p_2 = \tfrac{1}{2}\varrho_L v_{LP2}^2 + h_{z2}\varrho_L g \,. \tag{4}$$

On substituting this result into Eq. (*1*) the relation for liquid velocity in the downcomer pipe is obtained

$$v_{LP2}^2 = 2g[(h_1 - h_2)(1 - \varrho_{b2}/\varrho_L) - h_{z2}] \,. \tag{5}$$

Similarly from pressure balances in the plate plane 3 holds

$$v_{LP3}^2 = 2g[(h_2 - h_3)(1 - \varrho_{b3}/\varrho_L) - h_{z3}] \,. \tag{6}$$

Overall liquid flow rate through the downcomer pipe is

$$\dot{V}_{LPi} = \dot{V}_L + Q_i = v_{LPi} S . \qquad (7)$$

By combination of relations (5) and (7), or (6) and (7) the relation is obtained

$$(\dot{V}_L + Q_i)^2/S^2 = 2g[(h_{i-1} - h_i)(1 - \varrho_{bi}/\varrho_L) - h_{zi}] . \qquad (8)$$

From the definition of porosity results

$$1 - \varrho_{bi}/\varrho_L = \varepsilon_{Gi} , \qquad (9)$$

which by substitution into Eq. (8) for $h_{i-1} - h_i = H$ gives

$$(\dot{V}_L + Q_i)^2/S^2 = 2g(H\varepsilon_{Gi} - h_{zi}) . \qquad (10)$$

From this relation the back flow Q can be determined if the porosity ε_{Gi} and the height loss h_{zi} are known. We shall limit ourselves to the assumption that under conditions (1)–(4) $\varepsilon_{Gi} \neq \varepsilon_{Gi}(Q_i)$. So for determination of Q_i remains to express in Eq. (10) the value of the height loss, for which we must assume in general that $h_{zi} = h_{zi}(Q_i)$.

Resistance to the liquid flow in the circulation loop originated by backmixing can be expressed as a sum of three contributions: *a*) resistance of the downcomer tube to the liquid flow; *b*) resistance of the heterogeneous gas–liquid bed to the liquid flow and the wall friction; *c*) resistance of the plate to the back flow. For the height loss thus holds

$$h_{zi} = \frac{(\Delta p_{down})_i}{\varrho_L g} + \frac{(\Delta p_{Het})_i}{\varrho_L g} + \frac{(\Delta p_{plate})_{i-1}}{\varrho_L g} . \qquad (11)$$

It can be expected that the last contribution will be the greatest while the resistence due to friction in the bed and the wall friction can be considered negligible in comparison with the other two contributions. Pressure loss caused by the liquid flow through the downcomer pipe can be expressed by use of the known relation

$$(\Delta p_{down})_i = (f_i L/d_p)\, \tfrac{1}{2} \varrho_L v_{LPi}^2 , \qquad (12)$$

from where on substituting for v_{LP_i} and arrangement holds

$$\frac{(\Delta p_{down})_i}{\varrho_L g} = \frac{f_i L}{d_p} \frac{1}{2g} \left(\frac{\dot{V}_L + Q_i}{S} \right)^2 , \qquad (13)$$

where for the friction factor f_i holds $f_i = f_i(Q_i)$, and the form of this functional dependence is generally different in different regions of Re_i

$$Re_i = [(\dot{V}_L + Q_i/S)] (\varrho_L \cdot d_p/\mu_L) \,. \tag{14}$$

Resistance of the plate to the liquid flow can be expressed by relation

$$(\Delta p_{plate})_i/\varrho_L \cdot g = \xi_i \frac{1}{2g} v_{0Li}^2 \,, \tag{15}$$

where, generally $\xi = \xi(T, d_0, \varphi)$ and liquid velocity in the plate holes v_{0Li} is given by relation

$$v_{0Li} = Q_{i+1}/A_{0i} \,. \tag{16}$$

The friction factor for the perforated plate ξ and the area A_0 of plate holes open for the liquid are important hydrodynamic quantities, however, up till now there do not exist appropriate correlations (and in case of A_0 even nor direct experimental data). As a basis for expressing the friction factor ξ, the relation can be used for the dry plate pressure drop of a perforated plate[2] with downcomers in the form

$$\Delta p_D = K[0{\cdot}4(1{\cdot}25 - \varphi) + (1 - \varphi)^2] \, \varrho_G v_{0G}^2/2 \,, \tag{17}$$

where $K = K(T/d_0)$ which can be read from an empirically plotted diagram[2].

So far, relation (*17*) has been verified for the single-phase gas flow through the plate only. It has been found[3] that this relation correlates well also the pressure drop in the gas flowing through the wetted plate if instead of geometrical free plate area φ, is used that part of the free plate area through which actually the gas passes. At the assumption that Eq. (*17*) is valid for pressure drop in the liquid as well, and if instead of φ the part of free plate area through which the liquid flow is actually passing A_0/A is used, by comparison of relations (*14*) and (*16*) the relation is obtained

$$\xi_i = K[0{\cdot}4(1{\cdot}25 - A_{0i}/A) + (1 - A_{0i}/A)^2] \,, \tag{18}$$

which could serve at least for the estimate of the order of magnitude of the coefficient ξ_i. As for the quantity A_0, it is necessary in the given system to assume generally that $A_0 = A_0(\dot{V}_G, \dot{V}_L, d_0, \varphi)$ and that the dependence of A on individual variables can be rather complex. Until now no data on A_0 are available in literature and the experimental determination of this quantity can be expected to be very difficult. In the relation for the plate resistance which can be rewritten into the form

$$(\Delta p_{plate})_i/\varrho_L g = (1/2g) \cdot Q_{i+1}^2(\xi_i/A_{0i}^2) \tag{19}$$

the term (ξ_i/A_{0i}^2) thus represents an unknown correlation factor the value of which must be determined empirically for the given conditions. On substituting for individual contributions into Eq. (*11*) the relation is obtained

$$h_{zi} = \frac{1}{2g}\left\{\frac{f_i L}{d_p}\left(\frac{\dot{V}_L + Q_i}{S}\right)^2 + \frac{\xi_{i-1}}{A_{0i-1}^2} Q_i^2\right\}, \qquad (20)$$

which can be used for expressing the height loss in Eq. (*10*). This equation is then transformed to

$$Q_i^2[(S^2/D_i) + F_i + 1] + 2Q_i(\dot{V}_L + F_i\dot{V}_L) + \dot{V}_L^2(1 + F_i) - A_i = 0\,, \qquad (21)$$

where

$$A_i = 2gH\varepsilon_{Gi}S^2\,, \qquad (22)$$

$$D_i = A_{0i-1}^2/\xi_{i-1}\,, \qquad (23)$$

$$F_i = f_i L/d_p\,, \qquad (24)$$

$$f_i = f_i(Q_i)\,. \qquad (25)$$

By solving Eq. (*21*), relation for the actual back flow is

$$Q_i = \frac{-\dot{V}_L(1 + F_i) + \sqrt{(\dot{V}_L^2(1 + F_i)^2 - [(S^2/D_i) + F_i + 1]\,(\dot{V}_L^2 + \dot{V}_L^2F_i - A_i))}}{(S^2/D_i) + F_i + 1} \qquad (26)$$

or for the backmixing coefficient

$$E_{i,i-1} = \frac{Q_i}{\dot{V}_L} = \frac{-(1 + F_i) + \sqrt{((1 + F_i)^2 - [(S^2/D_i) + F_i + 1]\,[1 + F_i - (A_i/\dot{V}_L^2))}}{(S^2/D_i) + F_i + 1}\,. \qquad (27)$$

In these relations ε_{Gi} should be expressed by use of the relation on porosity of a bubbled bed in plate columns and the value of D_i must be determined for the given conditions from the respective empirical relation expressing dependence of D_i on individual quantities representing conditions in the bubbled plate column in the measured range of these quantities. For F_i holds

$$F_i = (L/d_p)\,f_i(Q_i) \qquad (28)$$

and values Q_i or $E_{i,i-1}$ can be so obtained by solving the system of Eqs (*28*) and (*26*) or (*27*). In the case when pressure drop in the flow through the downcomer tube can be expected in comparison to the plate resistance to be negligible the first right hand side term of Eq. (*20*) drops out and the resulting relation for Q_i is obtained

$$Q_i = \{-\dot{V}_L + \sqrt{(\dot{V}_L^2 - [(S^2/D_i) + 1](\dot{V}_L^2 - A_i))}\}/[(S^2/D_i) + 1] \qquad (29)$$

or for $E_{i,i-1}$

$$E_{i,i-1} = \{-1 + \sqrt{(1 - [(S^2/D_i) + 1][1 - (A_i/\dot{V}_L^2)])}\}/[(S^2/D_i) + 1], \qquad (30)$$

where for ε_{Gi} and D_i applies the same as in Eqs (*26*) and (*27*).

EXPERIMENTAL

The experimental equipment has been described in detail in the preceding paper[4]. Experiments were carried out with the system water–air under the following conditions: range of air velocities 0·008—0·042 m/s; range of water flow rates $2\cdot5 \cdot 10^{-3}$—$7\cdot5 \cdot 10^3$ m^3/m^2 s; number of plates 3, diameter of holes in plates 1·6—5 mm, free plate area 4—8%. A three-stage column was used of inside diameter 0·292 m, distance between the plates 0·464 m, on each plate were fixed two downcomer pipes one beside the other, inside diameter of pipes 0·04 m, length of pipes in the basical set of experiments 0·42 m. The static method[5] has been used for measuring the coefficients of liquid backmixing between individual stages. Into the bottom stage of the column solution of methylene blue was continually fed at a constant rate 1 l/h. The solution was fed below the exit from the downcomer pipes. After reaching a steady state, samples of the liquid phase were taken from individual stages. Samples were taken continuously for 15 min, with an effort to affect as least as possible the stationary concentration field in the reactor. For sampling were used glass tubes of inside diameter 5 mm, samples were taken from the centre of individual stages. In orientation experiments no differences were found in concentrations of samples taken from different locations along the stage diameter. The concentrations were measured by the spectrophotometer Spekol. A calibrated attachement EK-1 enabled quick measurement in a relatively wide interval of transmitance. According to concentration of methylene blue in samples taken from individual stages, the backmixing coefficients were calculated from relation

$$E_{i+1,i} = [(c_{i+1}/c_i) - 1]^{-1}, \qquad (31)$$

(where stages are numbered from the top). In writing the balance relations, on the basis of which the resulting calculation relation (*31*) was obtained, it was assumed that individual stages were ideally mixed and had equal volumes. The calculated coefficient then expresses the ratio of the back flow to the direct flow between two adjoining stages.

Accuracy. All the experiments in the basic set of measurements of the backmixing coefficients were twice repeated. From the reproducibility the relative deviations were obtained

$$\bar{\delta}(E_{32}) = 1\cdot8\%; \quad \delta_{max}(E_{32}) = 8\cdot8\%; \quad \bar{\delta}(E_{21}) = 2\cdot2\%; \quad \delta_{max}(E_{21}) = 6\cdot1\%;$$
$$\bar{\delta}(E) = 1\cdot6\%; \quad \delta_{max}(E) = 4\cdot9\%;$$

proving a good reproducibility of the whole used procedure for determination of backmixing coefficients.

Additionally to the basic set of measurements, the effect of length of downcomer pipes 0·1 m and zero length was checked. Some experiments were made with plates without downcomers and with covered holes for downcomer pipes which simulate the plates without downcomers.

RESULTS

Application of relation (*26*) or (*29*) is the knowledge of the relation for D_i as a function of individual considered variables. For our experimental conditions and the measured range of variables (W_L, w_G, d_0, φ) an empirical relation for D_i was derived based on evaluation of experimental data on backmixing coefficient between stages in the column. From graphically plotted dependence of E_{21} and E_{32} on individual variables (as an example in Fig. 2 are given dependences E_{21} and E_{32} on w_G or W_L for φ 4%, $d_0 = 5$ mm) resulted that the effect of individual variables on the coefficient has the same character in both stages, while coefficients E_{21} are greater than E_{32}; this phenomena can be explained by smaller porosity of the bed in the lower stage and consequently lower driving force of the back flow. In further evaluation of experimental data we limited ourselves to values E_{21} in view of the fact that relations in the middle stage can be considered representative for internal stages of plate columns. In calculations we substituted for ε_{Gi} values of the porosity in the middle stage ε_{G2}, representing mean values of measured porosities for individual w_G, at all W_L, d_0 and $\varphi : \bar{\varepsilon}_{G2} = 0{\cdot}019$ for $w_G = 0{\cdot}008$ m/s, $\bar{\varepsilon}_{G2} = 0{\cdot}062$ for $w_G = 0{\cdot}025$ m/s, $\bar{\varepsilon}_{G2} = 0{\cdot}110$ for $w_G = 0{\cdot}042$ m/s. With regard to an insignificant effect of w_L, d_0 and φ on porosity in the measured range, this simplification can be considered acceptable.

For experimental values of Q_2 and ε_{G2} were calculated values of $F(\dot{V}_L + Q_2)^2$ with A_2. From their mutual comparison resulted that resistance in the downcomer pipes can be neglected practically in the whole range of measured values of studied variables[6] (W_L, w_G, d_0, φ). Under assumption $F(\dot{V}_L + Q_2)^2 \ll A_2$, relation (*21*) was modified so that calculation of values D_2 from experimental data Q_2 and $\bar{\varepsilon}_{G2}$ was possible

$$D_2 = S^2 Q_2^2 / [A_2 - (\dot{V}_L + Q_2)^2] \,. \qquad (32)$$

Calculated values of D_2 were then used for an approximate determination of the area open for passage of liquid A_{01} from Eq. (*18*) and from definition relation (*23*).

From the diagram given by McAllister[2] were then for $d = 1{\cdot}6$; 3; 5 mm and $T =$ $= 2$ mm taken values of $K = 1{\cdot}0$; $1{\cdot}27$; $1{\cdot}37$; and under the assumption $(A_{01}/A) \rightarrow 0$ were from relation (*18*) calculated the values $\xi_1 = 1{\cdot}5$; $1{\cdot}905$; $2{\cdot}055$.

From relation (*23*) resulted that $A_{01} = \sqrt{(D_2 \xi_1)}$ and for values of D_2 were calculated values A_{01}. Values A_{01} are within the range $(0{\cdot}232 - 1{\cdot}983) . 10^{-3}$ m^2 and from comparison to the overall cross sectional area of the column $A = 66{\cdot}9 . 10^{-3}$ m^2 is obvious that the assumption $(A_0/A) \rightarrow 0$ in relation (*18*) was justified. Total free plate area is $2{\cdot}676 . 10^{-3}$ m^2 for $\varphi = 4\%$ and $5{\cdot}353 . 10^{-3}$ m^2 for $\varphi = 8\%$. Thus from the made calculation results that the area for passage of liquid represents 8 – 50% of the total free plate area and the maximum A_{01} corresponds in the measured range to minimum values of W_L and w_G (for all d_0 and φ). In several combinations of W_L, d_0 and φ, the dependence has an extreme (minimum) the position of which varies in accordance with values of these quantities (Fig. 3*a*,*b*).

The shape of dependence of A_{01}–w_G can be explained qualitatively on basis of the considered mechanism of liquid passage through the plate at back flow. Let us assume, in accordance with the results of visual observation of the passage of coloured liquid through the plate, that the liquid flows upwards through the holes which were prior opened by the passing gas. Liquid then passes through these holes when the passage of gas is interrupted. This assumption was verified also by results of studies of the back flow with plates without downcomer pipes with the pipe holes left free

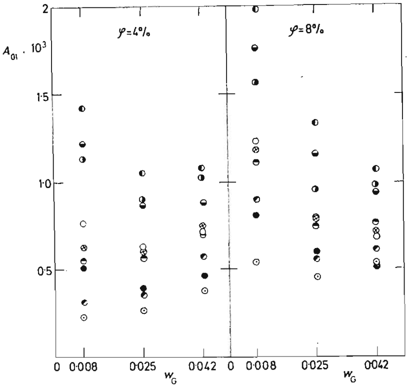

FIG. 3

Area of Plate Holes through which the Liquid Back Flow is Passing in Dependence on Gas Velocity w_G (m/s)

$W_L = 2{\cdot}5 . 10^{-3}$ m/s: ○ $d_0 = 1{\cdot}6$ mm, ◒ $d_0 = 3$, ◐ $d_0 = 5$; $W_L = 5{\cdot}0 . 10^{-3}$ m/s: ● $d_0 = 1{\cdot}6$, ⊗ $d_0 = 3$, ◑ $d_0 = 5$; $W_L = 7{\cdot}5 . 10^{-3}$ m/s: ⊙ $d_0 = 1{\cdot}6$, ◔ $d_0 = 3$, ◓ $d_0 = 5$.

when the gas is mostly passing upward through large holes without interruption of the gas flow and without any significant liquid back flow through these holes.

From visual observations of the bubbling character under various conditions also resulted that at low values of w_G the gas passes alternatively in pulses through different holes of the plate. Passage of bubbles opens in this way a great number of holes that remain free for the liquid for a relatively long period of time due to slow frequency of pulses and a relatively small number of holes through which the gas passes simultaneously.

With increasing w_G at first increases the frequency of bubbles passing through individual holes and in consequence a greater number of open holes is occupied by the gas in the given moment and value of A_{01} becomes smaller. Only gradually with increased number of holes occupied by gas a significant increase of the bubbled area A_G takes place with increasing w_G and in accordance with it also A_{01} increases. Thus the assumption results, that also in those cases when (at such combinations W_L, d_0 and φ) in Figs 3*a*,*b* the dependence A_{01}–w_G does not pass through the extreme, its existence can be generally expected in a region of values w_G not covered by our measurements. On this basis also the effect of other variables d_0, φ, W_L on

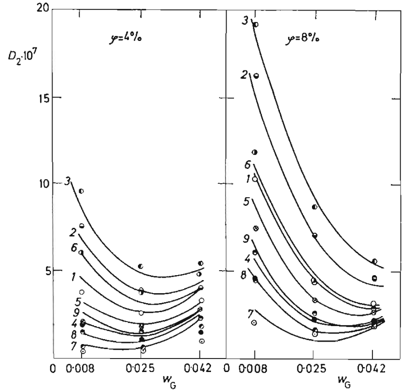

FIG. 4

Calculated (Eq. (*23*)) and Experimental Values of D (m²) in Dependence on Gas Velocity w_G (m/s) $W_L = 2{\cdot}5 \cdot 10^{-3}$ m³/m² s; *1* ○ $d_0 = 1{\cdot}6$, *2* ◓ $d_0 = 3$, *3* ◐ $d_0 = 5$; $W_L = 5{\cdot}0 \cdot 10^{-3}$ m³/m² s: *4* ● $d_0 = 1{\cdot}6$, *5* ⊗ $d_0 = 3$, *6* ◑ $d_0 = 5$; $W_L = 7{\cdot}5 \cdot 10^{-3}$ m³/m² s: *7* ⊙ $d_0 = 1{\cdot}6$, *8* ◐ $d_0 = 3$, *9* ◓ $d_0 = 5$. Curves *1* to *9* are calculated values of D, points are experimental values.

the character of dependence of A_{01}–w_G and especially on the shift of the extremes can be explained. If the total free plate area is decreased, there is at constant w_G a smaller number of holes at the gas disposal on the same plate area which results in a higher frequency of bubbles passing through individual holes open for the gas. The area A_{01} is thus at constant w_G smaller and the minimum of dependence of A_{01}–w_G is at lower values of w_G.

With increasing W_L the loading of holes by the liquid from above is larger so that the gas breaks through a smaller number of holes and the value of A_{01} decreases as well at constant w_G, d_0 and φ. With increasing w_G then the bubbles are passing through the holes at a higher frequency and the minimum on the dependence of A_{01}–w_G moves toward lower values of w_G so that at W_L $7{\cdot}5 \,.\, 10^{-3}$ m^3/m^2 s (at $\varphi = 4\%$) the extreme practically disappears. Decrease in the diameter of holes d_0 has obviously a similar effect as an increase in W_L.

From definition of D_i results an analogous character of dependence of this quantity on the studied variables (with exception of d_0) as for A_0. In agreement with conclusions of the above made qualitative analysis of dependence $A_0 = A_0(w_G, W_L, d_0, \varphi)$ in the range of measured values w_G, W_L, d_0, φ an empirical relation has been found for the dependence of D_2 on these quantities in the form

$$D_2 \,.\, 10^7 = 1{\cdot}88 \,.\, 10^4 \,.\, \left|(w_G - w_{G0})\right|^{2.3(2.5 . 10^{-3}/W_L)^{-0.025}} + \\ + 10^{[(\log d_0 + 1.61)/2.49]} \,.\, \exp(-209 W_L) - (1 - \varphi/8)\,, \tag{33}$$

where w_{G0} is the gas velocity corresponding to the minimum in dependence of D_2–w_G for which values holds

$$D_{20} \,.\, 10^7 = (3{\cdot}75 - 0{\cdot}25\varphi)^{[(v_{G0} - 0.015) . 10^2]} - 1\,. \tag{34}$$

The values D_{20} can be calculated from Eq. (*33*) for $(w_G–w_{G0}) = 0$ for given W_L, d_0 and φ and from Eq. (*34*) w_{G0} can be determined for these conditions. After substituting w_{G0} into relation (*33*) the dependence D_2–w_G can be calculated for the given W_L, d_0 and φ.

In Figs 4*a,b* are plotted the dependences of D_2–w_G obtained in this way (for all W_L, d_0, φ) and for comparison are also plotted values of D_2 found experimentally. From these figures as well as from comparison of experimental D_2 values with those calculated from empirical relations for corresponding w_G, W_L, d_0 and φ, is obvious a good agreement. By use of the obtained empirical relations for D_2 the back flow was then calculated for chosen values of w_G, W_L, d_0 and φ from Eq. (*29*). From the results given in Table I is obvious a good agreement of the calculated and experimental values of Q_2 (it can be seen from this Table that the backmixing coefficient can reach also high values).

TABLE I

Absolute Values of Back Flow

φ %	d_0 mm	$W_L \cdot 10^3$ m^3/m^2 s	w_G m/s	$Q_2 \cdot 10^3$, m^3/s experimental	$Q_2 \cdot 10^3$, m^3/s calculated	$\frac{Q_2}{Q_{2exp}} \cdot 100\%$
4	1·6	2·5	0·008	0·237	0·254	7·2
		5·0	0·008	0·152	0·146	3·9
		7·5	0·008	0·066	0·086	30·3
		2·5	0·025	0·372	0·368	1·1
		5·0	0·025	0·228	0·232	1·8
		7·5	0·025	0·149	0·117	21·5
		2·5	0·042	0·554	0·603	8·8
		5·0	0·042	0·364	0·438	20·3
		7·5	0·042	0·295	0·330	11·9
4	3	2·5	0·008	0·323	0·310	4·0
		5·0	0·008	0·165	0·204	23·6
		7·5	0·008	0·079	0·108	36·7
		2·5	0·025	0·445	0·444	0·2
		5·0	0·025	0·307	0·309	0·7
		7·5	0·025	0·180	0·176	2·2
		2·5	0·042	0·607	0·626	3·1
		5·0	0·042	0·511	0·524	2·5
		7·5	0·042	0·391	0·365	6·6
4	5	2·5	0·008	0·355	0·336	5·4
		5·0	0·008	0·267	0·262	1·9
		7·5	0·008	0·127	0·153	20·5
		2·5	0·025	0·512	0·493	3·7
		5·0	0·025	0·429	0·393	8·4
		7·5	0·025	0·270	0·268	0·7
		2·5	0·042	0·705	0·672	4·7
		5·0	0·042	0·654	0·595	9·0
		7·5	0·042	0·447	0·467	4·5
8	1·6	2·5	0·008	0·361	0·367	1·7
		5·0	0·008	0·230	0·259	12·6
		7·5	0·008	0·145	0·163	12·4
		2·5	0·025	0·462	0·482	4·3
		5·0	0·025	0·344	0·333	3·2
		7·5	0·025	0·256	0·225	12·1
		2·5	0·042	0·537	0·522	2·8
		5·0	0·042	0·404	0·421	4·2
		7·5	0·042	0·407	0·396	2·7
8	3	2·5	0·008	0·434	0·423	2·5
		5·0	0·008	0·286	0·306	7·0
		7·5	0·008	0·201	0·207	3·0
		2·5	0·025	0·580	0·579	0·2
		5·0	0·025	0·398	0·404	1·5

TABLE I
(*continued*)

φ %	d_0 mm	$W_L \cdot 10^3$ m^3/m^2 s	w_G m/s	$Q_2 \cdot 10^3$, m^3/s experimental	calculated	$\frac{Q_2}{Q_{2\,exp}} \cdot 100\%$
		7·5	0·025	0·277	0·277	0·0
		2·5	0·042	0·642	0·622	3·1
		5·0	0·042	0·496	0·475	4·0
		7·5	0·042	0·411	0·409	0·5
		2·5	0·008	0·460	0·456	0·9
		5·0	0·008	0·345	0·336	2·6
		7·5	0·008	0·230	0·236	2·6
8	5	2·5	0·025	0·631	0·653	3·5
		5·0	0·025	0·455	0·471	3·5
		7·5	0·025	0·349	0·329	5·7
		2·5	0·042	0·702	0·697	0·7
		5·0	0·042	0·631	0·523	17·1
		7·5	0·042	0·493	0·428	13·2

At the used gas velocities were, for plates with free areas 4 and 8%, found the minima on curves D_2–w_G in majority of the experiments which proved their existence. The found empirical relation for calculation of the backmixing coefficients can be easily applied but it can be expected that it can be improved on the basis of additional experiments especially with high gas flow rates, or that a more precise characteristics will be found for the dependence $D_i = D_i\left(w_G, W_L, d_0, \varphi\right)$. From this point of view it will also be necessary to carry out measurements with plates having a smaller free areas $\left(\varphi = 1 - 2\%\right)$ in order to define precisely the dependence of back flow on the free plate area. Plates with free areas larger than those used in this study will not be obviously used in bubble-type, multistage reactors because of their low distributing efficiency and high values of the negatively acting back flow.

In view of the fact that the calculation relations for the backmixing coefficient in flooded bubbled type plate reactors have not yet been known our relation can be considered satisfactory for calculation of the backmixing coefficient in the range of studied variables. Outside this region the proposed relations can be considered to be a reasonable approximation.

LIST OF SYMBOLS

A over-all cross sectional area of the reactor (L^2)
A_i coefficient defined by Eq. (*22*) (L^6/T^2)
A_0 over-all area of open plate holes for the back flow of liquid (L^2)

c concentration (M/L^3)
D_i coefficient defined by relation (*23*) (L^4)
d_0 diameter of plate holes (L)
d_p diameter of downcomer pipe (L)
E backmixing coefficient (—)
F coefficient defined by relation (*24*) (—)
f friction factor according to Fanning (—)
g gravitational acceleration (L/T^2)
H height of bubbled bed (L)
h height of liquid bed (L)
h_z friction loss (L)
K coefficient in Eq. (*17*) (—)
l length of downcomer pipe (L)
p pressure (M/LT^2)
Δp pressure drop (M/LT^2)
Q actual back flow (L^3/T)
Re Reynolds number (—)
S cross sectional area of downcomer (L^2)
T plate thickness (L)
$\dot{V}$ volumetric flow rate (L^3/T)
v actual flow velocity in plate holes (L/T)
w superficial velocity of phases (L/T)
W_L liquid feed rate (L^3/L^2T)
δ relative deviation (—)
ε_G porosity of the bubbled bed (—)
μ dynamic viscosity (M/LT)
ϱ density (M/L^3)
ξ friction factor of the plate (—)
φ relative free plate area (—)

Subscripts

b bubbled bed
G gas
L liquid
i general i-th quantity
p downcomer
1 top stage
2 middle stage
3 bottom stage
21 in between the 2nd and 1st stages
32 in between the 3rd and 2nd stages

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