DYNAMIC CHANGES IN POROSITY OF GAS–LIQUID MIXTURE*

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Time inhomogeneities in porosity of gas–liquid mixtures have been studied by the conductivity method on selected sieve plate without downcomers. The spectral and correlation theories of random processes by use of which the obtained results were evaluated pointed to a strong dependence of these inhomogeneities on the operating regime of the plate and the vertical coordinate. Mean value of fluctuations taken over the whole height of the bed reaches its maximum at the regime of homogeneous foam. The size of fluctuations, especially at lower gas velocities expressively differs with the varying vertical coordinate. These fluctuations are directly related to pressure and pressure drop fluctuations. Their magnitude is also being interpreted with respect to the in time averaged porosity values. Time homogeneities in all the regimes considered exert the weakest correlation in the region where the in time mean porosity becomes equal to 0·5. The presence of different frequencies in the spectrum of porosity fluctuations points to an effect of macro-oscillations of the bed and of circulation streams in dependence on the operating regime and vertical coordinate.

Study of time inhomogeneities of characteristic pressures and pressure drops in a gas–liquid bed on a sieve plate without downcomers enables to get a more detailed understanding of the plate activity and to form, on the basis of statistico-dynamic approach to a plate as a system with concentrated parameters, a quantitative model of its activity. Obviously, the time inhomogeneity of the studied pressures and pressure drops, *i.e.* quantities determining the energetic state of the gas–liquid mixture, must be closely related to fluctuation of its structural parameters such as are for inst. porosity and interfacial area. Fluctuation of these parameters with time is also determined by the presence of circulation streams in the mixture, by formation and disintegration of liquid agregates *etc.*[1].

In their recent publication[1], the authors have used for study of dynamic changes of structural parameters of the foam a photographic method enabling to take 54 shots per second under conditions simulating a two-dimensional rectangular cross-section of the foam. By visual evaluation of the shots they arrived at conclusion that behaviour of structural parameters such as the gas content (porosity) and contact area have a probability character pulsating with time. This

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phenomena results from non-uniformity of the structure and from the unsteady behaviour of the phase. The pressure drop across the foam Δp_f has also a similar character.

It can be thus assumed that there exists a relation between pressure pulsations and structural parameters in the sense that the behaviour of Δp_f reflects behaviour of non-uniformities and the state of the bed, most of all the coalescence intensity and destruction of gas and liquid aggregates. Examples given in this paper point to a strongly random character of the mentioned fluctuations with the spectrum in the region 0–10 Hz. Dynamic changes in porosity in a bubbled reactor by use of γ-radiation are studied in the paper by Kölbel and coworkers[2].

The authors concentrated themselves only to the study of characteristics in the amplitude domain in relation to operating parameters of the reactor, first of all to the bed height and gas velocities. Here too, the study of time inhomogeneities has led to the conclusion that it concerns a highly random process determined in general by superposition of two normal random processes corresponding to different forms in which the gas exists in the liquid. As for the spectrum of studied changes, the authors have limited themselves to the statement that their frequency is 2 Hz and is independent either on the location of the measuring point in the bed or on the gas flow rate. Illustrations of recorded fluctuations are, however, not in an agreement with this statement. In our recent study[3], we have applied the conductivity method to the study of structure of gas-liquid mixture. Evaluation of porosity profiles over the height of the mixture has shown the reliability of the selected method. This has been confirmed by the agreement with theoretical relations as well as with the results of the study on pressure profiles over the height of mixture. From this has also resulted an effort to use it to the study of dynamic porosity changes, especially when related and supported by the conclusions resulting from the extensive experimental study of dynamic behaviour of the gas-liquid mixture on sieve plates[2,3].

EXPERIMENTAL

The experiments were performed in the equipment described earlier[3]. The gas–liquid mixture water–air was studied which forms on a sieve plate without downcomers. The plate is made of perspex 2 mm thick, with the diameter of holes 2·5 mm, free plate area 15%. It was operated at the liquid flow rate $L = 0{\cdot}7\ \mathrm{kg\ m^{-2}\ s^{-1}}$ in the range of gas velocities $V_G = 0{\cdot}15 - 2{\cdot}00\ \mathrm{m\ .\ s^{-1}}$. The conductivity probe was used with magnets situated in the axis of the column[3]. The direct current signals from the unit of the measuring bridge SE 429, SE Labs Co., operated at the frequency 3 kHz with the built in amplifier and detector of voltage in the diagonale of the bridge, were evaluated and the statistical treatment derived earlier[4] has been applied to them. For conversion of measured values of voltage to values of porosity the linear transformation has been applied on basis of a statical calibration. The results of digital processing on Tesla 200 computer were compared with the one half of experiments evaluated on the correlator MUSA 6. The length of relations of individual records of porosity fluctuations was chosen about 100 s. By digital sampling at frequency of 64 samples/s systems consisting of 4000 data were obtained.

RESULTS

For the set of experiments in different plate regimes characterized by the data given in Table I the time inhomogeneities of porosities of the gas–liquid mixture in various heights of the mixture were evaluated. In this way the mean values of porosities, standard deviations of fluctuations, and their autocorrelation functions and spectral densities were obtained.

TABLE I

Results for Given Operating Conditions

Exp.	Regime	v_G ms^{-1}	z Nm^{-2}	$H \,.\, 10^2$ m	$[\sigma_e]_{\mathrm{mean}}$
1	bubbling	0·160	173	4	0·142
2	cellular	0·220	178	5	0·111
3	homogeneous	0·423	282	9	0·140
4	homogeneous	0·637	377	12	0·166
5	circulating foam	1·067	530	17	0·211
6	circulating foam	1·330	552	19	0·211
7	oscillating	1·930	323	17	0·190

Comparison of profiles of mean porosities over the foam height with profiles obtained for the same operating conditions as in our previous work where the times of realization were chosen 20 s and sampling frequency 1 sample/s, gave a good agreement illustrated in Fig. 1.

Amplitude domain. Standard deviations of porosities σ_e and the relative standard deviations $\sigma_e/\bar{e}$ were calculated for individual experiments and locations of the mea-

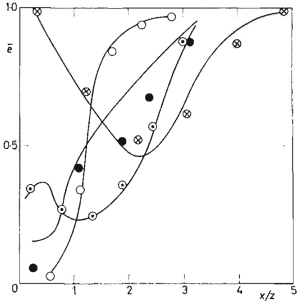

FIG. 1

Profile of the in Time Mean Porosities
○ Experiment 2, ●, 4, ⊙ 5, ⊗ 7.

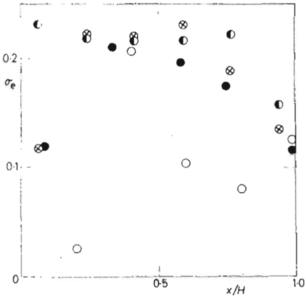

FIG. 2

Dependence of σ_e over the Foam Height
○ Experiment 2, ● 4, ◐ 5, ⊗ 7.

TABLE I
(*Continued*)

$[\bar{e}]_{\text{mean}}$	$[\sigma_e/\bar{e}]_{\text{mean}}$	α	$\tau_{0.10}$	$[\sigma_e]_{\text{eff}}/[\sigma_e]_{\text{mean}}$	$[\sigma_e]_{\text{eff}}$
0·568	0·232	48·4	0·047	—	—
0·644	0·384	41·2	0·061	1·11	0·123
0·687	0·355	38·9	0·064	0·62	0·087
0·686	0·423	32·9	0·076	0·47	0·078
0·688	0·566	24·8	0·101	0·33	0·069
0·709	0·494	22·6	0·111	0·29	0·061
0·811	0·264	6·70	0·344	—	—

suring probe. Their values in dependence on the dimensionless coordinate x/H are plotted for the experiments from individual regimes in Figs 2 and 3. The average values of both deviations for individual experiments were calculated by their aver-

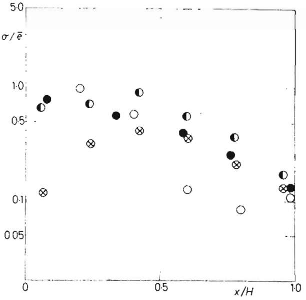

FIG. 3

Dependence of $\sigma_e/\bar{e}$ Along the Foam Height
○ Experiment 2, ● 4, ◐ 5, ⊗ 7.

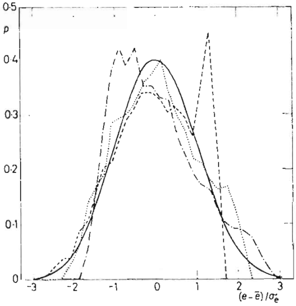

FIG. 4

Probability Density of Amplitude of Porosity Fluctuations for the Experiment No 4
—·—·— $x/H = 0·33$, ··········· $x/H = 0·58$, ----- $x/H = 0·75$, ——— normal distribution.

aging over the whole foam height. These are given in Table I. Simultaneously were calculated the histograms of probability density of porosities after their standardization into the form $(e - \bar{e})/\sigma_e$ and by their selection into the intervals of 0·2 width. With the exception of experiment No 7, the histograms have had positive skewness in lower parts of the mixture, negative in the upper parts. In experiment No 7 the skewness was negative in the lowest layer. In very low and very high locations, the distribution is leptocurtic and becomes more normal toward the foam centre.

The best agreement with the normal distribution has been found in all the experiments in the central part of the bed. For the experiment No 4 the agreement with the normal distribution is illustrated in Fig. 4.

Time and frequency domain. Together with the standard deviations the normalized autocorrelation functions[4] were calculated up to the maximum time lag $\tau_{\max} = 2$ s. By their digital Fourier transformation using the Hamming's spectral window of 0·5 Hz, values of the normalized spectral densities[4] were further obtained.

The obtained autocorrelation functions were smoothened by the function of the type

$$r^{xx}_{ee}(\tau) = \exp(-\alpha\tau)\cos(\omega\tau)\,, \tag{1}$$

by use of the Marquard's method of non-linear regression. As estimates of the charac-

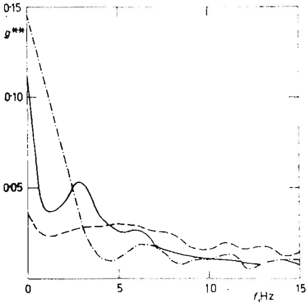

FIG. 5

Estimate of Spectral Density of Porosity Fluctuations; Exp. No 2

——— $x/H = 0{\cdot}20$, ----- $x/H = 0{\cdot}60$, —·—·— $x/H = 1{\cdot}0$.

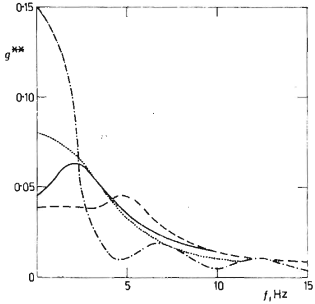

FIG. 6

Estimate of Spectral Density of Porosity Fluctuations; Exp. No 4

—·—·— $x/H = 0{\cdot}08$, ----- $x/H = 0{\cdot}58$, ——— $x/H = 0{\cdot}75$, ·········· $x/H = 1{\cdot}00$.

teristic frequency, the dominant components in individual spectra were chosen. Rather good agreement between values obtained by the MUSA 6 correlator and the smoothened ones was found. The spectra of fluctuations in individual levels at different regimes are illustrated in Figs 5 to 8. The dependence of the constant α for these selected experiments in dependence on the dimensionless coordinate x/H is illustrated in Fig. 9. The mean values of the constant α obtained by their averaging over the bed height is given for individual experiments in Table I. Values obtained by the digital approach and those from the correlator MUSA 6 differed by 5 to 15 rel.%. In Table I are further given values of the argument τ for which the "average" autocorrelation functions become equal to 0·10.

DISCUSSION

It is beyond doubt that the studied porosity fluctuations must be closely related to the pressure and pressure drop fluctuations. But it is not possible to expect that this relation will be simple in the whole region of tray operation. The reason is first of all in the existence of qualitatively differing mechanism at different operating conditions. In spite of the limited range of results published in this paper some interesting conclusions can be made.

Let us consider the relation between the liquid holdup z and the standard deviation

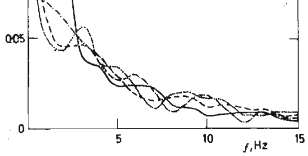

FIG. 7

Estimate of Spectral Density of Porosity Fluctuations; Exp. No 5

– – – – – $x/H = 0.06$, —·—·— $x/H = 0.41$,
··········· $x/H = 0.59$, ——— $x/H = 0.94$.

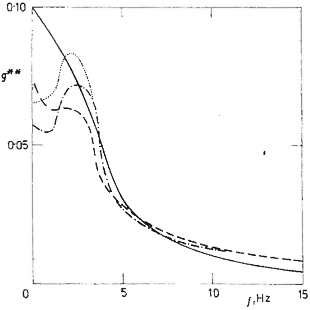

FIG. 8

Estimate of Spectral Density of Porosity Fluctuations; Exp. No 7

– – – – – $x/H = 0.6$, —·—·— $x/H = 0.23$,
··········· $x/H = 0.59$, ——— $x/H = 0.94$.

of pressure fluctuations over the foam bed which holds under the conditions of foam homogenity over the horizontal cross-section[4]

$$z = A \exp\left(B\sigma_{\Delta p_f}\right) . \qquad (2)$$

It has been determined, that the constant A, corresponding to the liquid holdup at zero gas flow rate *i.e.* the holdup kept on the plate by forces of surface tension is inversely proportional to the hole diameter and for the studied thin plates without downcomers its value varies within the limits 29·5 for the hole diameter 25 mm and 18·6 for the hole diameter 10 mm. It is in good agreement with the value

$$\Delta p_\tau = 2{\cdot}35\tau/d_0 \qquad (3)$$

calculated by Červinka[5].

The constant B is practically independent on the type of plate and the mean value calculated for the whole set of plates and operating conditions[4] equals to $B = 2{\cdot}15$ When we assume that fluctuation of pressure drop over the foam is given only by the variations in foam porosity in time, then

$$\sigma_{\Delta p_f} = \varrho_L g H[\sigma_e]_{\text{eff}} , \qquad (4)$$

where $[\sigma_e]_{\text{eff}}$ is the standard deviation of porosity fluctuations of the whole gas–liquid mixture *i.e.* also a quantity which is a lumped parameter.

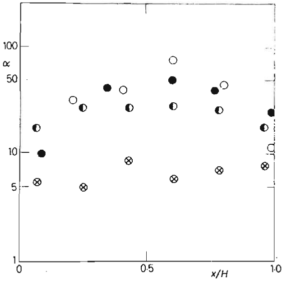

FIG. 9

Exponent α in the Autocorrelation Function; Eq. (*1*)

○ Experiment 2, ● 4, ◐ 5, ⊗ 7.

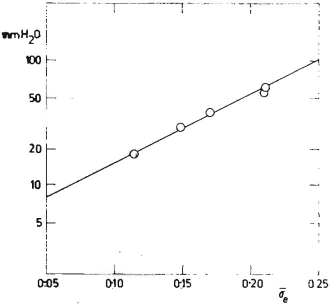

FIG. 10

Dependence of $[\sigma_e]_{\text{mean}}$ on z for Exp. Nos 2 to 6

—— calculated according to Eq. (*5*), ○ experiments.

In our experiments only the standard deviations of porosity fluctuations in individual foam heights were obtained but not in the foam as a whole. It is understandable that in the given time instant the values of fluctuations in different heights are different and it is not possible to eliminate in advance, mostly for high foam beds, the possibility of existence of fluctuations with a negative sign *e.g.* at the plate and at the interface liquid mixture–air.

A study of these relations requires a knowledge of cross-correlation functions. On the other hand it must hold in limit that for $[\sigma_e]_{eff}$ as well as for $[\sigma_e]_{mean}$ at the zero gas flow rate both quantities have a zero value.

Correlation of experiments in the region of homogeneous foam (Exp. 2 to 6) by an equation analogical to Eq. (*2*) *i.e.*

$$z = A' \exp \{B'[\sigma_e]_{mean}\} \tag{5}$$

results in a very good agreement (see Fig. 10) with the values $A' = 46{\cdot}7$, $B' = 12{\cdot}01$.

Value A' is in agreement with the value obtained by recalculation of the constant $A = 29{\cdot}5$ for plates with the hole diameter 2·5 mm or from Eq. (*2*) according to which $A = 67{\cdot}4$.

From the necessary equivalence of exponents in Eqs (*2*) and (*5*) the relation between $[\sigma_e]_{mean}$ and $[\sigma_e]_{eff}$ results

$$[\sigma_e]_{eff}/[\sigma_e]_{mean} = 5{\cdot}59 \,.\, 10^{-1}(1/H)\,. \tag{6}$$

Values of this ratio which are given in Table I demonstrate that only for small foam heights in the celular operating regime at the given moment, the ratio of both deviations is approximately equal to 1. The decreasing value of this ratio with increasing foam height indicates the mutual phase shift of fluctuations in various foam heights.

For the change of standard deviations of porosities along the foam height is characteristic that it is not monotonous in any of the regimes. This is understandable if we realize that in the limiting one-phase systems the fluctuations must be nill.

The standard deviation of fluctuations is determining the mean change of the gas-content in the volume element between both electrodes. Proportionally to the change in the gas content, also liquid must flow in or out from the volume element. The mean change in the gas content must be then proportional to the fractions of gas present which can be on the time average substituted by liquid

$$\sigma_e = K\bar{e}(1 - \bar{e})\,. \tag{7}$$

This function has a local extreme at $\bar{e} = 0{\cdot}5$.

The plot of the values σ_e in dependence on values $\bar{e}(1 - \bar{e})$ (Fig. 11) confirms that the dependence (7) is well satisfied with the value of $K = 1$ practically in the whole range of the experiments carried out. Exceptions are the values in close vicinity of the plate with the extremely low (for experiment No 7 extremely high) porosity. The best agreement is obtained in the vicinity of $\bar{e} = 0{\cdot}5$.

From Eq. (7) also results that the index of inhomogeneity of porosity $\sigma_e/\bar{e}$ is proportional to the liquid content $(1 - \bar{e})$.

The found deviations especially in vicinity of the plate depend also on the fulfillment of assumptions on random character of substitutions of the gas by liquid. It means simultaneously how exactly the standard deviations are expressing the mean degree of the change in gas content. When the forces of surface tension are significant, *i.e.* especially in the bubbling regime and in the regime of cellular foam in close vicinity of the plate, considerable deviations can be expected. The same effect can be caused also by macrooscilations of the gas–liquid mixture in vicinity of the plate and in the top layers of the foam. Then, the non-random mechanism of substitution of the liquid phase by gas becomes significant.

In the above mentioned cases the corresponding deviations from normal distributions appear, *i.e.* the distributions are strongly leptocurtic in vicinity of the plate especially for Runs No 1 to 4, which is accompanied by negative skewness. For Run No 7 the skewness is positive.

The analysis of spectral densities further completes our considerations about the character of fluctuations. The magnitude of static component of fluctuations given by the value g^{**} for $f = 0$ is reaching the minimum in all experiments in the central part of the gas–liquid mixture and is increasing in the direction toward the plate as

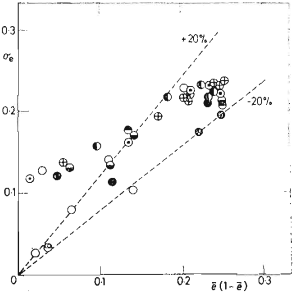

FIG. 11

Comparison of Experimental and Calculated Values of σ_e

◒ Experiment 1, ○ 2, ◓ 3, ● 4, ◐ 5, ⊕ 6, ⊙ 7.

well as toward the interface with air. By the strong presence of very low frequencies at the lowest levels in all experiments as well as at the highest level in Run No 7, the mechanism which leads to the deviations from normal distribution can be explained. In particular spectra the peaks of components are present in a varying degree which are about multiples of the frequency 2·5 Hz. These frequencies were also found in spectra of the corresponding pressure and pressure drop fluctuations[4,6]. The appearance of a single frequency 2·5 Hz on all levels at the oscillation regime (Exp. No 7) proves that the gas flow takes place on basis of macrooscillations of the whole mixture. These have for the given liquid holdup an approximate wave length $\lambda \approx 2D$ and frequencies 1·2 Hz (see[4]).

The complete interpretation of spectra in other experiments, especially in the experiments in the regime of circulation foam, has not yet been possible. The frequencies can be interpreted with respect to the waves of different wave length which are determining the frequency of gas flow rate into the plate and thus porosity fluctuations as well as the pattern of circulation streams in the mixture. In the lowest level in all the experiments carried out, with the exception of experiment No 7 the component with the peak around 7·5 Hz was present to a lower or greater extent. This component is obviously decisive in relation to the mechanism of gas flow into the plate as it was consistently present in the spectra of pressure fluctuations over the foam[4].

On basis of the obtained results some conclusions can be made as concerns the selection of the optimum operating regime of the plate. From these results is obvious that the greatest amplitude of fluctuations and the most profound random character occur in the region where the in time mean porosity $\bar{e} = 0{\cdot}5$. We can thus conclude that liquid mixing and therefore also the intensity of interphase contact is greatest just in this region. From this point of view the most advantageous regime would appear that one in which the region with the in time mean porosity $\bar{e} = 0{\cdot}5$ would form relatively the greatest fraction of gas–liquid mixture.

At the assumption of homogeneity of the foam in the horizontal cross-section for evaluation of the relative part of the region where the in time mean porosity $\bar{e} \in \langle 0{\cdot}4; 0{\cdot}6 \rangle$ the ratio can be used

$$[(x/h)_{\bar{e}=0\cdot6} - (x/h)_{\bar{e}=0\cdot4}]/(x/h)_{\bar{e}=0\cdot975}\,, \tag{8}$$

where values (x/h) were for the corresponding values of porosities $\bar{e}$ calculated from the equation derived by Kolář[7] for various values of the parameter φ_0, according to which

$$\frac{x}{h} = \frac{\varphi_0}{(1 - \varphi_0)} \left\{ \frac{\bar{e} - \varphi_0}{\bar{e}\varphi_0} + \ln \left[\frac{(1 - \varphi_0)\,\bar{e}}{(1 - \bar{e})\,\varphi_0} \right] \right\}. \tag{9}$$

This ratio has the maximum value 0·297 for $\varphi_0 = 0{\cdot}40$.

On basis of the experimentally found[3,5] correlation for φ_0 holds

$$\varphi_0 = 0{\cdot}824 \exp\left(-3{\cdot}6 z^{1/2} v_G^{-1/4}\right) \qquad (10)$$

according to which for the given liquid holdup the most advantageous gas velocity (and *vice versa*) can be calculated. From the resulting relation $v_G = 620\,\mathrm{h}^2$. According to this Eq. to the liquid holdup $5\,.\,10^{-2}$ m corresponds the most advantageous velocity $v_G = 1{\cdot}55\ \mathrm{m\ s^{-1}}$.

LIST OF SYMBOLS

A, A'	constants in Eqs (*2*), (*5*)
B	constant in Eq. (*2*)
B'	constant in Eq. (*5*)
H	height of the gas–liquid mixture
P	pressure
d_0	hole diameter
e	porosity
f	frequency
$\mathbf{g}$	gravitational acceleration
g	normalized spectral density
r	normalized autocorrelation function
x	distance from the plate in the gas–liquid mixture
v	velocity
z	holdup
α	exponent in autocorrelation function Eq. (*1*)
ϱ	density
σ	standard deviation
$\omega = 2\pi f$	frequency
φ_0	initial porosity
τ	time lag
τ	surface tension
$**$	statistical estimate
—	average in time
eff	effective
mean	mean in space

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