THE MEASUREMENT OF VOIDAGE OF NONUNIFORMLY FLUIDIZED BED BY MEANS OF THE WALL PRESSURE SIGNAL

Ján BEŇA and Ivan HAVALDA

Department of Chemical and Biochemical Engineering, Slovak Technical University, 812 37 Bratislava, The Slovak Republic

Received February 7, 1992
Accepted August 20, 1992

By the wall pressure signal, Δp_x, from a nonuniformly fluidized bed is here termed the excess pressure at a wall of open column over the atmospheric pressure measured at a distance x from distributor. The relation was investigated between the wall pressure signal, $\Delta\tilde{p}_x$, and some specifically defined voidages of a so-called standard bubbling bed characterized by the fact that the ratio of the experimentally determined pressure drop for minimum fluidization, $\Delta\tilde{p}_{0,\,mf}$, and of the theoretical pressure drop, Δp_t, is approximately equal to unity. We have shown that under certain conditions, the time-volume averaged voidage, $\bar{\varepsilon}$, of this bed can be determined in terms of simple relation (*13*).

The wall pressure signal represents[1] the pressure drop in a fluidized bed which can be also determined by means of piezometric tubes immersed in the bed[2 – 8].

Authors[1,3 – 7] assigned to the pressure drops $\Delta\tilde{p}_{ij}$ measured in the section of fluidized bed from x_i to x_j ($x_i < x_j$), the voidage $\bar{\varepsilon}_{ij}$ in terms of the relation

$$\bar{\varepsilon}_{ij} = 1 - \Delta\tilde{p}_{ij}/[(x_j - x_i)\, g\, (\rho_s - \rho_f)]\,. \tag{1}$$

Blickle and Ormós[2,8] found that the values of $\Delta\tilde{p}_{0,\,mf}/\Delta p_t$ established by them substantially differ from unity, and therefore considered the relation

$$\bar{\varepsilon}_{ij} = 1 - \Delta\tilde{p}_{0,\,mf}\, \Delta\tilde{p}_{ij}/[\Delta p_t (x_j - x_i)\, g(\rho_s - \rho_f)] \tag{2}$$

more suitable. In this way they reduced the difference between the values of $\bar{\varepsilon}_{ij}$ calculated from the pressure drop and from the visually determined mean bed height. Jolly and Doig[9] report that in their measurements as well as in the measurements of authors[10 – 13], the ratio $\Delta\tilde{p}_{0,\,mf}/\Delta p_t$ acquired the values from 0.45 to 1.75 but the quantities influencing these values were not defined.

Authors[14,15] found that in nonuniformly fluidized bed, it was possible to distinguish three regions, viz., the region in the vicinity of distributor where $d\bar{\varepsilon}_x/dx < 0$, the central region where $\bar{\varepsilon}_x \approx$ const. and the thin suspension region where $\bar{\varepsilon}_x$ abruptly increases with increasing x. However, the experimental data of Fan et al.[16] show that there exist such conditions under which the transition from the central region to the thin suspension region is gentle. It follows from it that the character of dependence $\bar{\varepsilon}_x$ on x may be different. The criteria for its specification are not known. On the basis of data by Jolly and Doig[9], it is possible to judge that the formulation of a universal relation $\bar{\varepsilon}_x = f(\Delta\tilde{p}_x)$ valid for an arbitrary type of nonuniformly fluidized bed, is probably unreal.

Paper[15] is significant by containing the experimentally determined dependence of $\bar{c}_x/c_{sb}$ on x, where $\bar{c}_x = \rho_s(1 - \bar{\varepsilon}_x)$, $c_{sb} = \rho_s(1 - \varepsilon_{sb})$. To determine $\bar{c}_x$, the gamma ray attenuation technique was applied. From this dependence and from the definition of $\bar{\varepsilon}_x^{(-)}$ or $\bar{\varepsilon}_x$ follows that both in the region close to the distributor and in the central region, $\bar{\varepsilon}_x^{(-)} > \bar{\varepsilon}_x$ applies, however, $\bar{\varepsilon}_x^{(-)}$ is approximately equal to $\bar{\varepsilon}_x$ already from such a value of x which is greater than double the distance of the central region beginning from the distributor. This fact can be utilized when developing the method for determining $\bar{\varepsilon}_x^{(-)}$ or $\bar{\varepsilon}$.

We have said here that more authors employed the pressure drop in a nonuniformly fluidized bed for the determination of voidages $\bar{\varepsilon}$ and $\bar{\varepsilon}_{ij}$. Adequacy of the values determined in this way, however, has not been sufficiently documented. The fundamental theoretical problems connected with it have not been specified and analyzed. In further text we shall attempt to provide a positive contribution in this direction.

THEORETICAL

In this paper, the following kinds of voidages are of basic importance:

1. Voidage $\bar{\varepsilon}_x$, which is time-area averaged in a column horizontal cross-section in distance x from distributor.

2. The time-volume averaged voidage $\bar{\varepsilon}_x^{(-)}$ in section of bed from distributor to level x

$$\bar{\varepsilon}_x^{(-)} = \frac{1}{x}\int_0^x \bar{\varepsilon}_x \, dx . \tag{3}$$

3. The mean voidage $\bar{\varepsilon}$ of the entire bed defined for its average height $\tilde{h}$ by the relation

$$\bar{\varepsilon} = 1 - (L/\tilde{h}) . \tag{4}$$

Under the conditions of measurements, the level of thick suspension (bed level) went up and down like a horizontal plane figure with small randomly originating perturbations. Its position could be observed visually by means of a sliding ring on the column wall. On the assumption of a symmetrical distribution of fluctuations, $\tilde{h} = (h_{min} + h_{max})/2$ holds. Values h_{min} and h_{max} represent the lowest and highest observed level height of fluidized bed, respectively, for a sufficiently long time interval (about 5 min).

4. The time-volume averaged voidage in section of bed from level x_i to level x_j, $x_j > x_i$

$$\bar{\varepsilon}_{ij} = \frac{1}{x_j - x_i} \int_{x_i}^{x_j} \bar{\varepsilon}_x \, dx . \tag{5}$$

It is apparent that

$$\bar{\varepsilon}_x^{(-)} = 1 - 4\tilde{m}_x^{(-)}/(\pi D^2 \rho_s x) = 1 - 4(m - \tilde{m}_x^{(+)})/(\pi D^2 \rho_s x) , \tag{6}$$

$$\bar{\varepsilon}_{ij} = 1 - 4(\tilde{m}_j^{(-)} - \tilde{m}_i^{(-)})/[\pi D^2 \rho_s (x_j - x_i)] =$$

$$= 1 - 4(\tilde{m}_i^{(+)} - \tilde{m}_j^{(+)})/[\pi D^2 \rho_s (x_j - x_i)] . \tag{7}$$

Let us imagine one bubble of volume V_b in a fluidized bed. On neglecting the change of volume and the change of velocity of the bubble rising along a short bed section Δx, then the particles of bed influenced by the bubble acquire energy $V_b \, g \, \rho_s \, \Delta x \, (1 - \bar{\varepsilon}_x)$. We assume that the particles obtain the energy only as a consequence of work of buoyancy force acting on the bubble. The influence of the bubble on the pressure drop in the fluidized bed depends only on the way in which the particles loose energy acquired in this manner. Since the momentum of the volume unit of gas in the bed is substantially lower that of the volume unit of particles, the particles fall below the bubble and come to a stop by the impact on the other particles. The local changes in the bed structure just behind the bubble bring about the horizontal pressure gradient and the gas velocity gradient corresponding to it without more essential dissipation of the gas mechanical energy. Then apparently

$$\Delta \tilde{p}_x \approx 4 \, g \, \tilde{m}_x^{(+)}/\pi \, D^2 . \tag{8}$$

In some cases, however

$$\Delta \tilde{p}_x > 4 \, g \, \tilde{m}_x^{(+)}/\pi \, D^2 \tag{9}$$

may hold when the gas ascertainably decreases the energy of particles by the mutual frictional force or has to break the surface forces between particles and/or between particles and the column wall which originated from the particle stop.

The region of distributor in a real standard bubbling bed contains the forming bubbles and torn-off bubbles. The latter move slowly but with a high acceleration and gradually combine. Since the residence time of bubbles is here long, also the values of $\bar{\varepsilon}_x$ are large. Smaller part of the column cross section corresponds here to the dense phase than in the region with constant value of $\bar{\varepsilon}_x$.

The mutual vertical and horizontal interaction of bubbles causes the formation of differently localized streams of circulating particles. These streams change direction at high beds. Consequently, it can cause local effects in the vicinity of taking the wall pressure signal, e.g., equally oriented circulating stream of particles repeats here with a certain frequency. In the dense phase among the gas bubbles in the stream of particles changing its direction, the voidage decreases. The lower cross section and smaller voidage of the dense phase cause an increase in $\Delta\tilde{p}_x$ in the sense of Eq. (*9*).

It follows from the said that it is possible to write

$$\Delta\tilde{p}_x = 4g\,\tilde{m}_x^{(+)}/\pi D^2 + \Delta\tilde{p}_{x,\,in}\,, \qquad (10)$$

where $\Delta\tilde{p}_{x,\,in}$ is the excess pressure difference, $\tilde{p}_{x,\,in} - p_a$, corresponding to pressure $\tilde{p}_{x,\,in}$ induced by the fluidized bed nonuniformity. It is assumed that the friction between the bed and column wall, the mutual impacts of particles, the circulation streams of particles in bed and the momentum of particles on fluctuating the bed height share in the value of $\Delta\tilde{p}_{x,\,in}$.

From Eqs (*6*) and (*10*) we get

$$\bar{\varepsilon}_x^{(-)} = 1 - 4m/(\pi D^2\rho_s x) + (\Delta\tilde{p}_x - \Delta\tilde{p}_{x,\,in})/(g\,\rho_s x)\,. \qquad (11)$$

Since in Eq. (*11*) we can measure only $\Delta\tilde{p}_x$ (we cannot measure $\Delta\tilde{p}_{x,\,in}$), it is suitable to introduce the estimated voidage $\bar{\varepsilon}_{x,\,e}^{(-)}$ through the relation

$$\bar{\varepsilon}_{x,\,e}^{(-)} = 1 - 4m/(\pi D^2\rho_s x) + \Delta\tilde{p}_x/(g\,\rho_s x) \qquad (12)$$

and to compare the actual value of $\bar{\varepsilon}_x^{(-)}$ with it. The difference of $\bar{\varepsilon}_{x,\,e}^{(-)} - \bar{\varepsilon}_x^{(-)} = \Delta\tilde{p}_{x,\,in}/(g\,\rho_s x)$ can be expressed as follows $\bar{\varepsilon}_{x,\,e}^{(-)} - \bar{\varepsilon}_x^{(-)} = \Delta\tilde{p}_x/(g\,\rho_s x) - 4\tilde{m}^{(+)}/(\pi D^2\rho_s x)$.

Since with increasing distance from the distributor, $\tilde{m}_s^{(+)} \to 0$ and $\Delta\tilde{p}_x \to 0$, therefore $\bar{\varepsilon}_{x,\,e}^{(-)} \to \bar{\varepsilon}_x^{(-)}$ and $\Delta\tilde{p}_{x,\,in} \to 0$. Then $\Delta\tilde{p}_{x,\,in}$ becomes comparable with the error of measurement of $\Delta\tilde{p}_x$ caused by manometer or pressure sensor.

Hence it follows that for sufficiently high beds, the value of $\bar{\varepsilon}_{x,\,e}^{(-)}$ approximately equals the value of $\bar{\varepsilon}_x^{(-)}$ already from a suitably chosen level x. For the determination of $\bar{\varepsilon}$ by the method presented in this work, we put $\bar{\varepsilon} = \bar{\varepsilon}_{h_{mf}}^{(-)}$ (i.e., $x = h_{mf}$) because h_{mf} is the highest distance from the distributor, where the dense phase still occurs. So that

$$\bar{\varepsilon} = 1 - 4m/(\pi D^2\rho_s h_{mf}) + \Delta\tilde{p}_{h_{mf}}/(g\,\rho_s h_{mf})\,. \qquad (13)$$

The induced pressure difference $\Delta\tilde{p}_{x,\,in}$ manifests itself also in manometric determination of $\bar{\varepsilon}_{ij}$ along a short section of bed from x_i to x_j because from Eqs (*7*) and (*10*) we get

$$\bar{\varepsilon}_{ij} = 1 - (\Delta\tilde{p}_i - \Delta\tilde{p}_j)/[g\,\rho_s(x_j - x_i)] + (\Delta\tilde{p}_{i,\,in} - \Delta\tilde{p}_{j,\,in})/[g\,\rho_s(x_j - x_i)]\,. \qquad (14)$$

Since $\Delta\tilde{p}_{i,\,in} - \Delta\tilde{p}_{j,\,in}$ is unknown, the estimated voidage is evaluated as

$$\bar{\varepsilon}^{*}_{ij} = 1 - (\Delta\tilde{p}_i - \Delta\tilde{p}_j)/[g\,\rho_s\,(x_j - x_i)] \qquad (15)$$

which is analogous to the quantity $\bar{\varepsilon}^{(-)}_{x,\,e}$.

EXPERIMENTAL

Apparatus

The standard bubbling bed was realized in a steel cylindrical column of inside diameter 0.143 m and height 2.1 m. A brass disc was used as a distributor into which 1 270 holes was bored of diameter 2.5 mm placed in vertexes of equilateral triangles of the leg length 3.81 mm. Two layers of filter cloth were under the disc to increase the hydraulic resistance of distributor which, in this arrangement, ensured the regularly fluidizing bed on the entire column cross section already at its small heights. The pressure taps were in the column wall in the following distances, x, from the distributor: x_1 = 11.05 mm, x_2 = 37.0 mm, x_3 = 86.0 mm, x_4 = 136.5 mm, x_5 = 236.0 mm, x_6 = 360.0 mm, x_7 = 485.5 mm, x_8 = 686.9 mm, x_9 = 786.5 mm, x_{10} = 887.5 mm. On the outside end of each pressure outlet, either a pressure transducer or a thermostatted damped U-manometer[17] was connected. The induction and tensometric pressure transducers were connected to an amplifier and analogue computer. The values of $\Delta\tilde{p}_x$ measured with the damped U-manometer agreed with the electrical measurements within ±10 Pa.

The distribution of $\bar{\varepsilon}_x$ along the bed height was measured with a special cylindrical capacitor, Figs 1 and 2. The external electrode was the steel column wall. The internal electrode was formed by two tubes located above one another on a supporting bar in the column axis. The lower electrode (of height 25 mm) was permanently connected to the measuring system. The upper electrode (of height 5 mm) could be connected either with the lower one so forming the capacitor of height 30 mm or with the supporting bar which had the same potential as the capacitor, in terms of a relais controlled from outside. In the latter case, the measuring capacitor had the height of 25 mm. It made it possible to measure with two capacitors with one bar position, and on comparing their data to check their correctness. The system was adapted so that the capacitor did not practically react to the change of the bed ohmic resistance.

The capacitor measured capacities C_4' and/or $C_4' + C_4''$ of the bed section between the horizontal planes which went through both the ends of the internal electrode. The capacitor capacity was transformed to an electric signal, U, which was averaged by the analogue computer and sensed with an oscillograph. The averaging interval was 120 s. The time-averaged value $\tilde{U}$ was assigned to the distance of the capacitor electrode centre from the distributor. The capacitometric probe could be placed in an arbitrary distance $x \geq 31$ mm from the distributor.

Capacitor Calibration

The standard bubbling bed ($\Delta\tilde{p}_{0,\,mf}/\Delta\tilde{p}_t \approx 1$) with a well-developed and long central region was realized in which voltage $\tilde{U}$ did not depend on x. The value of $\bar{\varepsilon}$ calculated from Eq. (*4*) for $\tilde{h} = (h_{min} + h_{max})/2$ was assigned to this signal $\tilde{U}$.

The values of h_{min} and h_{max} were determined visually in a low auxiliary column of the same design and diameter as the column described above. The auxiliary column had two opposite facing sight glasses. These values of $\bar{\varepsilon}$ were in accordance with the values of voidages determined from the measured pressure drop $\Delta\tilde{p}_{b_{mf}}$ according to Eq. (*13*). The typical form of calibration curve for the given specific conditions is in Fig. 3. Unlike the alleged linear calibration curve of capacitor indicating the time-averaged local voidage, the dependence in Fig. 3 is nonlinear. The transfer of particles from the column axis to its wall, where the influence of particles on the capacitor capacity decreases, corresponds to the conspicuous bend of the curve in the interval $\bar{\varepsilon}_x \approx 0.46 - 0.47$.

Particles

The air-particle bed was made on using the narrow-graded glass ballotini obtained by sieving. The particle diameter d was determined from the relation $d = (\sum n_k d_k^3)/(\sum n_k d_k^2)$. Diameters d_k were measured from 200 – 400 randomly selected and photographed particles. Velocities u_{mf} were determined from the dependence $\log \Delta\tilde{p}_0 = f(\log u)$ (ref.[18]). A survey of the particle properties is given in Table I.

TABLE I
Characteristics of particles used

d, mm	ρ_s, kg m^{-3}	u_{mf}, m s^{-1}	Ar
0.144	2 646.4	0.0219	280
0.290	2 646.4	0.0710	2 260
0.521	2 672.3	0.190	13 100

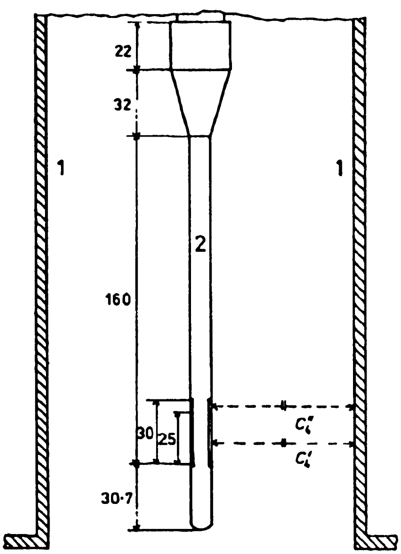

FIG. 1
Capacitor for determining the voidage by measuring capacities C_4' and C_4'': 1 Column steel wall, 2 steel tube with carrier bar and electrodes. Length are given in mm

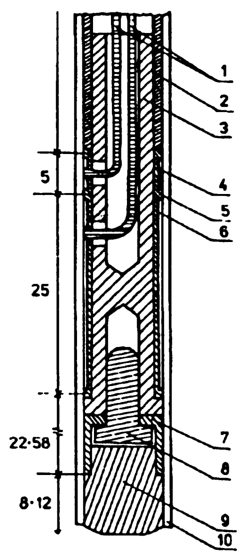

FIG. 2
Detail of the capacitor design: 1 Leads of electrodes, 2 steel tube, 3 carrier bar, 4 small electrode, 5 insulation, 6 large electrode, 7 lower butt (passive electrode), 8 screw, 9 insulation butt, 10 silicone insulating tube. Length are given in mm

Bed Characteristics

The bed height h_{mf} varied from 0.051 m up to 0.9 m. At the onset of fluidization, the bed was uniformly fluidized through the entire column cross section already at the checking height about 1 cm. All the fixed beds which were generated from the fluidized beds by a continuous slow reducing the gas velocity, had a horizontal level, and at $u = u_{mf}$, $0.98 < \Delta\tilde{p}_{0,\,mf}/\Delta p_t < 1.02$.

RESULTS AND DISCUSSION

Distribution of $\tilde{U}$ along Bed Height

Since large changes in $\tilde{U}$ correspond to small changes in $\tilde{\varepsilon}_x$, to illustrate the character of the dependences, we have chosen the plot of dependence $\tilde{U} = f(x)$. Figures 4 – 6 exhibit different forms of this dependence for the capacitor of height 25 mm. The solid (broken) vertical line denotes such a distance of the capacitor from the distributor at which the upper end (centre) of capacitor is on the level h_{mf}. From the shape of the curves on the section between both the given lines, it is evident that the level of fluidized bed practically decreases during pulsations down to h_{mf}. The graph in Fig. 4 is in

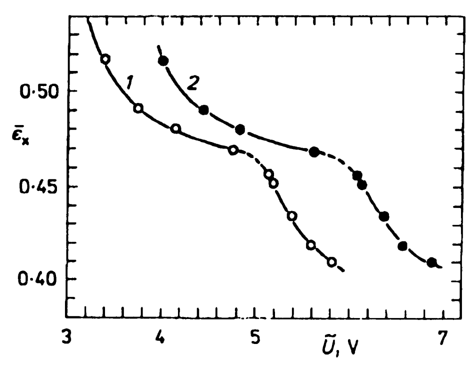

FIG. 3
Typical calibration plots of capacitor for the air–glass ballotini system, d = 0.290 nm: *1* Time-averaged voltage $\tilde{U}$ for 25 mm capacitor, *2* time-averaged voltage $\tilde{U}$ for 30 mm capacitor

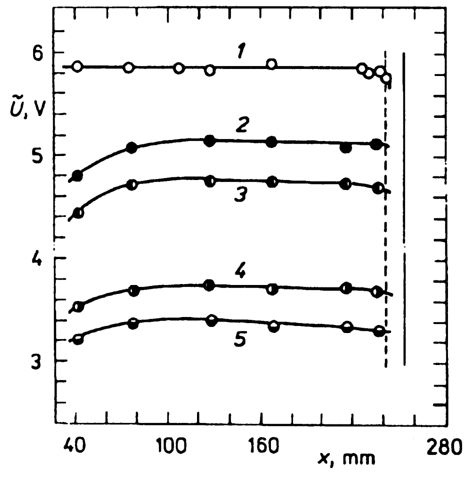

FIG. 4
Dependence of time-averaged voltage $\tilde{U}$ on the centre distance of 25 mm capacitor, x, from distributor. Vertical dashed line denotes such a position of capacitor centre when the upper part of capacitor was on the level h_{mf} (vertical solid line): m = 6.433 kg, d = 0.290 mm, h_{mf}/D = 1.776; *1* u/u_{mf} = 1, *2* u/u_{mf} = 2.01, *3* u/u_{mf} = 2.80, *4* u/u_{mf} = 5.79, *5* u/u_{mf} = 9.18

agreement with the measurements of authors[15]. According to Figs 5 and 6, there exist such conditions under which the voidage $\bar{\varepsilon}_x$ in the central region is not constant. The smaller is fraction u/u_{mf} the more pronounced is the central region with constant value of $\bar{\varepsilon}_x$. For comparatively high values of u/u_{mf}, the transition from the central region to the region of thin suspension is inexpressive.

Distribution of $\Delta\tilde{p}_x$ along Bed Height

The linear dependence is typical of the standard bubbling beds (see Fig. 7) for which $\Delta\tilde{p}_0 = \Delta p_t$ applies. When the standard bubbling bed turns into the slugging bed, then we get the dependence according to Fig. 8 which is nonlinear, and $\Delta\tilde{p}_0 > \Delta p_t$.

Distribution of $\bar{\varepsilon}^{(-)}_{x,e}$ along Bed Height

Figures 9 – 11 are characteristic of the dependence $\bar{\varepsilon}^{(-)}_{x,e} = f(x)$. The unreal high values of $\bar{\varepsilon}^{(-)}_{x,e}$ for $x \rightarrow 0$, a great many of them being greater than 1, are not depicted in them. It is caused by the fact that $\Delta\tilde{p}_{x,\,in} >> 0$ applies here, and this result follows from Eqs

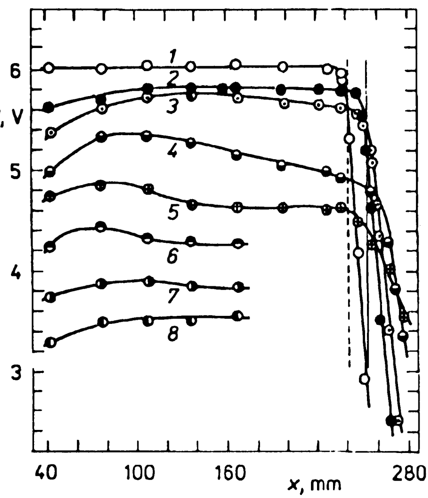

FIG. 5

Dependence of time-averaged voltage $\tilde{U}$ on distance of centre of 25 mm capacitor, x, from distributor. The meaning of vertical dashed line and vertical solid line as in Fig. 4: m = 6.375 kg, d = 0.144 mm, h_{mf}/D = 1.778, u/u_{mf}: *1* 1, *2* 1.66, *3* 2.27, *4* 4.11, *5* 6.38, *6* 9.83, *7* 15.33, *8* 20.13

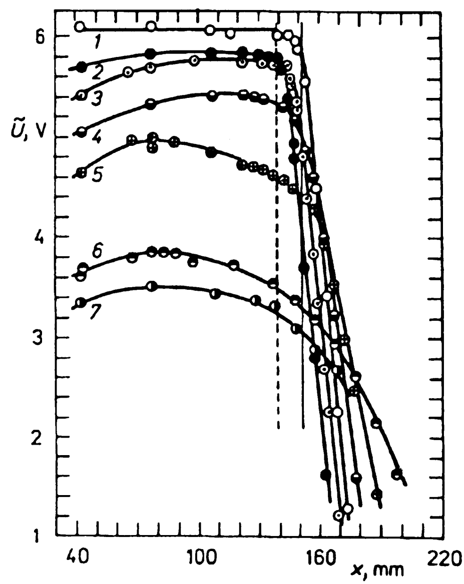

FIG. 6

Dependence of time-averaged voltage $\tilde{U}$ on distance of centre of 25 mm capacitor, x, from distributor. The meaning of vertical dashed line and vertical solid line as in Fig. 4: m = 3.825 kg, d = 0.144 mm, h_{mf}/D = 1.063, u/u_{mf}: *1* 1, *2* 1.59, *3* 2.31, *4* 4.07, *5* 6.62, *6* 15.48, *7* 20.07

(*10*) and (*12*). In these dependences it is necessary to distinguish the interval of values x, where $\overline{\varepsilon}^{(-)}_{x,e}$ markedly decreases with increasing x owing to decreasing the values of $\Delta\tilde{p}_{x,in}$, and the interval with relatively constant values of $\overline{\varepsilon}^{(-)}_{x,e}$ in which values $\Delta\tilde{p}_{x,in}$ become negligible compared to the values of $\Delta\tilde{p}_x$.

Comparison of $\overline{\varepsilon}^{(-)}_{x,e}$ *with Local Values of* $\overline{\varepsilon}_x$

The compared data were established by the capacitometric probe. The typical results are in Figs 12 – 14. The data for $x < 31$ mm in the interval of decreasing values of $\overline{\varepsilon}^{(-)}_{x,e}$ are not plotted in Figs 12 and 13 because the capacitor design did not allowed of their measurement. However, it follows from Fig. 14 that $\overline{\varepsilon}_x < \overline{\varepsilon}^{(-)}_{x,e}$ even for $x < 31$ mm. According to all three figures, $\overline{\varepsilon}_x \approx \overline{\varepsilon}^{(-)}_{x,e}$ applies in the interval with relatively constant values of $\overline{\varepsilon}^{(-)}_{x,e}$. The interval of distances x in which values of $\overline{\varepsilon}^{(-)}_{x,e}$ markedly decrease with increasing x is limited to the distributor region. It is apparent from Figs 12 – 14 that the width of this interval, under the remaining identical conditions, increases with

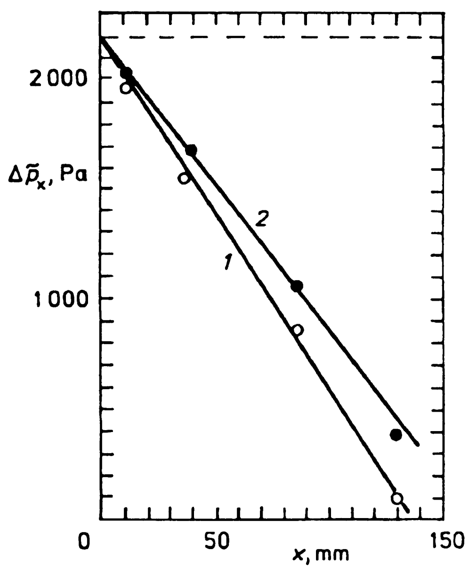

FIG. 7
Dependence of time-averaged pressure drop $\Delta\tilde{p}_x$ determined with damped liquid U-manometer on distance x of pressure measuring point from distributor: m = 3.586 kg, d = 0.144 mm, h_{mf}/D = 2.152; u/u_{mf}: *1* 1.23, *2* 18.00; $\Delta\tilde{p}_0 = \Delta\tilde{p}_x$ for $x = 0$

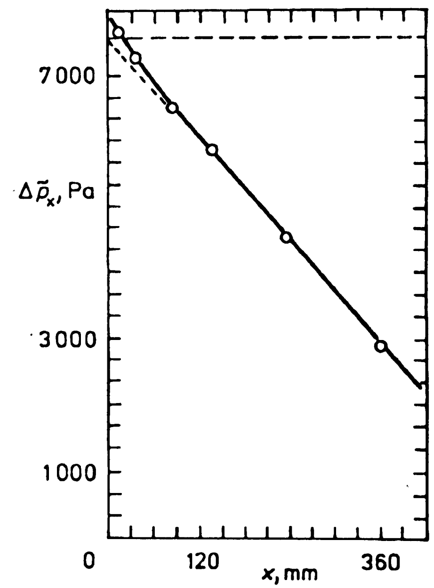

FIG. 8
Dependence of time-averaged pressure drop $\Delta\tilde{p}_x$ determined with damped liquid U-manometer on distance x of pressure measuring point from distributor: m = 12.400 kg, d = 0.521 mm, h_{mf}/D = 3.425, u/u_{mf} = 3.50, $\Delta\tilde{p}_0 = \Delta\tilde{p}_x$ for $x = 0$

increasing h_{mf}, and the smaller x the greater is $\Delta\tilde{p}_{x,\,in}$. This effect is to be ascribed to the effect of particle momentum connected with the fluctuations of bed height. Generally,

$$\Delta\tilde{p}_{x,\,in} = (\bar{\varepsilon}^{(-)}_{x,\,e} - \bar{\varepsilon}_x)\, g\, \rho_s\, x\,. \tag{16}$$

Since with growing x, $\bar{\varepsilon}_x \approx \bar{\varepsilon}^{(-)}_{x,\,e}$ and $\bar{\varepsilon}^{(-)}_x \rightarrow \bar{\varepsilon}^{(-)}_{x,\,e}$, it is possible to state that also $\bar{\varepsilon}^{(-)}_x \rightarrow \bar{\varepsilon}_x$, and for sufficiently high beds, also $\bar{\varepsilon}^{(-)}_{x,\,e} \approx \bar{\varepsilon}$. From it follows that with sufficiently high beds, it is possible to determine voidage $\bar{\varepsilon}$ with the precision of several percent.

We did not investigate from what bed height is this manometric method suitable for the determination of voidage $\bar{\varepsilon}$. However, from the material submitted follows that this method is suitable for the standard bubbling beds if the dependence $\bar{\varepsilon}^{(-)}_{x,\,e} = f(x)$ has a marked interval of values x with comparatively constant values of $\bar{\varepsilon}^{(-)}_{x,\,e}$, which can be found experimentally.

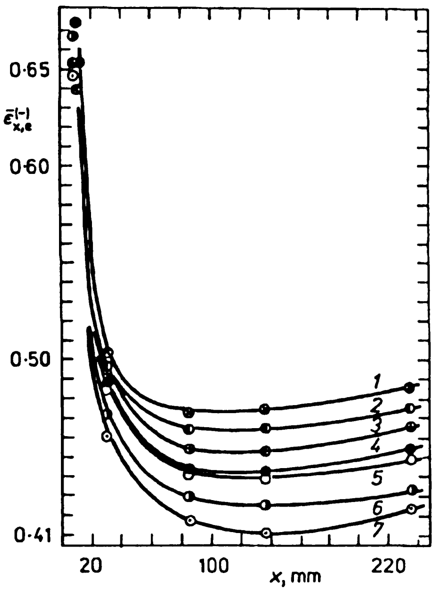

FIG. 9

Characteristic forms of dependence of estimated voidage $\bar{\varepsilon}^{(-)}_{x,\,e}$ on distance x of pressure measuring point from distributor: m = 6.4378 kg, d = 0.521 mm, h_{mf}/D = 1.776, u/u_{mf}: *1* 2.862, *2* 2.265, *3* 1.882, *4* 1.663, *5* 1.496, *6* 1.292, *7* 1.182

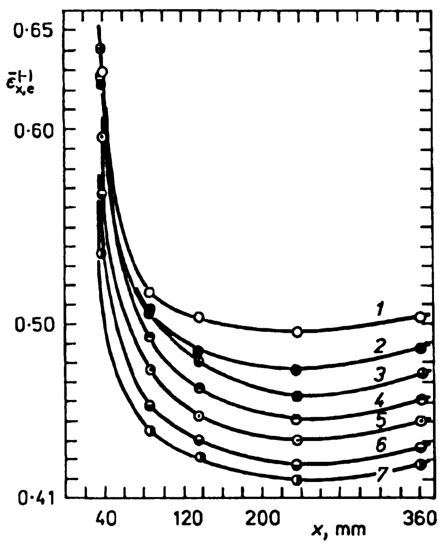

FIG. 10

Characteristic forms of dependence of estimated voidage $\bar{\varepsilon}^{(-)}_{x,\,e}$ on distance x of pressure measuring point from distributor: m = 10.000 kg, d = 0.521 mm, h_{mf}/D = 2.76, u/u_{mf}: *1* 2.786, *2* 2.210, *3* 1.843, *4* 1.615, *5* 1.451, *6* 1.258, *7* 1.161

Results of Manometric Measurements of $\bar{\varepsilon}^*_{i,\,i+1}$

The dependences $\bar{\varepsilon}^*_{i,\,i+1} = f(u/u_{mf})$ are in Figs 15 and 16, where subscript i denotes the x_i level given in the description of apparatus (e.g., i = 1 denotes x_1 = 11.05 mm, etc.). The results completely contradict the knowledge on the distribution of $\bar{\varepsilon}_x$ and $\bar{\varepsilon}_{ij}$ along the bed height. From that follows that the exchange of Eq. (*15*) for (*14*) is inadmissible because the influence of $(\Delta\tilde{p}_{i,\,in} - \Delta\tilde{p}_{j,\,in})/(x_j - x_i)$ is apparently considerable despite the fact that it is possible to expect the relation $\Delta\tilde{p}_{j,\,in} \rightarrow \Delta\tilde{p}_{i,in}$ when $x_j \rightarrow x_i$. Therefore it is not possible to determine manometrically the voidage of the section of bubbling bed from the level x_i to the level x_j for small values of difference $x_j - x_i$.

CONCLUSION

The relation between the wall pressure signal Δp_x and some specifically defined voidages of standard bubbling bed was investigated. One of them is the estimated voidage

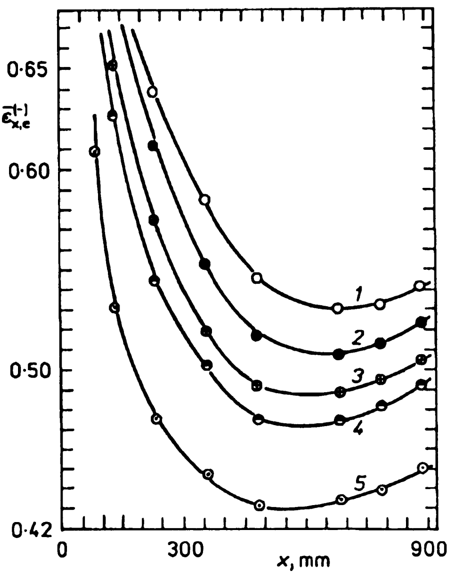

FIG. 11

Characteristic forms of dependence of estimated voidage $\bar{\varepsilon}^{(-)}_{x,\,e}$ on distance x of pressure measuring point from distributor: m = 20.601, d = 0.521 mm, h_{mf}/D = 5.59, u/u_{mf}: *1* 2.60, *2* 2.11, *3* 1.74, *4* 1.55, *5* 1.20

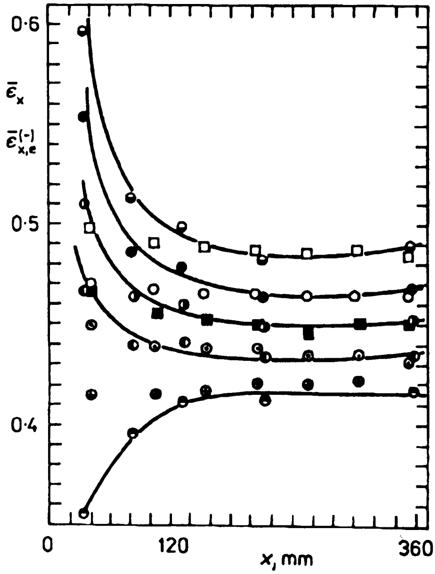

FIG. 12

Comparison of manometrically determined dependence $\bar{\varepsilon}^{(-)}_{x,\,e} = f(x)$ (first mark) with dependence $\bar{\varepsilon}_x = F(x)$ (second mark) determined with capacitor of length 25 mm, x is the height of capacitor centre above distributor: m = 6.433 kg, d = 0.290 mm, h_{mf}/D = 1.776, u/u_{mf}: ⊖, ☐ 8.97, ●, ○ 5.66, ◑, ■ 2.74, ◐, ⊙ 1.96, ⊖, ⊕ 1.13

$\bar{\varepsilon}^{(-)}_{x,e}$ along the section of this bed from the distributor up to level x defined by Eq. (*12*). We have found out that this voidage at first markedly decreases with increasing x and then acquires approximately identical values. Some manometric measurements of voidage $\bar{\varepsilon}^{(-)}_{x,e}$ were compared with voidages $\bar{\varepsilon}_x$ measured with special capacitor whose design is described in this paper.

Under the conditions when $\bar{\varepsilon}^{(-)}_{x,e}$ practically did not change, the manometrically determined values approximately agreed with the capacitor values $\bar{\varepsilon}_x$. In the vicinity of distributor, the values of $\bar{\varepsilon}^{(-)}_{x,e}$ excessively exceeded the values of $\bar{\varepsilon}_x$, and in some cases we measured $\bar{\varepsilon}^{(-)}_{x,e} > 1$. This discrepancy is ascribed to the effect of excess pressure $\Delta\tilde{p}_{x,\,in}$ induced by the nonuniformity of bubbling bed, $\Delta\tilde{p}_{x,\,in}$ approaching rapidly zero with increasing x. It makes it possible to measure the time-volume averaged voidage $\bar{\varepsilon}$ of the entire bed if we put $\bar{\varepsilon} = \bar{\varepsilon}^{(-)}_{x,e}$ for $x = h_{mf}$.

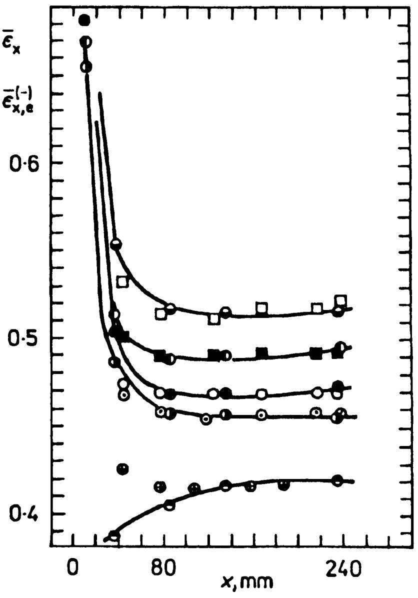

FIG. 13

Comparison of manometrically determined dependence $\bar{\varepsilon}^{(-)}_{x,e} = f(x)$ (first mark) with dependence $\bar{\varepsilon}_x = F(x)$ (second mark) determined with capacitor as in Fig. 12: m = 10.000 kg, d = 0.290 mm, h_{mf}/D = 2.762, u/u_{mf}: ◒, ❐ 3.87, ○, ■ 2.69, ●, ○ 1.95, ◑, ⊙ 1.42, ◓, ⊕ 1.10

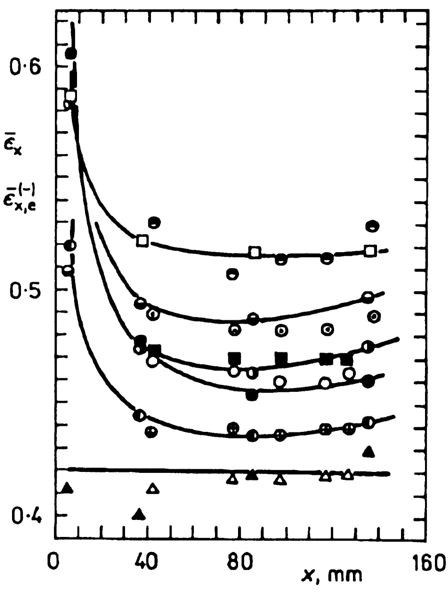

FIG. 14

Comparison of manometrically determined dependence $\bar{\varepsilon}^{(-)}_{x,e} = f(x)$ (first mark) with dependence $\bar{\varepsilon}_x = F(x)$ (second mark) determined with capacitor as in Fig. 12: m = 3.866 kg, d = 0.290 mm, h_{mf}/D = 1.070, u/u_{mf}: ◓, ❐ 9.19, ◒, ⊙ 5.51, ◑, ■ 2.86, ●, ○ 2.01, ◐, ⊕ 1.43, ▲, △ 1.14

SYMBOLS

Ar	Archimedes number ($d^3 g\, \rho_f(\rho_s - \rho_f)/\mu^2$)
c_{sb}	settled bulk density of solids
$\bar{c}_x$	time-area averaged concentration of solids on level x
d	particle diameter
D	column diameter
g	acceleration due to gravity
$\tilde{h}$	time-averaged bed height
h_{min}, h_{max}	minimum and maximum fluidized bed height, respectively
h_{mf}	bed height at minimum fluidization conditions
L	compact bed height ($4m/\pi D^2 \rho_s$)
m	mass of particles in bed
$\tilde{m}_x^{(-)}$, $\tilde{m}_x^{(+)}$	time-averaged mass of particles under and above level x, respectively
p_a	atmospheric pressure
u	superficial gas velocity
u_{mf}	superficial gas velocity at minimum fluidization conditions
$\tilde{U}$	time-averaged voltage
V_b	bubble volume

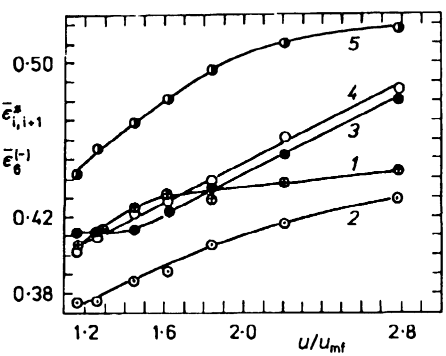

FIG. 15

Comparison of values $\bar{\varepsilon}^*_{i,i+1}$ calculated in terms of Eq. (*15*) from manometrically measured data $\Delta\tilde{p}_i$ and $\Delta\tilde{p}_{i+1}$ for different sections of nonuniformly fluidized bed: m = 10.000 kg, d = 0.521 mm, h_{mf}/D = 2.76; *1* $\bar{\varepsilon}^*_{1,2}$, *2* $\bar{\varepsilon}^*_{2,3}$, *3* $\bar{\varepsilon}^*_{3,4}$, *4* $\bar{\varepsilon}^*_{4,5}$, *5* $\bar{\varepsilon}^*_{5,6}$

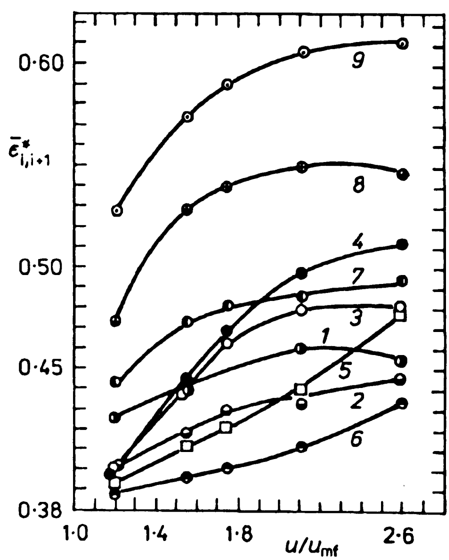

FIG. 16

Comparison of values $\bar{\varepsilon}^*_{i,i+1}$ calculated in terms of Eq. (*15*) from manometrically measured data of $\Delta\tilde{p}_i$ and $\Delta\tilde{p}_{i+1}$ for different sections of nonuniformly fluidized bed: m = 20.601 kg, d = 0.521 mm, h_{mf}/D = 5.69; *1* $\bar{\varepsilon}^*_{1,2}$, *2* $\bar{\varepsilon}^*_{2,3}$, *3* $\bar{\varepsilon}^*_{3,4}$, *4* $\bar{\varepsilon}^*_{4,5}$, *5* $\bar{\varepsilon}^*_{5,6}$, *6* $\bar{\varepsilon}^*_{6,7}$, *7* $\bar{\varepsilon}^*_{7,8}$, *8* $\bar{\varepsilon}^*_{8,9}$, *9* $\bar{\varepsilon}^*_{9,10}$

x	vertical coordinate measured from distributor
$\Delta\tilde{p}_{0,\,mf}$	time-averaged experimental pressure drop, $x = 0$, $u = u_{mf}$
$\Delta\tilde{p}_{h_{mf}}$	time-averaged pressure drop for $x = h_{mf}$
$\Delta\tilde{p}_{ij}$	time-averaged pressure drop in bed section from x_i to x_j
$\Delta\tilde{p}_t$	theoretical pressure drop $(4mg/\pi D^2)$
$\Delta\tilde{p}_x$	time-averaged pressure drop measured on level x
$\Delta\tilde{p}_{x,\,in}$	time-averaged excess pressure induced by nonuniformity of bed
$\bar{\varepsilon}$	mean voidage of bed
$\bar{\varepsilon}_{ij}$	time-volume averaged voidage in section of bed from x_i to x_j, see Eq. (*14*)
$\bar{\varepsilon}^*_{ij}$	estimated time-volume averaged voidage in section of bed from x_i to x_j, see Eq. (*15*)
$\bar{\varepsilon}^{(-)}_x$	time-volume averaged voidage in section of bed from distributor to level x
$\bar{\varepsilon}^{(-)}_{x,\,e}$	estimated time-volume averaged voidage, see Eq. (*12*)
ε_{sb}	voidage of settled bed
μ	viscosity of fluid
ρ_f	density of fluid
ρ_s	density of solid particles

REFERENCES

1. Mathur A., Saxena S. C., Zhang Z. F.: Powder Technol. *47*, 247 (1986).
2. Blickle T., Ormós Z.: Hung. J. Ind. Chem. *1*, 31 (1973).
3. Boichev G. J.: *Thesis*. Higher Institute of Chemical Technology, Sofia 1976.
4. Botterill J. S. M., Teoman Y., Yüegir K.: Powder Technol. *31*, 101 (1982).
5. Denloye A. O.: Presented at *7th Int. CHISA Congress, Prague 1981*; paper No. J2.23.
6. Doichev K., Boichev G.: Powder Technol. *17*, 91 (1977).
7. Gelperin N. I., Ainshtein V. G., Romanova N. A.: Khim. Prom. *11*, 781 (1962).
8. Ormós Z.: *Thesis*. College of Chemical Industry, Veszprém 1968.
9. Jolly R. D., Doig I. D.: Chem. Eng. Sci. *28*, 971 (1973).
10. Bhat G. N., Guconic-Murphy K., Weingaertner E. W.: Br. Chem. Eng. *8*, 813 (1963).
11. Toomey R. D., Johnstone H. E.: Chem. Eng. Process. *48*, 221 (1952).
12. Trivedi R. C., Rice W. J.: CEP. Symp. Ser. *62*, No. 67, 57 (1966).
13. Whitehead A. B., Dent D. C. in: *Proc. Int. Symp. on Fluidization, Eindhoven 1967* (A. A. H. Drinkenburg, Ed.), p. 802. Netherland University Press, Eindhoven 1967.
14. Bakker P. J., Heertjes P. M.: Br. Chem. Eng. *4*, 524 (1959).
15. El Halwagi M. M., Gomezplata A.: AIChE J. *13*, 503 (1967).
16. Fan L. T., Lee C. T., Bailie R. C.: AIChE J. *8*, 239 (1962).
17. Havalda I., Beňa J., Laciak D.: Chem. Eng. Commun. *52*, 135 (1987).
18. Kunii D., Levenspiel O.: *Fluidization Engineering*. Krieger Publ. Co., New York 1977.

Translated by J. Linek.