POROSITY OF THE HETEROGENEOUS BED AND LIQUID CIRCULATION IN MULTISTAGE BUBBLE-TYPE COLUMN REACTORS*

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On the basis of considerations concerning the liquid circulation in the interplate region, a relation is derived for the mean bed porosity. For the theoretical model two parameters need to be known *i.e.* the upward velocity of bubbles mutually affecting each other and the cross-sectional area of the upward liquid stream in the bed. The agreement of experimental and model values of porosities is very good in the region where the bubbles can be considered not to form clusters *i.e.* for the system water–air up to linear gas velocities 0·01 ms^{-1}. For higher gas velocities an empirical correction factor had to be introduced accounting for the mutual hindering of bubbles.

In the first study of this series[1] a relation was derived for calculation of porosity in a bubbled bed on basis of a model of gas flow in the bed and in a pipe of equivalent diameter at zero liquid flow rate in reactors with one distributing plate. The found relation has expressed very well the shape of the bed porosity in dependence of the linear gas velocity for various systems. However, the effect of the column diameter on this dependence could have been given only experimentally. Here, we have made an attempt to describe the porosity of the bubbled bed for a multistage flooded reactor on basis of some considerations on the character of flow of both phases in the interplate space. The made model considerations should be later useful also for theoretical considerations on scaling-up. At present, this model has been experimentally verified on the system water–air although we know that the effect of physico-chemical parameters of the model systems on the character of flow of phases in the given space and on the structure of the bubbled bed[1] is of prime importance.

At first, the general case of a non-zero liquid flow rate will be considered which has not yet been studied in this way. The flow direction of phases is countercurrent while inside the individual stages the liquid is forced to flow in a cross-flow because of the suitably situated downcomer pipes. The liquid flow inside the stage is then the result of superposition of the basical and of the circular flows which are in general, according to the present knowledge, a combination of the circulation inside the stage (1 or 2 loop)[2,3] and of the external circulation originated by the liquid of backmixing

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in between the stages (which always corresponds to the one-loop model[4]). The backmixing also affects the character of flow in the stage as it is affecting the amount of liquid passing through the stage or through some parts of the circulation loop where this effect cannot be neglected even in the case for which the backmixing is in the whole column constant ($E_{i,i-1} = E_{i+1,i} = E$). Thus on basis of these considerations it might be expected that the character of circulation inside the stages of bubbled plate columns will be very complex and will vary within a wide range in dependence on the ratio of flow rates of both phases. For determination of porosity in general none of existing theoretical relations can be applied that have been till now derived for porosity on basis of an analysis of the flow character of both phases in the bubbled bed[2,3].

We shall assume for simplification that in the whole range of considered operating conditions and variable design parameters always one of the circulation components is superior in such a degree that the circulation character inside the stage can be expressed by one of the two circulation schemes – one or two loop circulation. The validity of this assumption was confirmed by orientation experiments at which the motion of a coloured liquid introduced into various positions inside the reactor was observed visually and photographically together with the shape of the upward bubble path.

Further, let us assume that the pressure drop resulting from the difference of hydrostatic pressures of the bed of clear liquid in downcomer pipes (or in the region below them) and the bubbled bed which was considered to be the cause of occurrence of backmixing in between the stages[4] is acting only as the driving force of this external circulation and is not affecting directly the circulation inside the stage. For description of the internal circulation is thus considered only the pressure drop inside the bed in the stage which is resulting from the difference of densities in various regions of the bubbled bed.

THEORETICAL

Two-Loop Circulation

The assumed flow pattern, under conditions when the two-loop circulation can be expected to be superior, was verified by the above described orientation experiments and is illustrated in Fig. 1.* Liquid and gas bubbles are rising only in the central part of the ascending region part of liquid is leaving as backmixing into the above situated stage and the rest is flowing downwards in the space between the ascending region and the reactor walls. Part of bubbles are carried away by the liquid into this space and are in the descending part kept practically stationary or are circulating

* Next we assume that the stage has a circular cross-section of diameter D_K.

together with the liquid. The basis for the proposed flow model in this case was the model proposed by Freedman and Davidson[3] for expression of circulation in a single-stage reactor with a non-flow liquid bed. For the by us considered case of the general n-th stage of a plate column, the model was supplemented with the expression for the non-zero liquid flow rate through the stage and description of liquid transfer between the considered stage and both neighbouring stages which take place due to back-mixing. The final version of the model is presented in Fig. 2. We assume that all liquid entering the stage both from above through the downcomer pipe as well as the backmixing from the lower situated stage is at first passing through the ascending region of the circulation loop which has a shape of a cylinder of constant cross-section which is located symmetrically around the vertical axis of the stage. Unlike the Freedman's model, the value of the cross-sectional area of the ascending region is not known. In general it is necessary to assume that it is a function of flow of both phases and of the geometrical plate parameters (φ, d_0, a_0). In literature no correlation relations for the cross-sectional area of the ascending region are available for the two-loop circulation. The available experimental data[3,5] are obviously limited to the concrete conditions under which they were obtained and do not have any general validity. It can be assumed in the case when the two-loop circulation forms that the cross-sectional area of the ascending region is proportional to the plate are a_0 on which the holes are situated

$$a = k_1 a_0 , \tag{1}$$

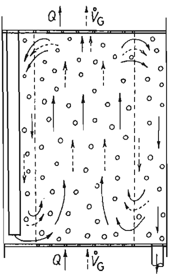

FIG. 1

Flow Pattern in a Bed for Two-Loop Circulation

——→ Liquid flow, - - - - -→ gas flow, - - - boundaries of the ascending region.

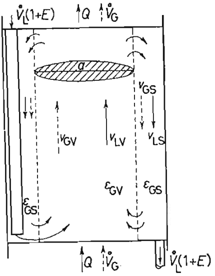

FIG. 2

Two-Loop Circulation Model

while the coefficient k_1 is, for the given gas–liquid system a function of flow rates of both phases and of other geometrical plate parameter. The functional dependence

$$k_1 = k_1(\dot{V}_G, \dot{V}_L, d_0, \varphi) \quad (2)$$

must be determined for the given experimental station and for the given two-phase system either from the directly measured value a (which of course is rather difficult) or from evaluation of the experimental data on porosity in this unit and into the relation for calculation of porosity is then substituted for a the corresponding correlation relation.

For description of the circulation flow in the stage we shall assume that both regions of the circulation loop are mutually separated by the interface of negligible thickness and we shall not consider phenomena which are actually taking place in the region of contact of the ascending and descending streams. Then, in the general case when the gas holdups in both regions of the circulation loop are different, the bed density in both regions is also different and the formed pressure drop is compensated by pressure losses at the reversal of the circulation flow at the vessel bottom (from the descending to ascending region) under the assumption that the friction losses at the wall and the resistance of the bubbled bed can be neglected: This balance of energy can be expressed by relation

$$\Delta p_S - \Delta p_V = \varrho_L g(v_{LS}^2/2g + v_{LV}^2/2g)\,, \quad (3)$$

where

$$\Delta p_S = H\varrho_L g(1 - \varepsilon_{GS})\,, \quad (4)$$

$$\Delta p_V = H\varrho_L g(1 - \varepsilon_{GV})\,. \quad (5)$$

For actual liquid flow rates in both regions of the circulation loop holds

$$v_{LV} = w_{LV}(1 - \varepsilon_{GV})\,, \quad (6)$$

$$v_{LS} = w_{LS}/(1 - \varepsilon_{GS}) \quad (7)$$

and their mutual relation is obtained from the continuity equation for the liquid phase

$$v_{LS}(A - a)(1 - \varepsilon_{GS}) = v_{LV}a(1 - \varepsilon_{GV}) - \dot{V}_L E\,. \;* \quad (8)$$

On arrangements, Eq. (3) has got the final form

$$\varepsilon_{GV} - \varepsilon_{GS} = (\tfrac{1}{2}gH)\,\{(w_{LS}/1 - \varepsilon_{GS})^2 + [(w_{LS}(A - a) + \dot{V}_L E)/a(1 - \varepsilon_{GV})]^2\}\,. \quad (9)$$

* For simplicity we assume in the derivation that backmixing in between the stages and in the whole column is constant ($E_{i,i-1} = E_{i+1,i} = E$).

The gas velocity in individual regions of the circulation loop can be expressed by use of relations derived for the non-circulating flow[6]

$$v_{GV} = v_{LV} + v_s/(1 - \varepsilon_{GV}) , \qquad (10)$$

$$v_{GS} = v_{LS} - v_s/(1 - \varepsilon_{GS}) , \qquad (11)$$

where for v_s the following relations[7,8] hold

$$v_S = u_{B\infty}(1 - \varepsilon_G) , \qquad (12)$$

$$v_S = u_{B\infty}(1 - \varepsilon_G)^2/(1 - \varepsilon_G^{5/3}) , \qquad (13)$$

in which for ε_G is substituted ε_{GV} or ε_{GS}.
Under assumption that gas bubbles are kept in the descending region and that they are not circulating with the liquid,* for the gas velocity in the ascending region thus holds

$$v_{GV} = \dot{V}_G/(a\varepsilon_{GV}) . \qquad (14)$$

After substituting into Eq. (*10*) and by expressing v_{LV} from relation (*7*) and (*8*), Eq. (*10*) can be arranged into the form

$$\dot{V}_G/a\varepsilon_{GV} - w_{LS}(A - a)/(1 - \varepsilon_{GV})a - \dot{V}_L E/a(1 - \varepsilon_{GV}) = v_s/(1 - \varepsilon_{GV}) . \qquad (15)$$

For v_{GS} from the given example results

$$v_{GS} = 0 \qquad (16)$$

and from Eq. (*11*) then

$$w_{LS} = v_s . \qquad (17)$$

Eqs (*9*), (*15*) and (*17*) are then together with the corresponding relation for v_s representing a system of equations, and by its solution values of porosities in individual regions ε_{GV} and ε_{GS} and the resulting mean porosity are then calculated from the relation

$$\varepsilon_G = [\varepsilon_{GV}a + \varepsilon_{GS}(A - a)]/A . \qquad (18)$$

The given system of equations, where moreover for a the corresponding correlation

* Validity of this assumption has been generally discussed[3] and in our study it was verified by visual observation of motion of bubbles in the experimental station.

relation is to be substituted, cannot be solved analytically and for calculation of porosities the numerical solution must be used. The mean porosities ε_G for the given conditions must be in the interval

$$\varepsilon_{G\min} < \varepsilon_G < \varepsilon_{G\max}\,, \tag{19}$$

where $\varepsilon_{G\min}$ and $\varepsilon_{G\max}$ are values of porosities for two limiting hypothetical cases limiting the behaviour of the considered system. For the case where it is possible to assume that bubbles are not entrained into the descending region, porosity in this region is nill ($\varepsilon_{GS} = 0$) and equation (*9*) becomes

$$\varepsilon_{GV} = \tfrac{1}{2}gH\{w_{LS}^2 + [(w_{LS}(A - a) + \dot{V}_L E)/a(1 - \varepsilon_{GV})]\}^2\,. \tag{20}$$

Porosities in the ascending region ε_{GV} are obtained by simultaneous solution of Eqs (*15*) and (*20*) together with the corresponding relation for v_s; the mean porosity is determined from the relation

$$\varepsilon_G = \varepsilon_{GV} a/A\,. \tag{21}$$

On the contrary, if it can be assumed that the porosity is constant in the volume ($\varepsilon_{GV} = \varepsilon_{GS} = \varepsilon_G$), because of the bubbles entrained into the descending region, then in Eq. (*15*) can be written instead of ε_{GV} directly ε_G so that it holds

$$\dot{V}_G/a\varepsilon_G - w_{LS}(A - a)/(1 - \varepsilon_G)\,a - \dot{V}_L E/(1 - \varepsilon_G)\,a = v_s/(1 - \varepsilon_G) \tag{22}$$

and calculation of porosity is simplified to the solution of the system of Eqs (*17*) and (*22*) and of the corresponding relation for v_s. If relation[7] (*12*) is used the system of equations can be solved analytically and the resulting relation for calculation of ε_G becomes

$$\varepsilon_G = [T \pm (T^2 - 4U)^{1/2}]/2\,, \tag{23}$$

where

$$T = (\dot{V}_G + \dot{V}_L E + u_{B\infty} A)/A u_{B\infty}\,, \quad U = \dot{V}_G/u_{B\infty} A\,, \qquad (24), (25)$$

By visual observations and by filming the conditions in the bubbled bed of the model it becomes possible to assume that under conditions when in the system the two-loop circulation prevails, the actual state with increasing w_G is approaching the case of constant porosity in the bed ($\varepsilon_{GV} = \varepsilon_{GS} = \varepsilon_G$) where ε_G can be calculated directly from Eq. (*23*).

One-Loop Circulation

The block diagram of flow in the stage under conditions of the prevailing one-loop circulation is given in Fig. 3. Again we assume that the liquid and gas are moving upwards only in the ascending part of the circulation loop having a constant cross-sectional area which in general has for a circular reactor a shape of a section of a circle. Similarly as in the two-loop circulation the ascending liquid stream is divided into the backmixing flow into the next upper stage and the circulating stream flowing downwards in the descending region of the circulation loop. Part of the bubbles can be entrained again into this descending region. The flow model in a general n-th stage presented in Fig. 4 contains, similarly as for the two-loop circulation, beside the circulation flow also the liquid flow rate through the stage and backmixing flows into and out of the stage while it is again assumed that all the liquid entering the stage is at first passing through the ascending part of the circulation loop. Again, the cross-sectional area of the region is, for the case of the one-loop circulation, in general an unknown quantity the value of which is dependent on flow rates of both phases and geometrical plate parameters. But unlike the two-loop circulation, on basis of our visual observations and studies of other authors, the dependence on a_0 is not straightforward and thus in this case it seems to be more appropriate to

$$a = k_2 A \,, \tag{26}$$

where

$$k_2 = k_2(\dot{V}_G, \dot{V}_L, \varphi, d_0) \,. \tag{27}$$

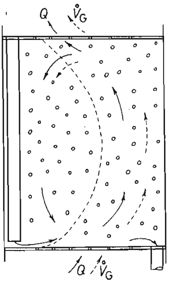

FIG. 3

Flow Pattern in a Bed for the Two-Loop Circulation

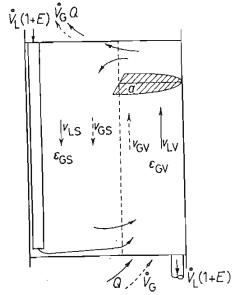

FIG. 4

One-Loop Circulation Model

assume that the shape of this functional dependence for the given unit and for the given two-phase system must be again determined experimentally and the obtained correlation relation for a is substituted into the relations for calculation of porosity. On basis of considerations concerning the bubbling character it may be assumed, in agreement with the conclusions made by Reith[2], that for the one-loop circulation the cross-sectional area of the ascending region is limited by the condition

$$a \leqq A/2 . \tag{28}$$

The effects on boundaries of the circulation region are neglected as for the case of the two-loop circulation. Then, for the general case when porosities and thus bed densities are in both circulation regions different, from the balance of pressures in the bed and from the balance for flow velocities of individual phases in both regions (a stationary holdup of bubbles is assumed in the descending region) the same relations as those for the two-loop circulation (*9*), (*15*) and (*17*) may be obtained, but there in general a different shape of the correlation relation for a must be expected. By solving this system of equations together with the corresponding relation for v_s values of ε_{GV} and ε_{GS} can be obtained and for ε_G relation (*18*) holds. The range of the mean porosity is again limited by two simplified cases similarly as that with the two-loop circulation.

From visual studies follows that in the case of prevailing one-loop circulation the state in the stage with the decreasing V_G gets close to the limiting case of zero porosity in the descending region which is in agreement with the conclusions made by Reith[2]. From determination of porosity for this case the system of Eqs (*15*) and (*20*) can be used where for a is substituted the correlation relation for the one-loop circulation.

EXPERIMENTAL

The experimental three-stage reactor with the inside diameter 292 mm and the geometry of the used plates with downcomers is in detail given in the preceding study[11]. The distance between the plates was 0·464 m, the length of two downcomer pipes without weirs 0·04 m in diameter situated at the edge of the plate was in majority of experiments 0·42 m. Geometrical plate parameters: $d_0 \in \langle 1{\cdot}6 - 5 \rangle$ mm; $\varphi \in \langle 4 - 8\% \rangle$. Flow rates of both phases: $W_L \in \langle 2{\cdot}5 \,.\, 10^{-3} - 7{\cdot}5 \,.\, 10^{-3} \rangle$ m^3/m^2 s; $w_G \in \langle 0{\cdot}008 - 0{\cdot}042 \rangle$ m/s.

For measurement of porosity[9] the method of pressure differences was chosen based on measurements of static pressure along the bed height[2,3,5,10]. The static pressure on the plate and at various distances from it is measured. The scales of all manometric tubes are related to the plate height which for the given liquid used as the manometric fluid means that the reading of the manometer (v_i) represents the sum of pressures at the given point (h_i) and the distance of the corresponding pressure tap from the plate (x_i).

The mean porosity in the beds was then calculated from the relation

$$\varepsilon_G = \frac{1}{x_k} \cdot \int_0^{x_k} \frac{y_i - y_{i-1}}{x_i - x_{i-1}} \, dx \,, \tag{29}$$

where x_k is the distance of the last pressure tap from the plate. In each stage were determined pressures along the bed height in ten levels in 50 mm distances. Into glass walls of individual stages were drilled eight holes in which the umaplex tubes of inside diameter 5 mm were sealed. Other two holes in each stage were drilled into the lower flange and into the ring separating both flanges which enabled to take pressure measurements next above the plate and in the upper part of the bed in the stage. For these two taps brass pipes were used instead of those umaplex having the same inside diameter. The pressure readings were taken on the manometers with the water column which were connected with the pressure taps by polyethylene hoses of inside diameter 8·5 mm (their use enabled simple detection of air bubbles and their simple removal). Into the hoses connecting the pressure taps and the manometers were situated glass capillary tubes 0·05 long which prevented pulsation of the liquid surface in the manometers. By comparison of manometer readings with the capillary tubes used with the values obtained under the same conditions with manometers without capillary tubes (the average of ten measurements of the maximum and minimum readings taken) we have determined that the capillary tubes do not affect the readings of pressure values while experimentation is considerably simplified by their use.

Into relation (*29*) which was solved graphicaly were for v_0 substituted values from the lowest situated side taps while their distance from the plate (it was in three stages 0·006 m) was neglected. The preliminary experiments have demonstrated that readings obtained from these taps do not differ from those taken at the plate bottom. The side taps were used since their arrangement enabled simple removal of gas bubbles from the connecting hoses.

From two repeated measurements of the basical system were obtained values of relative deviations $\bar{\delta}_{\varepsilon G3} = 2{\cdot}6\%$, $(\delta_{\varepsilon G3})_{max} = 9{\cdot}1\%$; $\bar{\delta}_{\varepsilon G2} = 2{\cdot}6\%$, $(\delta_{\varepsilon G2})_{max} = 9{\cdot}4\%$; $\bar{\delta}_{\varepsilon G1} = 2{\cdot}9\%$, $(\delta_{\varepsilon G1})_{max} = 12{\cdot}5\%$, which demonstrated a good reproducibility of the used measuring method. The experimental gas porosities were correlated in dependence on the flow rates of both phases W_L and w_G and on geometrical plate parameters d_0 and φ.

From the obtained data is obvious a difference between the porosity values in individual stages (the porosity is increasing from stage to stage in the upward direction). These differences cannot be only explained by the change of the hydrostatic pressure and they are obviously the result of the effect of internal plates on the bubbling character in units of the stage type. For a general plate reactor it may be assumed that the internal plates together with the bubbled bed in individual stages cause an additional distribution of gases. In the direction toward the upper stages less and less gas is rising in the form of large clusters of bubbles passing quickly through the bed and gas distribution in the bed is from one stage to the other more and more uniform. As the result of breaking of clusters of bubbles on the plate and of their redispersion the bubbled bed contains in the upper stages large number of small, relatively individual bubbles with a long residence time in the stage which results in an increase of the gas holdup toward the reactor top. This assumption has been verified also by visual observations of the bubbling character in our experimental unit. In the bottom stage a passage of large clusters of bubbles took place having a small residence time in the stage. These clusters were redispersed by the middle plate and they usually did not pass further into the upper part of the reactor. Across the middle and top plates the gas has been passing through a greater number of holes than across the bottom plate, the character of bubbling in the middle and top plates was mostly uniform and both stages containing in comparison with the bottom stage a greater number of bubbles. In general it may be anticipated that at a certain distance (beginning with a certain stage) a steadying of the bubbling character should take place and the gas holdup or the corresponding bed porosity should be affected only by the height of the liquid head above the considered stage. This assumption could not have been verified in our three-stage unit. From the made measurements followed that the character of the porosity distribution along the height in individual stages in general corresponded to the literature data based on studies in single stage units[2,12]. Because of the relatively small ratio of the height of stages to the reactor diameter (in the published papers the single-stage units had the ratio $H/D_K > 10$), the region of constant porosity in individual stages was small and practically insignificant. In all experiments made its existence was determined in the middle stage within the range of bed heights 0·1 to 0·3 m. The distribution of porosity in the top and especially in the bottom stage was rather different (the height of the region with constant porosity mostly did not exceed 0·1 m) which can be explained by different character of the bed in individual stages as discussed above. For individual stages the dependence $\Delta y_i - x_i$ and the character of the porosity distribution was similar at all combinations of the independent variables (W_L, w_G, d_0, φ).

We have not considered in this study the distribution of porosity along the bed height and in further evaluation of the results of our experiments we have used the mean porosities in stages.

RESULTS

In all three stages the porosities are most distinctly affected by the inlet gas flow rates into the reactor. In the studied range effect of the free plate area on gas holdup has not been found, the effect of parameters W_L and d_0 was less distinctive in comparison to that of w_G. The values of porosity have decreased with increasing liquid flow rate W_L and with decreasing size of holes d_0, where the effect of these variables has slightly differed in individual stages and in none of them appeared in the whole range of studied values w_G.

Theoretical relations for porosity derived on basis of a general description of flow of both phases in the stage were verified by experimental data obtained in the middle stage which in out case represents a general internal stage of a plate column. It may be concluded from visual observations of the bed and from photographs of the bed made at various combinations of individual values of variables (w_G, W_L, d_0, φ) that the bed character in the central stage changes considerably only with the gas velocity w_G regardless values of other variables[13]. From visual observations was also obvious

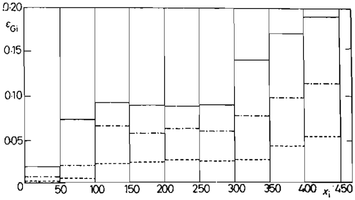

FIG. 5

Porosity in Dependence on Height in the Stage

$\varphi = 4\%$, $d_0 = 5$ mm, $W_L = 5{\cdot}0 \,.\, 10^{-3}$ m^3/m^2 s, $w_G = 0{\cdot}008$ m/s – – –, $w_G = 0{\cdot}025$ —·—·—, $w_G = 0{\cdot}042$ ———.

that with increasing w_G the upward gas stream is considerably spreading and the number of bubbles kept in the stage beside the upward stream also increases. Also with increasing w_G it has been observed that the upward stream is moving from the wall toward the vertical axis of the stage.

From orientation experiments, in which the motion of a stream of a coloured liquid injected into various places of the stage has been both observed visually and filmed, the circulation character of the liquid stream has changed with increasing w_G in correspondence with changes in the bubbling character (Fig. 5). At $w_G = 0{\cdot}008$ m/s the circulation pattern has uniquelly corresponded to the one-loop model. With increasing w_G an oscillation of the circulation stream took place in between two basic circulation types in agreement with the variable character of the upward stream. At $w_G = 0{\cdot}042$ m/s already clearly dominated the two-loop circulation though the axial symmetry of circulation loops was in our case negatively affected by the effect of the simultaneously supperposed cross-flow of liquid due to mutual situation of downcomer pipes. Of course, with increasing w_G the visual observation of circulation became more and more difficult because of increasing number of accidental, disturbances that made observation of the basic liquid motion very dubious. Without regard to the found changes in the flow character both phases with w_G, from photographs of the bed became obvious that in the whole range of all considered variables the equivalent diameter of the majority of bubbles was in the interval $d_B \in \langle 0{\cdot}1; 0{\cdot}8 \rangle$ cm in which it was possible to assume the velocity of free rise of bubbles to be constant $u_{B\infty} = 0{\cdot}235$ m/s[3,14].

At first, we have compared the experimental data of ε_{G2} with the calculated porosities for the limiting case $\varepsilon_{GV} = \varepsilon_{GS} = \varepsilon_G$ from relation (*23*) where for $u_{B\infty}$ was substituted the value $u_{B\infty} = 0{\cdot}235$ m/s. From this comparison followed that in the whole range of w_G values the experimental porosities were considerably smaller. Thus the assumption $\varepsilon_{GV} = \varepsilon_{GS}$ has not been fulfilled in the studied stage and the conditions in this stage corresponded to the general case $\varepsilon_{GV} > \varepsilon_{GS}$. The system of Eqs (*9*), (*15*) and (*17*) which is describing this general case must be thus supplemented with the relation enabling to determine the cross-sectional area of the region of upward flow a for the given conditions. In general, we have assumed that a may be a function of all studied variables. On basis of the experimental data of ε_{G2} and from comparison of their dependences on individual variables with the form of Eqs (*9*), (*15*) and (*17*); it can be assumed in the experimentally studied range that values of a do not depend on φ, and further on, that quantities W_L and d_0 are only affecting the porosities practically through their effect on the value of a.

Since accurate experimental measurement of the cross-sectional area of the upward flow is very complex, we have used for expressing the quantity a an indirect method of reversed procedure of its calculation from the experimental data of porosities where because of the formally identical form of equations derived in the theoretical part for description of both the one and two-loop circulations it does not matter if, under conditions for which experimental data were obtained, the circulation in the stage corresponded to one or to two-loop circulation. In order to be able to compare at least approximately the calculated and the experimental data, the width of the upward region was determined by a simple method in which the direction, of motion of threads situated on wires was observed where at different heights of the stage it was possible to move the threads perpendicularly to the vertical axis. Then, on basis of the determined mean linear dimension it was possible to calculate the cross-sectional area of the region for upward flow under the assumption of a circular shape of the cross-sectional area for the two-loop circulation model and the shape of circular segment for the one-loop circulation model. The measurements were made with the plates having $\varphi = 4\%$, $d_0 = 3$ mm and in the range of the accuracy of the measuring method there was found no effect of the liquid flow rate on a. On basis of the experiments for $w_G = 0{\cdot}008$ m/s the value of the mean cross-sectional area of the region for upward flow $a \sim 250 \,.\, 10^{-4}\,m^2$ was obtained. At higher gas velocities the measurement became more and more difficult because of transition to the two-loop circulation and due to an increasing chaotic eddy motion so that the obtained values of $a \sim 400$ or $500 \,.\, 10^{-4}\,m^2$ for $w_G = 0{\cdot}025$ or $0{\cdot}042$ m/s can be considered to be only a verification of the model made on basis of visual observations according to which a increases with increasing w_G.

By arranging the system of Eqs (*9*), (*15*) and (*17*), for calculation of a the relation has been derived

$$a = \frac{\dot{V}_L E \varepsilon_{GV} - \dot{V}_G(1 - \varepsilon_{GV}) + \varepsilon_{GV} A u_{B\infty}\left\{1 - \varepsilon_{GV} + \frac{1}{2gH}\left[u^2_{B\infty} + \left(\frac{\dot{V}_G}{a\varepsilon_{GV}} - u_{B\infty}\right)^2\right]\right\}}{\frac{\varepsilon_{GV} u_{B\infty}}{2gH} \cdot \left[u^2_{B\infty} + \left(\frac{\dot{V}_G}{a\varepsilon_{GV}} - u_{B\infty}\right)^2\right]}, \qquad (30)$$

where

$$\varepsilon_{GV} = \frac{\dot{V}_G}{A u_{B\infty}(1 - \varepsilon_G) + \dot{V}_L E + \dot{V}_G}. \qquad (31)$$

For experimental data of ε_{G2} (for the plate with $\varphi = 4\%$, $d_0 = 3$ mm) values of a were calculated (Table I) from Eq. (*30*) by the method of successive approximations.

From the results is obvious that the changes of a and W_L correspond to the experimentally determined effect of W_L on ε_{G2} which verifies the assumption that W_L is affecting the gas holdup practically only through its effect on the cross-sectional area of the region for upward flow. From Table I is also obvious a decrease of a with increasing $\dot{V}_G(w_G)$ which is contradictory to the conclusions made on basis of visual observation of flow in the stage and with the results of orientation measurements by use of the method of threads.

From an analysis of relations for a ((*30*) and (*31*)) followed that the most probable reason lies in the use of relations (*12*) and (*13*) for calculation of the upward velocity of the gas phase in the bed.

These relations are obviously valid only in the case when individual bubbles are not mutually affecting each other which, as can be seen from the photographs, is fulfilled only for $w_G = 0{\cdot}008$ m/s while at $w_G = 0{\cdot}025$ or $0{\cdot}042$ m/s this assumption cannot be already considered to be fulfilled. In agreement with these considerations the value of a obtained by the experiments with the threads at $w_G = 0{\cdot}008$ m/s is, due to the accuracy of the experiments made, in very good agreement with the calculated values unlike those at $w_G = 0{\cdot}025$ or $0{\cdot}042$ m/s. Hindering of bubbles taking place under these conditions is obviously responsible for independence of the upward velocity of the gas phase on velocity of individual bubbles which corresponds to their size and which is thus higher than corresponds to relations (*12*) and (*13*).

A detailed explanation of these problems related with determination of factors affecting the upward gas velocity under conditions of mutual affect on bubbles and the qualitative or quantitative analysis of their action would require an experimental method for determination of the velocity v_s under the given conditions. Methods proposed by Reth[2] or Nicklin[6] are not suitable for plate units with the relatively small height of the stage. It would be necessary for calculation of v_s from experimental data on porosity to measure simultaneously also reliable data on the size of the cross-sectional area of the upward region a or eventually on velocity w_{LS}. Our experimental methods have not yet made this possible.

Under these circumstances the values of a as calculated by us are not in agreement at higher gas velocities with the actual conditions in the experimental unit but they can be considered empirical factors giving the correction for changes in v_s resulting from the mutual hindering

TABLE I

Calculated Cross-Sectional Areas of Ascending Region of the Circulation Loop

W_G m/s	$W_L \cdot 10^3$ m^3/m^2 s	$a \cdot 10^4$ m^2	W_G m/s	$W_L \cdot 10^3$ m^3/m^2 s	$a \cdot 10^4$ m^2
0·008	2·5	250	0·025	7·5	179
0·008	5·0	235	0·042	2·5	179
0·008	7·5	240	0·042	5·0	174
0·025	2·5	196	0·042	7·5	166
0·025	5·0	185			

TABLE II

Experimental and Calculated Porosities

$\varphi = 4\%$, $d_0 = 3$ mm, $W_L = 2\cdot5-7\cdot5 \,.\, 10^{-3}$ m^3/m^2 s.

W_G m/s	ε_{G2} experimental	ε_{G2} calculated
0·008	0·018	0·18
0·025	0·060	0·062
0·042	0·109	0·106

of the rising bubbles in relation for calculation of porosity (*9*), (*15*) and (*17*). So in the whole range of w_G these relations can be used for calculation of porosities where for v_s are substituted values calculated from relation (*12*) and where $u_{B\infty}$ corresponds to the determined size of bubbles in the bed regardless of mutual hindering taking place and thus also without need to determine the actual values of v_s for the given conditions. For expressing the dependence of the mean values of the correlation factor $\bar{a}[\bar{a} = \bar{a}(w_G) \neq f(W_L)]$ on w_G an empirical relation has been obtained

$$\bar{a} = 0\cdot13 w_G^{-0.21} \,.\, A\,, \tag{32}$$

and for values of a calculated from this relation were calculated values of $\bar{\varepsilon}_{G2}[\bar{\varepsilon}_{G2} = \bar{\varepsilon}_{G2}(w_G) \neq \neq f(W_L)]$ for individual w_G from relations* (*9*), (*15*) and (*17*).

From comparison made in Table II is obvious a good agreement of the calculated and experimental values. Due to the more or less empirical nature of the quantity a (and thus of $\bar{a}$ as well) the use of relations (*9*), (*15*) and (*17*) for calculation of porosities does not represent under the given circumstances a more general procedure than an application of another simple, purely empirical relation obtained on basis of measurements of porosities, *e.g.* the linear dependence on the gas velocity.

We see the main advantage of the here proposed method for calculation of porosities in the relatively simple mathematical model based on information on the flow character in the bubbled bed. Porosities calculated on its basis have reasonable values. To use the model, parameters a and v_s must be known, which have a clear physical sense defined and whose experimental determination though obviously difficult is basically possible.

* For $\dot{V}_L E$ were in the relations substituted values of $\bar{Q}_2 = \bar{Q}_2(w_G) \neq f(W_L)$.

LIST OF SYMBOLS

A total cross-sectional area of column (L^2)
a cross-sectional area of ascending region of the circulation loop (L^2)
a_0 plate area on which holes are situated (L^2)
a correction factor
D_K column diameter (L)
d_0 diameter of holes in plate (L)
d_B diameter of bubbles (L)
E backmixing coefficient
g gravitational acceleration (L/T^2)
H height of bubbled bed (L)
k_1 coefficient
k_2 coefficient
L length of downcomer pipe (L)
Δp pressure drop (M/LT^2)
Q absolute value of backmixing flow (L^3/T)
$u_{B\infty}$ ascending velocity of a single bubble (L/T)
$\dot{V}_G$ volumetric gas flow rate (L^3/T)
$\dot{V}_L$ volumetric liquid flow rate (L^3/T)
v actual flow velocity of phases (K/T)
v_s ascending velocity of a group of bubbles (see 2·2) (L/T)
w superficial velocity of phases (L/T)
W_L liquid feed rate (L^3/L^2T)
x distance from the upper end of plate (L)
y height of liquid in manometer (L)
δ relative deviation
ε_G porosity of bubbled bed
ϱ density (M/L^3)
φ relative free plate area

Subscripts

S descending region
V ascending region
L liquid
G gas
1 upper stage
2 middle stage
3 bottom stage
i i-th stage or pressure tap

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