INTENSIFICATION OF MASS TRANSFER IN SIEVE PLATE BUBBLE COLUMNS

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The effect was studied of gas distribution on the character of the gas-liquid mixture and its porosity in 0·15 and 0·30 m in diameter bubble reactors.

The experiments covered a wide range of gas-liquid mixture height to reactor diameter ratios (2—18) with the superficial gas velocities ranging between 0·015 and 0·184 m/s. The gas was distributed by a sieve plate of 0·2 or 0·5% free area exhibiting various configurations of the openings. The obtained experimental evidence suggests that the degree of affecting the character of the bubble layer and its porosity through the design of the distributing plate varies in dependence on the size of the bubble layer. The effect was evaluated of the size of the bubbling layer and the plate free area on the porosity for uniformly bubbling columns. The nonlinear course of the experimentally found dependences of porosity on the superficial velocity of gas was fitted by a simple semi-empirical relation valid for the whole range of experimental conditions covered by experiments.

A characteristic feature of bubble column reactors is its versatility stemming from the flexibility of the operating regime that can be adjusted in accord with the requirements of the process over a wide range. Apart from the application to slow reaction taking place predominantly in the bulk liquid phase, bubble column reactors may be used also in those cases when the net reaction rate is controlled by mass transfer. The intensity of mass transfer and hence the productivity of the reactor are in these cases influenced markedly by the extent of the interfacial area. Maximum interfacial area plays therefore a key role in bubble reactor design under such conditions. The efficiency of bubble reactors without mechanical mixing in this respect depends directly on the distribution of the feed gas and hence on the choice of the distributing plate and its construction parameters. For this reason considerable attention has been paid recently to the study of new types of distributors; as promising appear, for instance, various distributors working on the ejector principle. In comparison with these new types, the major advantage of sieve plates is their simplicity and low power input requirements, not to speak about the application in stage-wise units where perforated plates can be hardly substituted without considerable construction complications. It thus remains practicable to search for optimum conditions for the operation of sieve plate columns or for optimum design of the distributing plate for given experimental conditions.

Our previous work[1] dealing with the hydrodynamics of shallow gas–liquid mixtures ($H/D_K = 2$) indicated that proper design of the distributing plate may significantly affect intensity of contact of both phases in the bubbling layer. Distributing plates with uniformly distributed openings operated above the stability limit, *i.e.* under conditions when all openings bubble, permit higher hold-up of gas as well as higher value of the volume mass transfer coefficient to be achieved in comparison with the case when nonuniform gas distribution induces circulatory flows[1] in the layer. The aim of this work has been to assess the effect of gas distribution on the properties of the gas–liquid mixture in a wide interval of gas velocities as well as the size of the layer. The aim has been also to determine factors affecting porosity of the uniformly bubbling layer. Porosity has been selected as a quantity characterising conditions in the layer owing to the ease of its measurement and for the fact that for the given way of dispergation there exists a unique relationship between porosity and interfacial area[2].

EXPERIMENTAL

The experiments were carried out in a single-stage column reactors 0·152 and 0·292 m in diameter. The columns consisted of cylindrical glass sections 0·5 and 0·6 m high for the two respective column diameters, mounted between aluminium flanges. Individual sections were separated by aluminium rings. The top of the column was firmly mounted to fix the vertical position and eliminate vibrations which would otherwise have occurred during bubbling.

Gas at the inlet was distributed by sieve plates made of brass 0·003 m thick sheets. The edges of the openings were left unbevelled. In both reactors we have tested five plates of the same free area ($\varphi = 0{\cdot}2\%$) and opening diameter ($d_0 = 0{\cdot}0016$ m) differing mutually in the shape and extent of the active surface, *i.e.* the part of the plate with the openings. On the plates A and B the active surface was represented by segments of a circle $l_a = 0{\cdot}17D_K$, or $0{\cdot}33D_K$; for plates C and D by concentric circles ($d_a/D_K = 0{\cdot}33$ or $0{\cdot}53$). On the plate E the openings were distributed evenly over the whole surface. The plates were designed so as to provide well defined limiting regimes of bubbling: The regime with one-loop circulation, two-loop circulation and the regime of uniform bubbling[1]. The active surface as a fraction of the plate surface (A_a/A_K) equalled for plates A and C 0·11, for B and D 0·30. The openings were in all cases arranged in a triangular pitch 0·012 m (plates A and C), 0·020 m (plates B and D) and 0·035 m (plate E). In the column 0·292 m in diameter we also worked with a plate with 0·5% free area. The diameter of the openings arranged in a triangular pitch evenly over the whole surface of the plate 0·0255 m apart, was also 0·016 m.

The experiments were carried out with the water/air system at zero rate of liquid. In the 0·152 m column the range of gas flow velocities was between $0{\cdot}278 \,.\, 10^{-3}$ and $3{\cdot}333 \,.\, 10^{-3}$ m^3/s, in the 0·292 m in diameter column between $1{\cdot}667 \,.\, 10^{-3}$ and $5{\cdot}020 \,.\, 10^{-3}$ m^3/s. Corresponding superficial gas velocities were 0·015 to 0·184 m/s ($D_K = 0{\cdot}152$ m) and 0·025 to 0·075 m/s ($D_K = 0{\cdot}292$ m). In the smaller reactor the experiments involved three different heights of the liquid $H_0 = 0{\cdot}4$; 1·3; 2·1 m, while in the larger of the two reactors H_0 was 0·5 and 1·9 m. Corresponding ratios of the height of the bubbling liquid column to reactor diameter in the experimental range of w_G

were $H/D_K = 4$; 10; 18 (for $D_K = 0{\cdot}152$ m) or $H/D_K = 2$; 7 (for $D_K = 0{\cdot}292$ m). Porosity of the bubbling layer was measured by the manostatic method.

RESULTS AND DISCUSSION

Character of the Bubbling Layer

To reach a well defined character of bubbling on sieve plates it is necessary to work in region of stable operation, *i.e.* under the conditions when all openings on the plate bubble. Our earlier experiments in the 0·292 m in diameter column and $H/D_K = 2$ with plates of the type B, C, E used in this work ($\varphi = 0{\cdot}2\%$, $d_0 = 0{\cdot}0016$ m) have shown[1] that for the assessment of the stability limits one can use critical value of the F-factor proposed by Haug[4] ($F = u_0\,\varrho_G^{1/2}$) $F_{crit} = 14$ m/s (kg/m³)$^{1/2}$ or corresponding critical value of gas velocity within the plate openings u_0

$$u_0 = w_G/\varphi\,. \qquad (1)$$

For air at 20°C u_{0crit} equals 12·7 m/s. From the above equation there follows that excepting the lowest superficial gas velocities in the column $D_K = 0{\cdot}152$ m($w_G = 0{\cdot}0152$ m/s), all measurements of this work were carried out under the conditions of stable operation of the plates. Visual observation confirmed that in the given interval of gas flow rates all plates really did exhibit stable operation regardless of D_K or H/D_K. Under such conditions the regime within the bubbling layer was observed visually as well as from the photographs of the layer. From the standpoint of the character of bubbling no significant qualitative deviations were observed between the two columns differing in diameter which is in accord with Nývlt's findings[5] regarding the unstable operating plates.

During the experiments in columns with a shallow and medium height layer, *i.e.* with $H/D_K = 2(D_K = 0{\cdot}292$ m) and $H/D_K = 4(D_K = 0{\cdot}152$ m), it was found that the used plates A–D permit fairly well various circulatory regimes of bubbling to be simulated. The character of the layer for the stabilized one-loop and two-loop

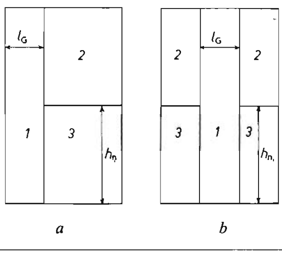

FIG. 1

Scheme of Circulation Models of Bubbling Layer

a) One-loop circulation; *b*) two-loop circulation; *1* region of rising main stream, *2* homogeneously bubbling region, *3* region by-passed by bubbles.

regimes has been described earlier[1]; Fig. 1 shows schematically corresponding simplified models of the layer for both types of circulation. From the viewpoint of gas flow and gas hold-up distribution the layer may be in both cases thought to consist of three principal regions[1]: The region of rising main stream of gas (*1*), homogeneously bubbling region (*2*) and the region completely by-passed by bubbles (*3*). Unlike the earlier proposed circulatory models[3,6], the proposed model contains, apart from the characteristic extent of the region of the rising main stream (l_a), still another parameter — the height of the region by-passed by bubbles (h_n). Our exploratory measurements in the column $D_K = 0{\cdot}292$ m have shown h_n to depend on the type of the plate and the value A_a; the decrease with growing superficial gas velocity in the investigated interval $w_G = 0{\cdot}025 - 0{\cdot}075$ m/s could be roughly approximated by a straight line.

Examination of the character of bubbling in tall columns have shown that, independently of the height of the gas–liquid layer and the character of circulation induced

TABLE I

Experimental Porosities for $D_K = 0{\cdot}152$ m Column

H/D_K	w_G, ms^{-1}	Plate				
		A	B	C	D	E
4	0·015	0·027	0·035	0·034	0·042	0·047
4	0·031	0·046	0·075	0·070	0·074	0·092
4	0·061	0·128	0·126	0·125	0·136	0·152
4	0·092	0·163	0·185	0·179	0·193	0·202
4	0·123	0·204	0·212	0·198	0·223	0·237
4	0·153	0·253	0·248	0·220	0·261	0·273
4	0·184	0·288	0·290	0·285	0·296	0·306
10	0·015	0·035	0·039	0·038	0·042	0·043
10	0·031	0·066	0·073	0·079	0·086	0·090
10	0·061	0·111	0·124	0·116	0·131	0·133
10	0·092	0·150	0·166	0·161	0·167	0·177
10	0·123	0·186	0·196	0·192	0·201	0·212
10	0·153	0·217	0·219	0·218	0·225	0·240
10	0·184	0·251	0·255	0·246	0·258	0·264
18	0·015	0·040	0·041	0·042	0·043	0·045
18	0·031	0·077	0·083	0·085	0·088	0·092
18	0·061	0·121	0·127	0·129	0·130	0·138
18	0·092	0·163	0·163	0·162	0·168	0·171
18	0·123	0·189	0·191	0·193	0·194	0·198
18	0·153	0·217	0·223	0·219	0·223	0·232
18	0·184	0·251	0·255	0·243	0·259	0·272

by individual plates, there always exists only one section with fully developed circulatory flow. Its height, H_c, was in the investigated range independent of gas velocity and corresponded approximately to the column diameter doubled. With the height of the liquid column exceeding the H_c limit, no other circulation sections appeared and the character of the layer along the whole column height approached uniform bubbling.

The experiments with the plate E with openings uniformly distributed over the whole surface lead always to the stable regime of bubbling corresponding to the uniformly bubbling layer independently of column diameter and liquid column height.

Porosity of Bubbling Layer

Tables I and II summarize mean porosities of the bubbling layer (ε_G) found experimentally in the two columns using the distributing plates of the A–E types for individual superficial gas velocities and the ratio H/D_K. From the presented data it may be apparent that with the plate E, distributing the gas evenly over the column cross section ($A_a = A_K$), the porosity of the bubbling layer in both columns was higher in the whole investigated range of w_G and H/D_K than in the cases with circulation. The porosity decreased with increasing maldistribution of entering gas, *i.e.* with decreasing area A_a (in the sequence E – B – A or E – D – C). Also, under otherwise the same conditions (φ, d_0, A_a, w_G) the porosity in layers with induced two-loop circulation was greater than in those with one-loop circulation (pairs of plates C – A or D – B).

The effect of nonuniform distribution of porosity became most obvious in the larger diameter column ($D_K = 0{\cdot}292$ m); for the column of a given diameter the effect of

TABLE II

Experimental Porosities for $D_K = 0{\cdot}292$ m Column

H/D_K	w_G, ms^{-1}	Plate				
		A	B	C	D	E
2	0·025	0·028	0·031	0·029	0·034	0·059
2	0·042	0·058	0·083	0·063	0·086	0·108
2	0·058	0·094	0·132	0·098	0·129	0·146
2	0·075	0·149	0·165	0·151	0·161	0·178
7	0·025	0·053	0·060	0·062	0·070	0·081
7	0·042	0·083	0·095	0·094	0·104	0·123
7	0·058	0·118	0·129	0·121	0·131	0·150
7	0·075	0·142	0·157	0·146	0·161	0·166

distribution grew weak with increasing value H/D_K. For given values of D_K and H/D_K the effect of maldistribution decayed with increasing superficial velocity of gas. All these findings comport with the results of visual observation of the character of the bubbling layer under the given conditions.

A comparison of experimental data revealed that in 0·292 m in diameter column (for $H/D_K = 2$) with the distributing plate E a doubled porosity was reached in comparison with the one-loop circulation induced by the plate A. Table III shows the differences of porosity ε_G for these two plates in dependence on the variables D_K, H/D_K, w_G. The quantity $\Delta\varepsilon_G$ is defined as

$$\Delta\varepsilon_G = (\varepsilon_{GE} - \varepsilon_{GA})/\varepsilon_{GE}\, 100\,. \qquad (2)$$

Increasing gas maldistribution enhances also the nonuniformity of gas hold-up distribution along the column height. In accord with the observed character of the bubbling layer it was found by comparing the axial porosity profiles in a uniformly bubbling layer and in layers with circulation that gas hold-up distribution differs most at the bottom part up to a height h equalling approximately twice the column diameter, *i.e.* in those parts of the column where gas flow maldistribution gives rise to one- or two-loop circulations. Fig. 2 shows comparison of axial porosity profiles

TABLE III

Values of $\Delta\varepsilon_G$ in % for Plates A and E

w_G, ms^{-1}	H/D_K				
	2	4	7	10	18
		$D_K = 0{\cdot}152$ m			
0·015	—	43	—	20	11
0·031	—	50	—	27	16
0·061	—	16	—	16	12
0·092	—	19	—	15	5
0·123	—	14	—	12	5
0·153	—	7	—	10	6
0·184	—	6	—	5	7
		$D_K = 0{\cdot}292$ m			
0·025	52	—	24	—	—
0·042	46	—	32	—	—
0·058	36	—	21	—	—
0·075	16	—	14	—	—

(ε_{Gi} *versus* h_i) in the uniformly bubbling layer and in the layer with one-loop circulation (for $A_a = 0.11\ A_K$) for the column $D_K = 0.292$ m, $H/D_K = 7$, for $w_G = 0.042$ m/s.

Porosities in the columns of the two diameters in uniformly bubbling layers (distributing plate E) are plotted in Fig. 3 in dependence on the superficial velocity of gas w_G. For all pairs of D_K, H/D_K values we evaluated the dependences $\varepsilon_G - w_G$; the qualitative agreement of their course for the two column diameters points at identical character of bubbling observed visually in both columns.

The presented data further indicate relatively weak influence of the size of the layer on the porosity. In region of low superficial gas velocities ($w_G \leqq 0.05$ m/s) the porosity differences for individual combinations of D_K, H/D_K were insignificant. Lower porosities were obtained only for $H/D_K = 2$, $D_K = 0.292$ m, which may be accounted for by the marked influence of the region of lowered porosity immediately above the plate on the relatively shallow layer. The axial porosity profiles showed that the height of this layer in this region at uniform bubbling is substantially smaller than that of layers with circulation (Fig. 2) and does not depend on the overall height of the layer. At higher gas velocities ($w_K > 0.06$ m/s) in columns of both diameters the porosity in shallow layers ($H/D_K = 2$ for $D_K = 0.292$ m and $H/D_K = 4$ for $D_K = 0.152$) exceeded values found for the same D_K and higher H/D_K. For layers with corresponding H/D_K equal 10 and 18 the porosities found in the 0·152 m in diameter column were practically the same. The cause for the difference is the foaming taking place at high gas velocities in region below the liquid level[5,7]. The axial profiles indicate that the height of the region of increased porosity is independent of the overall height of the layer and its effect on mean porosity thus grows with decreasing H or H/D_K. Table IV summarizes porosities for the column $D_K = 0.152$ computed for the layer without the top foaming part. The table clearly evidences the good agreement of the corrected values (ε_{GK}) in the whole investigated region of H/D_K.

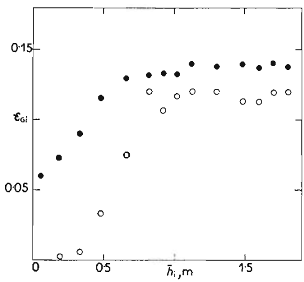

FIG. 2

Profiles of Porosity along Column Height

$D_K = 0.292$ m, $H/D_K = 7$, $w_G = 0.042$ ms^{-1}

○ Plate A, ● plate E.

The dependence of porosity of a uniformly bubbling layer on the superficial velocity of gas at zero flow rate of liquid may be expressed by the relation[1,8]

$$\varepsilon_G = w_G/u_B \,. \tag{3}$$

The quantity u_B designated generally the mean rising velocity of bubbles of unequal size under the conditions of mutual interference. Its value (or the value of the difference $(u_B - u_{B\infty})$) is a measure of the departure of the true conditions in the column from those of ideal bubbling characterized by the rise of isolated, mutually noninterfering equal-diameter bubbles[9,10]. In our previous work we have confirmed that in region of low superficial velocities ($w_G \leqq 0.042$ m/s) the quantity u_B may be regarded as a constant the value of which is determined by physical properties of the two phase system, column diameter and gas distribution. Our present data as well as data of other authors[8,11], however, indicate that u_B in region of higher gas superficial velocities is not constant, but grows with increasing w_G. This in turn causes the deviations of the dependence ε_G *versus* w_G from the linear course predicted by Eq. (*3*) for $u_B =$ = const. Our experimental data (Fig. 3) suggest that the plot ε_G *versus* w_G is nonlinear in the whole investigated range of D_K and H/D_K for $w_G > 0.05$ m/s.

The nonlinear relationship ε_G *versus* w_G in layers with uniformly distributed gas has been fitted[4,12] by an expression of the type

$$\varepsilon_G = w_G/(A + Bw_G) \,, \tag{4}$$

where the expression in the denominator on the right hand side represents a functional relation $u_B = u_B(w_G)$. The coefficients A and B in Eq. (*4*) may be assigned a definite

TABLE IV

Experimental Porosities of Uniformly Bubbling Layer without the Top Foaming Section, $D_K =$ = 0·152 m, Plate E

w_G, ms^{-1}	H/D_K 4	H/D_K 10	H/D_K 18
0·015	0·042	0·042	0·044
0·031	0·086	0·084	0·087
0·061	0·126	0·129	0·131
0·092	0·162	0·165	0·167
0·123	0·212	0·192	0·194
0·153	0·227	0·215	0·222
0·184	0·250	0·247	0·255

physical meaning based on a simplified concept: B characterizing the departure of the conditions within the layer from these in the ideal layer, while A, which has a physical dimension of buoyancy force, is determined by the properties of the given two phase system. Generally, however, both coefficients are clearly not mutually independent and the conditions in an arbitrary uniformly bubbling bed are characterized from the viewpoint of porosity *versus* gas velocity dependence always by a certain combination of A and B values (for given apparatus and gas–liquid system) computed for given experimental $\varepsilon_G - w_G$ data from Eq. (*4*).

Fig. 3 plots the ε_G *versus* w_G dependence computed from Eq. (*4*) for $A = 0{\cdot}3$ m, $B = 2$, obtained by Mashelkar[12] by processing an extensive set of experimental data of various authors. The same coefficients were also computed from Eq. (*4*) for our experimental data obtained under the conditions of uniform bubbling in the whole investigated range of variable D_K, H/D_K. w_G. The figure shows a fairly good agreement of the computed dependence with our experimental data especially for deep layers, where the experiments, as above noted, were free of the anomalous phenomena in the bottom and the top part of the layer. In the whole investigated range of variables (D_K, H/D_K, w_G) even the data from shallow layers fall within $\pm 15\%$ of the computed course (these limits are shown by broken line); in region of higher gas

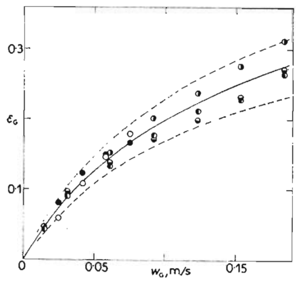

FIG. 3

Porosity of a Uniformly Bubbling Layer as a Function of Superficial Gas Velocity

◑ $D_K = 0{\cdot}152$ m, $H/D_K = 4$; ◐ $D_K = 0{\cdot}152$ m, $H/D_K = 10$; ◒ $D_K = 0{\cdot}152$ m, $H/D_K = 18$; ○ $D_K = 0{\cdot}292$ m, $H/D_K = 2$; ● $D_K = 0{\cdot}292$ m, $H/D_K = 7$. ——— computed values, ----- limits of $\pm 15\%$.

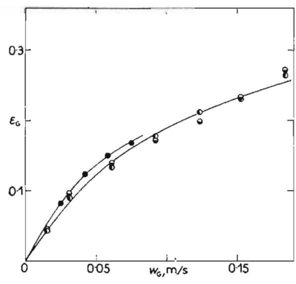

FIG. 4

Comparison of Experimental and Computed Data ε_G *versus* w_G for Deep Layers

◐ $D_K = 0{\cdot}152$ m, $H/D_K = 10$; ◒ $D_K = 0{\cdot}152$ m, $H/D_K = 18$; ● $D_K = 0{\cdot}292$ m, $H/D_K = 7$. ——— computed values.

velocities, however, a systematic deviation appears which may be attributed to increasing contribution of the foaming part on the mean value of porosity of the layer.

The values of the coefficients A and B computed from Eq. (*4*) for high layers ($H/D_K \geqq 7$) are summarized in Table V correspondingly to individual pairs of D_K, H/D_K values. As may be seen the experimental data for H/D_K equal 10 and 18 ($D_K = 0\cdot152$ m) have the same corresponding pairs of A, B values. Fig. 4 shows a very good agreement of the ε_G *versus* w_G function computed for individual pairs of A, B values evaluated from Eq. (*4*) with the experimental data.

An interesting conclusion from the viewpoint of intensification of sieve plate bubble reactors followed from comparison of porosities measured in the column $D_K = 0\cdot292$ m (for $H/D_K = 2$; 7) with gas being distributed by plates E and F. This comparison, furnished in Table VI indicates that in the range of w_G between 0·042 and 0·075 m/s the porosity corresponding to the plate F was significantly higher for both ratios H/D_K. For this plate Eq. (*1*) gives that the critical velocity $u_{0crit} = 12\cdot7$ m/s necessitates superficial velocity $w_G = 0\cdot064$ m/s. This means that the plate F worked almost in the whole investigated interval of gas velocities below

TABLE V

Parameters A and B (Eq. (*4*)) Computed from Experimental Porosities

D_K, m	H/D_K	A, ms^{-1}	B
0·152	10	0·30	2·3
0·152	18	0·30	2·3
0·292	7	0·23	2·8

TABLE VI

Porosity as a Function of Plate Area, $D_K = 0\cdot292$ m, Plates E and F

H/D_K	φ, %	w_G, ms^{-1}			
		0·025	0·042	0·058	0·075
2	0·2	0·059	0·108	0·146	0·178
2	0·5	0·061	0·129	0·186	0·224
7	0·2	0·081	0·123	0·150	0·166
7	0·5	0·080	0·142	0·169	0·178

the limit of stable operation. The explanation for this seeming discrepancy may be apparent from Fig. 5 showing the number of bubbling openings as a function of gas velocity within the opening for plate F. The plot shows that for $u_0 = 8{\cdot}4$ m/s and corresponding superficial velocity $w_G = 0{\cdot}042$ m/s there are about 150 bubbling openings on plate F, which is substantially more than the total number of openings on plate E ($n = 67$). Plate F thus permits a more uniform distribution of gas over the plate surface at lower gas velocity in the openings. Besides, the fluctuations of the number of openings which at this w_G still do not bubble cannot give rise to significant macro circulations.

Fig. 5 plots also the n_B/n *versus* u_0 function obtained earlier for plate E. A similar shape of the curves for both plates points at the existence of a generally valid n_B/n *versus* u_0 dependence enabling estimates of the number of bubbling openings for a given w_G on an arbitrary plate. In view of the error of the visual estimate of the number of bubbling openings it is impossible to ascertain from data for only two plates in a relatively narrow interval of values φ whether the n_B/n *versus* u_0 function is or is not affected by the extent of the free area. The obtained dependences indicate that for both plates at $u_0 = 2/3\ u_{0crit}$ there is at least 80% of all openings bubbling. This estimate may be used when making the choice of the distribution plate for the required velocity of gas[13].

CONCLUSION

It has been found that in region of stable operation of the plates there exists in a layer with nonuniformly distributed gas only one section with fully developed circulatory flow (one- or two-loop circulation), independently of the total height of the liquid column. The height of this circulatory section equals approximately twice the column diameter. It has been confirmed that over a wide range of the dimensions of the

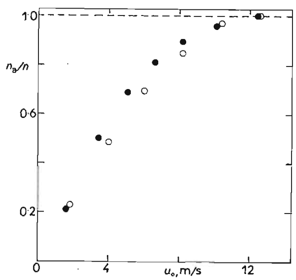

FIG. 5

Number of Bubbling Openings as a Function of Gas Velocity within Plate Opening
○ Plate E, ● plate F.

layer and gas superficial velocities, a significant increase of porosity may be achieved by uniform distribution of gas in comparison with layers exhibiting circulation. The porosity decreases with increasing degree of maldistribution of the feed gas while increasing height of the column and superficial velocity of the gas both diminish this effect.

Only a minor effect has been detected of the dimensions of the layer, D_K, H/D_K on porosity in uniformly bubbling layers in the investigated range. Nonlinear dependences ε_G *versus* w_G have been found for all tested dimensions of the layer characterized by the parameters D_K and H/D_K. This dependence can be fitted in the whole investigated interval fairly well by the relation of the type as in Eq. (*4*) with constant values of the coefficients $A = 0.3$ m/s and $B = 2$, recommended in the literature for the air/water system.

It has been established that in the region of stable operation of the plates, porosity of the uniformly bubbling layer grows with increasing free area of the distributing plate. In addition, experimental data have shown that the operation of the plate may be regarded as practically stable already at gas velocity in plate openings equaling two thirds of the critical value corresponding to the stability limit. From the standpoint of reaching maximum porosity for the given gas flow rate, a plate with larger free area is more favourable than the one recommended in the literature[4,13]. Such plate, in addition, has the advantage of offering also a lower pressure drop.

LIST OF SYMBOLS

A	coefficient in Eq. (*4*)
A_a	active surface of plate
A_K	cross sectional area of reactor
B	coefficient in Eq. (*4*)
d_a	characteristic dimension of active surface of plate
d_0	plate opening diameter
D_K	reactor diameter
$F = u_0 \varrho_G^{1/2}$	F-factor
h	distance from upper edge of the plate
h_n	height of region by-passed by bubbles
H	height of bubbling layer
H_c	height of circulatory section
H_0	clear liquid height
$k_L a$	volume mass transfer coefficient
l_a	characteristic dimension of active surface of plate
l_G	characteristic dimension of rising stream of gas
n	number of plate openings
n_B	number of bubbling openings
u_B	rising velocity of a cluster of bubbles
$u_{B\infty}$	rising velocity of an isolated bubble
u_0	gas velocity within plate opening

w_G	superficial gas velocity
ε_G	porosity of bubbling layer
$\Delta\varepsilon_G$	dimensionless difference of porosities, Eq. (*2*)
ϱ_G	gas density
φ	relative free area of plate

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