

## THE STRUCTURE OF THE GAS-LIQUID MIXTURE ON A SIEVE PLATE WITHOUT DOWNCOMER. THE CONDUCTIVITY METHOD\*

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The one-dimensional model of the structure of the gas-liquid mixture due to Kolář has been tested using a method based on electric conductivity. The results have been confronted with the porosity of the gas-liquid mixture obtained from experimental course of the pressure along the height of the mixture. The formation of waves in the gas-liquid mixture, particularly under the moving froth and the oscillatory regimes, leads to a uniform structure of the froth in horizontal levels. The discrepancy between the averages obtained by integrating the experimental profiles of the conductivity along the column axis and the average porosity resulting from the hold-up of liquid and the height of the froth increases for the above mentioned regimes with the column diameter. A good agreement has been found in case of the cellular froth regardless of the magnitude of liquid hold-up. The same may be said about the average porosities obtained by integrating the smoothed curves obtained by fitting the data to the Kolář's equation. On the other hand a very good agreement was found for all regimes and column diameters between the average porosity computed from liquid hold-up and that obtained by integrating the Kolář's equation in which the hold-up in the column axis is replaced by the average hold-up found by weighing. The algorithm of the computational routine determines a parameter  $\bar{\epsilon}_0$  — the equivalent initial porosity under the oscillatory and the moving froth regimes — mainly from the course of the porosity in upper layers of the froth. Thus one can infer on the nonhomogeneity of the froth in horizontal levels in the bottom layer rich on liquid and on the wave motion as a source of nonhomogeneity. The liquid is thus concentrated around the column axis which is in agreement with the earlier compared pressure courses in the level of the plate. The experimental technique may be applied also to two-phase liquid-liquid and liquid-solid systems.

Porosity of a dynamic two-phase mixture is one of the basic parameters identifying separation equipment. This quantity is directly associated with the process of expansion of one of the phases in an element of the separation equipment as a consequence of the flow of the other phase. The bulk of the work in this field are studies of the average porosity as a function of the quantities characterizing the separation equipment from the hydrodynamic point of view: the flow rates of phases, the hold-up of the heavier phase in an element of the separation equipment, its design, physico-chemical properties of both phases *etc.*

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Although porosity represents only an integral characteristics of the system, no satisfactory correlation has been proposed to date despite of a considerable number of papers dealing with the subject. The main cause of this situation rests in the formation of two-phase systems mutually widely different under various and often even under identical operating conditions. Accordingly, the range of applicability of both the empirical and semiempirical correlations based on a unidimensional theory of the two-phase flow is necessarily very confined.

In this context the problem has been examined in a monograph by Wallis<sup>1</sup> and a review paper of Prince and coworkers<sup>2</sup>.

The following correlation is often recommended for typical regimes prevailing in gas-liquid plate columns

$$V_G = [\bar{\epsilon}/(1 - 1.2\bar{\epsilon})] \cdot 0.35 (gD)^{1/2} \quad (1)$$

or the A.I.C.H.E. correlation<sup>3</sup>. A majority of the experimental work starts either from direct evaluation of the average porosity from the known hold-up and the height of the froth, or from the ratio of the pressure drop between two points and their distance. The latter method is suitable for gas-liquid mixtures homogeneous in horizontal levels. Already Kutateladze and Styrikovich noted in their monograph<sup>4</sup> the existence of nonhomogeneities along the height of the two-phase dynamic mixture. The course of the porosity was examined by the authors with the aid of  $\gamma$ -rays. It was found that the character of the distribution of the phases along the height of the layer was the same in gas-liquid and liquid-liquid systems. On the basis of an extensive set of experimental evidence the authors arrived at the following qualitative conclusions: *a*) in the major part of the mixture the density is practically constant, *b*) increased density occurs mainly near the openings distributing the lighter phase; upper part of the layer displays decreased density. While at low flow rates of the lighter phase and hence low porosities the transition region is not wide (20–30 mm), at high flow rates this transition region expands up to 400–500 mm.

As interesting appear also the findings regarding the accuracy of the  $\gamma$ -ray method. In the low porosity region where the accuracy of measuring the hold-up of the heavier phase and of the height of the layer are very good the deviations are random. At higher porosities the  $\gamma$ -method gives systematically higher results by 10–15%. In large diameter columns (200–250 mm) the local porosities in the center part are higher than those near the wall.

A theoretical approach to the problem of the structure of the gas-liquid mixture can be found in papers by Azbel<sup>5,6</sup> and Kolář<sup>7</sup>. Both authors use the unidimensional approach; Azbel assumes a minimum energy of the layer to derive a relation for the course of the porosity along the height of the layer as well as a dependence relating the average porosity to liquid hold-up and gas velocity. Apart from these quantities Azbel's relation contains no other additional parameter. In contrast, Kolář<sup>7,8</sup> starts from the assumption of minimum dissipated energy to obtain ultimately a relation between the porosity of the froth and the distance from the plate. His relation contains a parameter  $e_0$  corresponding to the porosity of the froth in the upper level of the plate. This parameter is a function of certain characteristics, *e.g.* the flow rates of phases, liquid hold-up, plate design and physico-chemical properties of the phases. Kolář<sup>7</sup> pointed also at certain shortcomings of Azbel's approach. Earlier papers<sup>9</sup> have shown that the agreement with experiments is considerably inferior.

According to Kolář<sup>7</sup> the porosity of the gas-liquid mixture,  $e$ , in the distance  $x$  above the plate is given implicitly by

$$\frac{x}{h} = \frac{e_0}{1 - e_0} \frac{e - e_0}{ee_0} + \ln \frac{(1 - e_0)e}{(1 - e)e_0}, \quad (2)$$

where for  $h$  one obtains from the balance on liquid

$$h = \int_0^H (1 - e) dx. \quad (2a)$$

In order to verify the equation experimentally by the course of pressure it is convenient to transform the relation with the aid of the force and momentum balance into the form

$$\frac{x}{h} = \frac{e_0}{1 - e_0} \left[ \frac{1 - e_0}{e_0} \frac{\Delta p_p - \Delta p_x}{\Delta p_p} + \ln \frac{\Delta p_p}{\Delta p_x} \right]. \quad (3)$$

On eliminating  $h$  then

$$x = \frac{1}{\rho_L g} \left( \Delta p_p \frac{e_0}{1 - e_0} + \rho_G V^2 \right) \left[ \frac{1 - e_0}{e_0} \frac{\Delta p_p - \Delta p_x}{\Delta p_p} + \ln \frac{\Delta p_p}{\Delta p_x} \right]. \quad (3a)$$

To calculate  $e_0$  Červenka<sup>9</sup> took the first four terms of the Taylor expansion of Eq. (3a). In the processing he weighted individual pressures by the inverse of the maximum experimental error of the pressure difference  $\Delta p_x$  taking only those pairs of data  $x$ ,  $\Delta p_x$  satisfying the following condition:  $\Delta p_{x1} \in (0.1 \Delta p_p, \Delta p_p)$ .

On an extensive set of data on sieve plates without downcomers 288 mm in diameter he found a very good agreement of the experimental pressure profiles along the column axis with those predicted by Eq. (3a) under the cellular foam regime and on transition to the adjoining regimes. In this region the author succeeded in correlating the parameter  $e_0$  with the dimensional group  $h^{1/2} v^{-1/4}$  regardless of plate construction parameters. Under the developed moving froth and the oscillatory regimes the experimental pressure profiles deviate severely from the theoretical ones, and particularly so in the proximity of the plates. In this connection there are several explanations at hand: Formation of waves in the gas-liquid system, sudden expansion of gas above the plate openings, the way of the pressure within the froth is measured or perhaps a combination of these effects. At the same time it turned out that Eq. (3a) can be also used to determine the expansion of liquid on the plate, i.e. the height of the gas-liquid mixture. Processing an extensive set of data from the region of the froth homogeneous in horizontal levels according to the relation

$$\frac{H}{h} = \frac{e_0}{1 - e_0} \left[ \frac{e_H - e_0}{e_H e_0} + \ln \frac{e_H(1 - e_0)}{(1 - e_H)e_0} \right] \quad (4)$$

lead to  $e_H = 0.975$ . The relation gave also a good agreement with the values of  $e_0$  computed from the mentioned correlation with the dimensional group  $h^{1/2} v^{-1/4}$  even under moderately developed regime of moving froth.

The aim of this work is to confront the results obtained by the conductivity method with Kolář's model as well as with the results obtained from pressure measurements.

## EXPERIMENTAL

The experiments were carried out on 50, 118 and 288 mm diameter models. In the first of the models the plate was replaced by a disc of fritted glass. The 118 mm column had 2 mm openings and 8.21% of free area, or 5 mm openings in a plate with 6.35% of free area. The largest column used had 2.5 mm openings at 14.68% of plate free area. The plates were made of perspex glass 3 mm thick. The system used was air and 0.5% solution of NaCl in distilled water. The hold-up of liquid was measured on the two latter columns by disconnecting simultaneously the gas and liquid inflow and weighing. The results were corrected on the volume of "dead" hold-up in interplate space. An in-advance-known volume of liquid was used in the 50 mm column. The experiments on the 118 mm column were performed at zero through-flow of liquid and a plate with outer downcomer while on the largest column the superficial velocity of liquid was 0.4 and 7 kg/m<sup>2</sup>s. The conductivity probes consisted of glass electrodes located retractably in an opening in the center of the plate. Thus we have eliminated the changes of the displaced volume when measuring in various distances from the plate. The elimination of the stray electric field was tested by placing the electrodes in a magnetic field. The detail of the electrodes is shown in Fig. 1. A comparison of the "effective radius" of the electrodes and the effect on the resolution of measurement of the conductivity profile is shown in Fig. 2. From the figures it is apparent that the electrodes with permanent magnets suit for the purpose better, particularly by confining the interference between two neighbouring levels. The variations due to temperature changes were eliminated by thermostating the liquid to  $\pm 0.2^\circ\text{C}$ , reducing the measurement to short time intervals and determining the reference conductivity of pure liquid and gas for each experiment. Under the steady state the specific conductivity of liquid is constant and the relative conductivity on individual horizontal levels is a function of liquid-to-gas volume ratio only. Since the absolute conductivity of the air-water mixtures was not needed, the measured quantity was the voltage in the diagonal of the resistance bridge. The unit used was SE 429, a product of SE Laboratories, operating with 3 kHz frequency and a built-in amplifier and voltage detector in the diagonal of the bridge. The output signal of this unit could be processed by the Dynamco data logger with alternatively an electric typewriter or a paper tape punch as peripheries.

Local porosity in the gas-liquid mixture displays considerable random fluctuations necessitating preliminary experiments designed to find a sufficient extent of the set of the conductivity data on a given level which would compromise between the requirement of statistical likelihood on one hand and reasonable time economy of the experiment on the other hand. Duration of the experiment on each level was taken 20 s providing 20 values punched on paper tape.

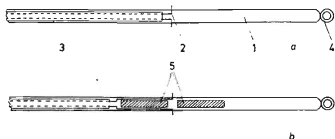


FIG. 1

The Conductivity Probe (a) Without Magnet, (b) With Magnets

1 12 mm diameter glass tube, 2 platinum electrodes, 3 insulated leads to the bridge, 4 loop for retractable mounting, 5 permanent magnets.

The final product of the first part of the data processing program was a set of average voltages  $U_I$  as a function of the porosity of the gas-liquid mixture on individual levels. The data were further normalized according to

$$e_1 = (U_I - U_L) / (U_G - U_L), \quad (5)$$

where  $U_G$ ,  $U_L$  are the reference voltages for air and water, to obtain the corresponding set of porosities. Preliminary tests on the 50 mm column have shown a good agreement between the average porosities obtained by integrating the conductivity profiles with those obtained from the known height of the gas-liquid mixture and confirmed thus the assumption of linear relation between porosity and conductivity.

The bulk of the computer work was a search for the parameters of the mathematical model of the investigated system formulated in Eq. (2). Although at first it appeared that the problem could be solved by some standard method of regression analysis, as *e.g.* the Newton-Raphson or the Marquardt technique, it turned out later that partial derivatives of the function in Eq. (2) with respect to the sought parameters display local extremes in the examined interval of the independent variable. A direct

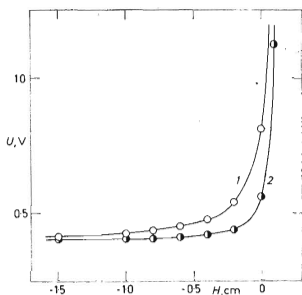


FIG. 2

Test of Probe Sensitivity Near the Air-0.5% NaCl Water Solution Interface

○ Probe without magnet, ● with magnet.

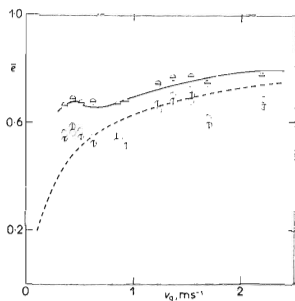


FIG. 3

A Plot of Average Porosity versus Gas Velocity for 118 mm Diameter Plate with 5 mm Openings,  $h = 5$  cm

○  $\bar{e}$  Obtained by integration of experimental porosities, ●  $\bar{e}$  obtained by integration of smoothed (Eq. (2)) profiles, ⊙  $\bar{e}$  obtained by integration of smoothed (Eq. (1)) profiles, —  $\bar{e} = 1 - \bar{h}/H$ , - - -  $\bar{e}$  according to Eq. (1).

consequence of this fact was the instability of the solutions of the set of pertaining non-linear equations and the iterations did not converge. Seeking a new strategy we had to abandon the standard routines, which in the search for local extremes process simultaneously a whole family of functions on the given interval such as *e.g.* the least square technique. As a useful tool proved evaluating the sought parameters for each pair of data and only then applying the least square technique.

The essence of the iterative search for the selected parameter is as follows. Suppose the function is generally defined as

$$y = f(x, \beta_1, \beta_2 \dots \beta_k) . \quad (6)$$

For two subsequent iterations related *e.g.* to the first parameter and the experimental value  $x = x_0$

$$\begin{aligned} y_1 &= f(x_0, \beta_{11}, \beta_{20}, \dots \beta_{k0}) , \\ y_2 &= f(x_0, \beta_{12}, \beta_{20}, \dots \beta_{k0}) , \end{aligned} \quad (7)$$

where  $\beta_{12} = \beta_{11} + \delta\beta$ , the elements of the matrix of differences will be

$$\begin{aligned} D(1, 1) &= y - y_1, \quad D(2, 1) = y - y_2, \quad D(1, 2) = (y - y_1)^2, \\ D(2, 2) &= (y - y_2)^2 . \end{aligned} \quad (8)$$

The sign and the magnitude of the elements of the matrix define unambiguously the mutual position of both the quantities  $y, y_1, y_2$  and experimental  $y_0$  and hence the strategy of the choice of the magnitude and the sign for next iteration.

In Eq. (2) we thus have a single parameter  $\beta_1$  corresponding to the initial porosity  $e_0$ . The fact that in some experiments, particularly those under the moving froth and the oscillatory regime, the good agreement between the experimental and the fitted data was not achieved in the whole range of the variable  $x$ , *i.e.* from  $x = 0$  to  $x = H$ , lead us to an attempt to modify Eq. (2) by another parameter

$$x/h = \frac{e_k}{1 - e_k} \left[ \frac{e - e_k}{e e_k} + \ln \frac{(1 - e_k)}{e_k} \frac{e}{(1 - e_k)} \right] + k . \quad (9)$$

In this two-parameter equation we took for the first parameter,  $\beta_1$ , the porosity  $e$  on the level  $k$ , and for the second parameter,  $\beta_2$ , the quantity  $k$ . This approach provided a better fit of the experimental and computed values in the above mentioned cases for a narrower range of  $x$ .

Physically this approach may be interpreted as a transformation that causes the curve to fit the true experimental course of the porosity starting from a certain

TABLE I  
Results of Experiments

Number of experiments	Regime	$(\Delta\bar{e})_1 = \Sigma(\bar{e}_{\text{exp}} - \bar{e}_{\text{weighed}})/n$	$(\Delta\bar{e})_2 = \Sigma(\bar{e}_{\text{calc}(2)} - \bar{e}_{\text{weighed}})/n$	$(\Delta\bar{e})_3 = \Sigma(\bar{e}_{\text{calc}(11)} - \bar{e}_{\text{weighed}})/n$
50 mm Column				
12	cellular froth	0.074 (12.59) <sup>a</sup>	0.005 (0.82)	0.008 (0.30)
118 mm Column				
Plate A				
29	cellular froth	0.113 (21.70)	0.014 (2.80)	0.021 (3.43)
8	moving froth			
4	oscillatory			
Plate B				
9	cellular froth			
7	moving froth	0.114 (17.40)	0.015 (2.43)	0.021 (2.99)
8	oscillatory			
Probe 1 without magnet				
16	cellular froth			
9	moving froth	0.162 (27.02)	0.012 (2.17)	0.010 (1.44)
4	oscillatory			
Probe 2 with magnet				
14	cellular froth			
4	moving froth	0.130 (20.97)	0.014 (2.57)	0.014 (2.11)
10	oscillatory			

<sup>a</sup> Data in parentheses indicate percentual fractions related to  $(\bar{e}_{\text{exp}} + \bar{e}_{\text{weighed}})/2n$  or  $(\bar{e}_{\text{calc}} + \bar{e}_{\text{weighed}})/2n$ .

distance from the plate. Physical meaning given to this distance is that of a boundary below which the simplifying assumptions of Kolář's model are not met.

In Eqs (2) and (9) we have regarded as a dependent variable the distance from the upper surface of the plate ( $x/h$ ); for the independent variable we took the porosity  $e$ . This formulation of the problem was regarded as more convenient for the inverse function

$$e = g(x/h, e_k, k) \quad (10)$$

cannot be expressed explicitly.

In another part of the computer program reading the output data we computed also the formally defined inverse functions (2) or (9) for the calculated values of  $e_0$  or  $e_k$ .

The evaluation of a single experiment took about 5 minutes depending on the number of experimental levels and the number of iterations.

## RESULTS AND DISCUSSION

**50 mm Column.** A total of 12 experiments were performed on this column. All these experiments were designed mainly to test the reliability of the conductivity method with the probe without magnets under conditions of homogeneous froth in horizontal levels. It was for this purpose that we used fritted glass as gas distributor because it gives rise to cellular froth in a wide range of air flow rates. The height of liquid used was  $h = 5, 10, 15$  and  $20$  cm.

These experiments confirmed a good agreement of the average porosities obtained on one hand as an integral mean of the experimental profile and as an integral mean numerically from Eq. (2) on the other hand with the average porosities following from the known hold-up and the height of the froth (Table I).

Under the developed cellular foam regime the course of the experimental curves was in most cases well described by the single-parameter equation (2).

**118 mm Column.** A total of 73 experiments were performed, 42 of which with 2 mm diameter plate openings (plate A), the rest with 5 mm openings (plate B).

Plate A displays a markedly wide region of the cellular froth regime, plate B of the moving froth regime. By the experiments we also attempted to test the responses of the probe to various ways of gas distribution (*e.g.* from small or large openings) and to verify the independence of  $e_0$  on the design characteristics of the plate by Červenka.

The average porosities were again compared and the results are summarized in Table I with  $(\Delta e)_1$  and  $(\Delta e)_2$  as criteria of fit. These criteria do not indicate any significant effect of the character of the flow regime on the agreement of the average porosities mainly because of relatively small absolute deviations of the porosities under all regimes. This is further illustrated in Fig. 3 plotting average porosities *versus* gas velocity for plate B and the height of the hold-up  $h = 5$  cm. For comparison the figure shows also the function in Eq. (1).

Nevertheless, Fig. 3 clearly indicates that the average porosities obtained by the conductivity method (either direct numerical integration of the experimental data or the smoothed profiles) are systematically lower than the average porosities obtained from the weighed hold-up. The magnitude of this deviation (see  $(\Delta e)_1$  in Table I) is significantly higher than in case of the 50 mm column, where the latter was moreover largely random. As an explanation one can offer mainly the non-uniformity of liquid distribution over the surface of the plate brought about by increased scale of experi-



ments. This effect thus should become even more profound in the largest column used.

Although the curves computed from Eq. (2) do give a good agreement of the average porosities, they do not follow the true course of the experimental porosity, particularly not under the moving froth and the oscillatory regimes. The calculation according to the two-parameter equation (9) lead to higher values of  $k$ , especially under the moving froth and the oscillatory regime. For plate A displaying at low gas velocity a part of the hold-up almost by-passed by the gas the values of  $k$  were higher even at the cellular froth regime. For both plates A and B the average  $k$  for all experiments amounted to  $k = 0.30 H/h$ . For the oscillatory regime  $k = 0.4 H/h$ , for the cellular froth regime  $k = 0.20 H/h$  and for the moving froth regime  $k = 0.30 H/h$ .

The results thus show that by suitable transformation the true experimental course of porosity can be described satisfactorily only starting from a certain distance above the plate. Physically this distance may be thought of as a limit below which the simplifying assumptions of Kolář's model no longer hold.

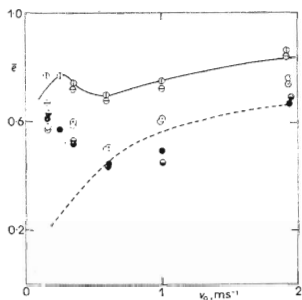


FIG. 4

A Plot of Average Porosity versus Gas Velocity for 288 mm Diameter Plate,  $L = 0.4 \text{ kg/m}^2 \text{ s}$

○  $\bar{\epsilon}$  Obtained by integration of experimental porosities, ⊙  $\bar{\epsilon}$  obtained by integration of smoothed (Eq. (2)) profiles, ⊕  $\bar{\epsilon}$  obtained by integration of smoothed (Eq. (11)) profiles, ● ⊙ ⊕ the same for probe with magnet, —  $\bar{\epsilon} = 1 - h/H$ , - - - -  $\bar{\epsilon}$  according to Eq. (1).

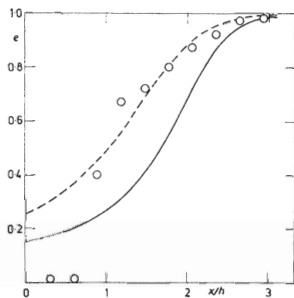


FIG. 5

A Typical Profile of Porosity along the Height of the Gas-Liquid Mixture in 288 mm Column, Cellular Froth Regime

$L = 0.4 \text{ kg/m}^2 \text{ s}$ ,  $v_G = 0.35 \text{ ms}^{-1}$ , ○ Probe with magnet, — smoothed (Eq. (9)) profile, - - - - extrapolation according to Eq. (9), - - - - smoothed (Eq. (2)) profile.

288 mm *Column*. 54 experiments were carried out in this column altogether. The experiments were designed to test for a given plate the effect of the type of the probe as well as the flow regime on the reproducibility of the results (always two experiments were performed under identical conditions) as well as the effect of further scale-up of the column on the reliability of the experimental technique.

The results in Table I indicate that the disagreement between the average porosities obtained by integrating experimental conductivity data or the profiles smoothed according to Eq. (2) and the average porosities following from the known hold-up obtained by weighing has further increased in comparison with the 118 mm column. The fact that this discrepancy cannot be attributed to different proportions of the various regimes in individual sets of data on the three columns is evidenced in Fig. 4. From the figure it is apparent that the average porosities obtained by the conductivity method are here also lower especially under the moving froth and the oscillatory regimes. It may be also observed that the experiments with probe 2 provided better results than those with probe 1. This further confirms the utility of the magnetic field for checking undesirable effects.

Let us examine now the porosity profiles plotted for selected experiments under the cellular, mobile froth and the oscillatory regimes in Figs 5–7. Under the cellular froth regime the experimental porosities deviate from those computed from Eq. (2) only in close proximity of the plate, which, on a plate with small openings, is caused by the presence of poorly aerated liquid near the plate. This is of course, at odds with the assumptions of Kolář's model. Under the mobile froth regime the expe-

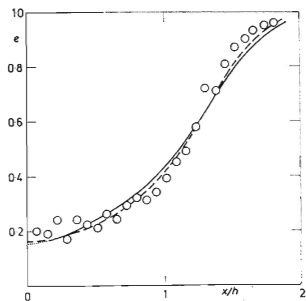


FIG. 6

Moving Froth Regime

$$L = 0.7 \text{ kg/m}^2 \text{ s}, v_G = 0.637 \text{ ms}^{-1}.$$

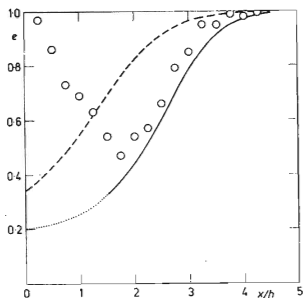


FIG. 7

Oscillatory Regime

$$L = 0.4 \text{ kg/m}^2 \text{ s}, v_G = 1.930 \text{ ms}^{-1}.$$

rimental porosities in the bottom layers are lower than it would follow from the smoothed profiles according to Eq. (2). Similarly, under the oscillatory regime the profiles differ mainly in the bottom layers of the froth. The experimental profile under the oscillatory regime differs from that under the moving froth regime mainly in that the former is not monotonous but rather displays a minimum the position of which depends on the intensity of oscillations.

The different character of the regimes becomes manifest also in the calculation according to the two-parameter equation: The average value of  $k$  for the moving froth is  $0.28 H/h$ , for oscillations  $0.35 H/h$ .

The character of the deviations for the last two regimes corresponds to the deviations of the experimental and the computed pressure profiles in the bottom layer of the gas-liquid mixture found by Červenka<sup>9</sup>. This author also measured the pressure distribution in the level of the investigated plate and found pressure maxima in the column axis in some experiments. On taking into account also our own results on the dynamics of the gas-liquid mixture<sup>10</sup>, which have proven the existence of the waves of variable length causing non-uniformities of liquid distribution over horizontal levels, one may justly expect the probe located in the column axis to be in a region of higher density and hence lower porosity. The limits of this region are determined by the frequency and the amplitude of the waves.

In accord, for the regime of moving froth displaying<sup>10</sup> mostly the waves of  $\lambda = D/4$  and frequency equal 4.5 Hz, the found experimental porosity profiles exhibit also a character different from that under the oscillatory regime characterized by waves of  $\lambda = D$  and frequency 2.5 Hz. The formation of the waves should also affect the character of the dynamic changes of the porosity which shall be investigated in the following paper. It is not surprising though that the course of porosity along the column axis and outside the mentioned region will be described by Eq. (2) with another parameter  $e_0$  than that we would obtain *e.g.* from measurements near the wall. On the other hand one can assume that in the top high-porosity part of the gas-liquid mixture the nonhomogeneity brought about by wave formation will not be marked. Relating now the porosity of the top part of the mixture to the hold-up obtained by weighing  $\bar{h}$ , *i.e.* averaged over the cross section, in a fashion analogous to Eq. (2)

$$\frac{x}{\bar{h}} = \frac{\bar{e}_0}{1 - \bar{e}_0} \left[ \frac{e - \bar{e}_0}{e\bar{e}_0} + \ln \frac{1 - \bar{e}_0}{\bar{e}_0} \frac{e}{1 - \bar{e}_0} \right], \quad (11)$$

one can expect the equivalent initial porosities  $\bar{e}_0$  to provide a satisfactory over-all description of the system. This has been confirmed by comparison of the average values of the integrated conductivity profiles calculated with the aid of  $\bar{e}_0$  for individual experiments with the average porosities obtained from weighed hold-up and the height of the gas-liquid mixture.

The good agreement for the 288 mm column is evidenced in Table I in terms of the deviation

$$(\Delta e)_3 = \sum [\bar{e}_{\text{calc. from Eq. (11)}} - \bar{e}_{\text{weighed}}] / n.$$

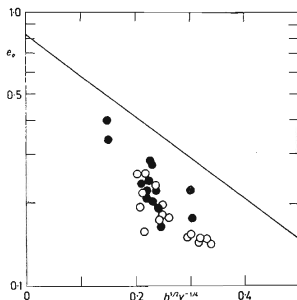
This agreement made us calculate  $\bar{e}_0$  also for the 118 mm column.

Summarily it may be said that despite of the nonhomogeneity over horizontal levels leading to lower values of the porosity near the column axis and hence higher porosities on the circumference owing to the wave formation, one can achieve a good agreement of the average porosities with the values following from the hold-up. However, the experimental data must be smoothed by Eq. (11) assigning higher statistical weight to points in the top part of the froth. This finding can be interpreted also in connection with the original one-dimensional model of Kolář or the rate of energy dissipation. The fact that  $e_0$  calculated from Eq. (11) provides the best agreement of the calculated average porosities with the values obtained by weighing even in case of the froth non-homogeneous over horizontal levels suggest that the rate of energy dissipation is the same even under these conditions. The wave formation, causing non-uniformities of the porosity in horizontal direction, brings about no additional dissipation. It should be noted, however, that water, *i.e.* a low viscosity liquid was used in these experiments.

All results processed according to Eq. (4) lead in case of the 288 mm column to  $e_H = 0.9408$ , *i.e.* a value close to that found by Červenka from pressure profiles.

For comparison we have plotted in Fig. 8 initial porosity obtained by the conductivity method against the dimensional group  $h^{-1/2} v_G^{-1/4}$  as well as the dependence found on the basis of pressure profiles also by Červenka. Although our values are consistently lower the dependence on the above group is well seen.

FIG. 8  
 $e_0$  as a Function of the Group  $h^{-1/2} v^{-1/4}$   
 in 288 mm Column  
 ○ Probe with magnet, ● probe without magnet, — curve  $e_0 = 0.824 \exp(-3.6 h^{-1/2} v^{-1/4})$  obtained by Červenka.



## LIST OF SYMBOLS

$e$	porosity	$n$	number of experiments
$e_0$	initial porosity	$p$	pressure
$e_H$	parameter	$\Delta p_p$	pressure drop across the froth
$\bar{e}$	average porosity	$\Delta p_x$	pressure drop up to point $x$
$f$	function	$v_G$	superficial velocity of gas
$g$	acceleration due to gravity	$x$	vertical distance from plate
$g$	inverse function	$D$	column diameter
$h$	liquid hold-up	$H$	height of froth
$k$	additive constant	$U$	voltage

## Subscripts

G	gas	exp	experimental
L	liquid	calc	calculated
k	liquid level	weighed	determined from weighed hold-up

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