Hungarian Journal
of Industrial Chemistry
Veszprém
Vol.1. pp. 31-52 (1973)

STUDIES ON THE HYDRODYNAMICS OF FLUIDIZED LAYERS I. MEASURING METHODS FOR THE DETERMINATION OF THE EXPANSION OF FLUIDIZED LAYERS

T. BLICKLE and Z. ORMÓS

(Research Institute for Technical Chemistry of the Hungarian Academy of Sciences, Veszprém)

Received: June 30, 1972.

Knowledge of the expansion of fluidized layers is important both with regard to calculations connected with heat and material transfer processes, and for apparatus design. The expansion of the layer can - among others - be characterized by the void fraction of the fluidized bed. The determination methods of the void fraction can be divided into three groups:

a) those applicable in the case of fluidization with a liquid or a gas,

b) those applicable only in the case of liquid fluidization,

c) those applicable only in case of fluidization with a gas.

The authors describe the measuring techniques published in literature according to the above grouping. A report is presented on the research work carried out to investigate the applicability of measuring techniques, the elaboration of new techniques, and to improve those already known. The conditions of the applicability and the possibilities of methods for the determination of the free volume ratio are summarized in a tabular form.

An important characteristic of fluidized layers is the degree of expansion of the layer. The degree of expansion can be characterized by the height of the layer/the minimum height of layer ratio; by the density of the layer and by the void fraction. The

height of the layer/the minimum height of layer ratio - if the weight of the layer, and the characteristics of the particles and of the apparatus are known - and the density of the layer - if the densities of the solid and the fluid are known - can be calculated from the void fraction; accordingly, the knowledge of the free volume ratio is sufficient for characterization of the layer expansion.

The clearing of the conditions of the layer expansion is important both from the point of view of the calculations of heat and material transport processes, and from that of apparatus design. In addition to measuring techniques for the determination of layer expansion (void fraction), in the present series of papers the following problems will also be dealt with: characteristics and calculation methods concerning the expansion of layers fluidized with a gas or liquid, the influence of auxiliary processes (e.g. mechanical stirring, etc.) on layer expansion, and other hydrodynamic problems.

Numerous techniques are known for the determination of fluidized layer expansion. These can be divided into three groups:

a) those applicable in the case of fluidization with a liquid or gas,

b) those applicable only in the case of fluidization with a liquid, and

c) those applicable only in the case of fluidization with a gas.

In the following, the determination methods of void fraction published in literature will be described in accordance with the above grouping. The new techniques that have been elaborated and the improvements carried out on existing techniques will also be dealt with.

a) The Void Fraction Determination Methods in the Case of Fluidization with a Liquid or Gas

Determination of Void Fraction on the Basis of the Layer Height

The simplest and most frequently used method for the determination of the void fraction is that based on the measurement of the height of the layer. This can be used both in case of liquid and gas fluidization.

The calculation directly follows from the definition of void fraction:

$$\bar{\varepsilon}' = \frac{V_r - V}{V_r} \tag{1}$$

If the volumes of the solid material and layer are expressed, after rearrangement the following is gained:

$$\bar{\varepsilon}'_y = \frac{Y - \frac{G}{\gamma \cdot F}}{Y} \tag{2}$$

By means of Eq. (2) the void fraction can be simply calculated from the characteristics of the layer, the solid particles and the apparatus.

During the experiments a large number of measurements were made with various solid materials, liquids and gases. The method based on layer height determination gave very good results in the cases of liquid fluidization, whereas in case of gas fluidization its accuracy was poor, because the boundary of the layer was not sufficiently sharp and consequently the determination of the layer height was difficult. A further drawback of this method is that only the mean void fraction can be determined.

The experiments - including the parallel determinations - led to the conclusion that both in liquid and with a gas fluidization the scattering of the measured void fraction values vary depending on the extent of layer expansion and three distinct ranges can be defined.

In the case of fluidization with a liquid, the first stage of layer expansion - where the range $0.50 < \bar{\varepsilon}'_Y < 0.65$ is valid - the scattering of the void fraction values is relatively high, about ± 2 %. Although the layer height is well defined, the influence of the low reading error on the void fraction can be strongly felt. In the second stage of expansion $0.65 < \bar{\varepsilon}'_Y < 0.75$ the scattering of the measured values is lower, about ± 1 %. In this range, the upper boundary of the layer can be well determined and, the small reading error has no significant influence upon the determined void fraction values. In the third range $0.75 < \bar{\varepsilon}'_Y < 0.9$ the upper boundary of the layer tends to diffuse, because upon the increase of the flow velocity, the smaller particles reach a state of levitation. Considerable errors in the measured layer height are possible, which result in an increased scattering of the void fraction values; the scattering is about ± 2 %.

In the case of fluidization with a gas, the scattering of the void fraction values is generally higher than in the case of fluidization with a liquid. In the first range $0.5 < \bar{\varepsilon}'_Y < 0.6$ the scattering of the values is ± 2 %, this figure being equal to that measured in the case of fluidization with a liquid. The layer is relatively well defined and the layer height can be easily determined. In the second range of layer expansion $0.6 < \bar{\varepsilon}'_Y < 0.8$ the scattering of the values is large, it amounts to ± 3 %, and a thin layer is formed whose height can be measured only with considerable difficulty because the boundary of the layer is diffuse and variable in time. In the third range $0.8 < \bar{\varepsilon}'_Y < 0.9$ the scattering of the results is lower, about ± 2 %, despite the fact that the determination of the layer height is no better than in the previous case, only the same fluctuations in layer height manifest themselves to a lower degree in the void fraction value.

Despite the drawbacks described in the foregoing, the void fraction values determined with other methods or calculated with various equations are generally comparable with those obtained by layer height measurements, because the latter method is the simplest and most reliable of all the methods known for the determination of void fraction, provided that adequately trained personnel carry out a sufficient number of determinations and the application of glass apparatus is possible. The method is based, in accordance with the definition of void fraction, on the measurement of the layer volume.

Determination of Void Fraction Based on the Measurement of a Pressure Drop in the Fluid [1, 2]

A technique was elaborated for the determination of the void fraction in fluidized layers, based on the measurement of the pressure drop in the fluid [1, 2]. As it is known, the pressure drop of the fluid across the fluidized layer is nearly equal to the layer weight with reference to a unit cross section:

$$\Delta p_Y = \frac{G}{F}\,\frac{\gamma - \gamma'}{\gamma} \tag{3}$$

or, in another form:

$$\Delta p_Y = Y(1 - \bar{\varepsilon}')(\gamma - \gamma') \tag{4}$$

Eq. (4) could be applied for the calculation of the void fraction only if the height of the layer was also measured. However, the latter value enables the free volume ratio to be calculated without measuring the pressure drop.

If a suitable pair of static pressure-sensing tubes are placed into the layer in such a way that there is a height difference (y) between their positions, the pressure drop in the fluid along

a given length of the layer can be measured. If this pressure drop is expressed in accordance with Eq. (4), the following is gained:

$$\Delta p_y = y(1 - \bar{\varepsilon}')(\gamma - \gamma') \tag{5}$$

Eq. (5) could be directly applied for the determination of the free volume ratio on the basis of the pressure drop in the fluid. However, the following experimental, empirical finding should be taken into consideration. If the pressure drop values of the fluid across the fluidized layer obtained by actual measurement are compared to those determined on the basis of the layer weight according to Eq. (3), it is seen that the two sets of values are not always in exact agreement. In the evaluation of experimental results, a difference of about ± 5 % was found between the measured and calculated data in the case of liquid fluidization;in the case of gas fluidization this difference may be as high as ± 20 %. This error can be eliminated, if Eq. (5) is divided by Eq. (3), since the equation so obtained takes into consideration the deviation of the pressure drop from the theoretical value:

$$\varepsilon'_{\Delta p} = 1 - \frac{G}{y\,\gamma\,F} \cdot \frac{\Delta p_y}{\Delta p_Y} \tag{6}$$

The void fraction of the fluidized layer can be determined to a satisfactory accuracy by Eq. (6) in a given place of the layer, if the pressure drop is measured across the whole layer and across a length (y) at a given place of the layer [2,3]. The accuracy of the method can further be increased if the pressure drop across a layer of (Y) height is calculated by summation of the pressure drops measured across portions of the length (y):

$$\Delta p_Y = \sum_{i=1}^{i=n} \Delta p_{yi} \tag{7}$$

where $Y = n \cdot y$.

A schematic representation of the apparatus used for the measurements in connection with the above considerations is shown in Fig.1. An interesting feature of the apparatus is that condens-

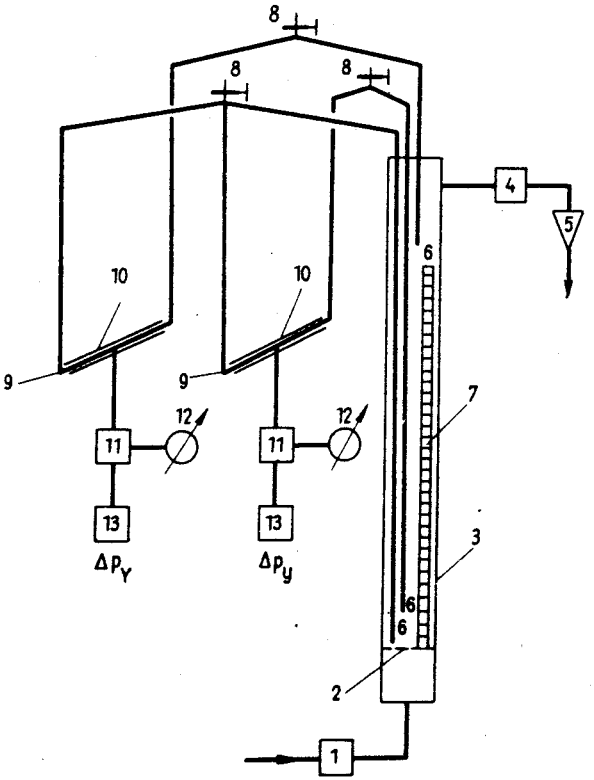

Fig. 1.

1 - quantity meter
2 - support plate
3 - glass apparatus
4 - cyclone
5 - effluent
6 - pressure measuring probes
7 - scale, subdivided in mm.
8 - deaeration stopcock
9 - oblique-tube type pressure gauge
10 - capacitor plates
11 - capacity measuring device
12 - meter
13 - potentiometric recorder

er plates were placed on the oblique-tube type micromanometer tubes and the capacity - proportional to the displacement of the manometer liquid - was measured. The capacity values, which are proportional to the pressure drop, were recorded by a potentiometric strip-chart recorder,whereby not only the pressure drop values, but also any fluctuations in them could be determined. In experiments where fluidization was carried out with a gas, slightly acidified water was used as the pressure gauge fluid, whereas in the case of fluidization with water, carbon tetrachloride was applied. Pressure drop across the total height of the layer, along a 2 cm portion on its bottom,as well as the layer weight and layer thickness were determined.Knowing the specific gravity of the particles and the I.D. of the apparatus, the void fraction of the lower part of the layer was calculated by Eq.(6), whereas the mean void fraction of the whole layer was determined from the layer height value by Eq. (2).

Fig.2. shows the difference between the mean free volume ratio (determined by layer height measurement), and that pertaining to the lower part of the layer (determined by measurement of the pressure drop along a given height) plotted against the mean value determined by layer height measurement for the case of fluidization of sand with water and air, respectively. It is apparent from the Figure that both in the case of fluidization with a gas and with a liquid there is a difference between the values determined with the two methods, but this difference is slight in the case of fluidization with a liquid.This experimental result is in good agreement with that obtained by COEURET and LE GOFF [4], who studied changes in the void fraction along the axis of the layer - among other methods - by conductance measurements. They came to the conclusion that the decrease of voidage along the height axis is not significant, i.e. the void fraction pertaining to the lower part of the layer differs (is lower) only slightly from the mean value, if a narrow fraction of particles is studied.

It is also apparent from Fig.2. that in the case of fluidization with a gas there is a considerable deviation between the compared values.This considerable difference originates from the fact

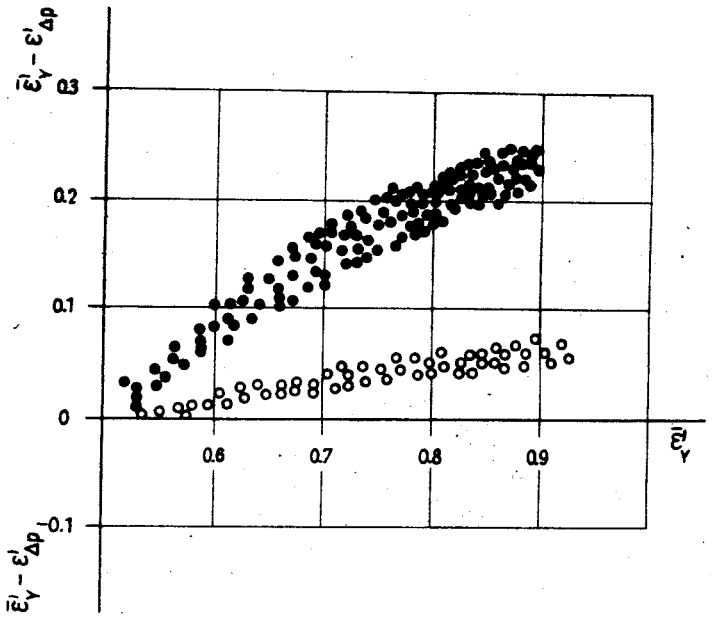

Fig.2. o - sand-water system; • - sand-air system

that in systems fluidized with a gas, the mean void fraction is substantially different from that of both the dense and the thin layers, and it was the dense layer in which the void fraction was determined on the basis of the pressure drop. The difference shown in the Figure is, to a good approximation, equal to the difference of the void fraction of the dense layer and the mean void fraction.

In addition to the apparatus described in the foregoing, another apparatus was constructed in which a pair of probes could be moved along the height and along the radius of the apparatus, whereby the pressure drop produced across a 1 cm portion of the layer

could be determined. The pressure drop was measured by high-sensitivity micromanometers filled with alcohol. In the experiments the pressure drop was measured along the height and at different distances from the axis of a layer fluidized with different air flow rates. The void fraction values were calculated from the measured pressure drops with Eq. (6) in such a way that the Δp_Y values were determined by summation of the measured pressure drop values in accordance with equation (7).

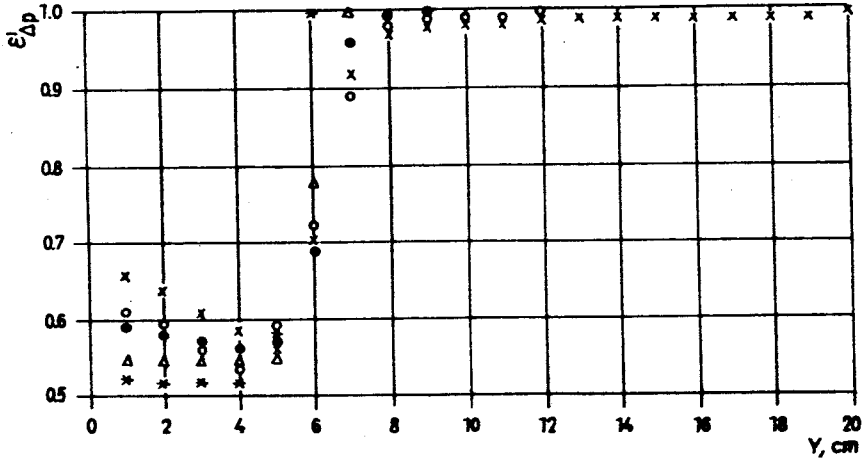

Fig.3. Sand-air system.

d = 0.1 - 0.2 mm
• - u' = 0.132 m/sec
x ÷ u' = 0.04 m/sec
o - u' = 0.265 m/sec
Δ - u' = 0.067 m/sec
x - u' = 0.595 m/sec

Fig.3. snows the mean void fraction values measured at five different air flow rates, determined on the basis of the pressure drop at different distances from the middle of the layer, plotted against the distance measured from the fritted plate, in the case of fluidization of sand of d = 0.1 to 0.2 mm particle size with air. It is apparent from the Figure that there is a jump-like change in the void fraction values at a height of about 6 cm, as measured from the fritted plate (Y_m = 5.4 cm).

The mean values of void fractions determined on the basis of pressure drop measurement at different heights of the layer were compared to the mean void fraction values obtained by calculation on the basis of layer height determinations and it could be concluded that the deviation was smaller than ± 5 % and consequently the accuracy of the method is adequate and therefore it can be applied to the determination of the mean void fraction. The method described in the foregoing, based on pressure drop determination in the fluid, are especially important in connection with experiments where the wall of the apparatus is opaque. Both the mean void fraction of the layer and the dependence of the free volume ratio on place can be determined relatively easily and quickly even in such cases. By means of the apparatus shown in Fig.1. it is possible to record continuously the value of the pressure drop and consequently changes and fluctuations of it and of the void fraction in time can also be recorded. A drawback of the technique is that the mean void fraction is not determined directly, and the probes brought into the layer slightly disturb the motion of the particles.

Determination of the Void Fraction on the Basis of γ-Ray Absorption [5, 6]

A method was elaborated for the determination of the void fraction of layers fluidized with a gas by application of a radiating isotope [5].

The phenomenon of γ-ray absorption makes it possible to determine the thickness and real density of solid and liquid materials as absorbents with reference to the unit area. According to the basic law of the phenomenon, the γ-radiation of I_{γ_o} intensity, having passed a material of ρ_F "surface density", is weakened according to the formula:

$$I_\gamma = I_{\gamma_o} \cdot e^{-\alpha \rho_F} \qquad (8)$$

By expressing the "surface density" the following Equation holds:

$$\rho_F = \frac{2.3}{\alpha} \cdot \log \frac{I_{\gamma_o}}{I_\gamma} \tag{9}$$

The void fraction can be calculated from the "surface density", if the length of the layer (y) in which the γ-rays are absorbed, is known:

$$\varepsilon'_\gamma = 1 - \frac{\rho_F}{\rho \cdot y} \tag{10}$$

The above basic principles were considered in the void fraction determination based on γ-ray absorption.

A chromium-51 isotope was used radiating γ-photons of 0.33 MeV energy as a radiation source in the gas fluidization experiments. The apparatus was made so as to allow exact determination of the position of the practically point-like radiation source in the layer [5].

An improved model of this apparatus was produced [6]. This apparatus also enables experiments of fluidization with liquids to be carried out. In the experiments made with water, a sodium-51 isotope radiating γ-photons of 1.27 MeV energy was used as a radiation source.

Accordingly, the determination of the void fraction of a fluidized layer based on γ-ray absorption can be used with fluidization both with a liquid and a gas, and this technique makes it possible to determine changes in the void fraction along the radius and also along the bed height [6].

It is a drawback of the technique that due to the radiating isotope used it requires a "hot" laboratory, and expensive instruments are needed.

b) Void Fraction Determination Methods in the Case of Fluidization with a Liquid

Determination of the Void Fraction Based on the Measurement of the Layer Density [7]

In the case of fluidization with a liquid, the void fraction of the layer can be determined on the basis of the bed density [7].

The apparent layer density can be obtained from the densities of the fluid and solid material:

$$\rho_r = \varepsilon' \rho' + (1 - \varepsilon')\rho \tag{11}$$

By expressing the void fraction the following is gained:

$$\varepsilon'\rho_r = \frac{\rho - \rho_r}{\rho - \rho'} \tag{12}$$

Accordingly, in order to be able to calculate the void fraction, one has to know densities of the solid and the liquid, and the density of the layer has to be determined. The latter was determined by a hydrometer. This method was compared to that based on layer height determination; the two methods showed good agreement [7]. The layer density method is very simple. However, it can be carried out only rarely. It can be used only with apparatus having transparent walls and it furnishes information only on the mean void fraction. In such cases, the method based on layer height measurement can be applied equally well, the latter method being simpler and more reliable for mean void fraction determination. A further drawback of the density method is the use of a hydrometer which interferes with the free motion of the particles and the diameter of the apparatus has to be considerably larger than that of the hydrometer.

Determination of the Void Fraction Based on the Measurement of the Conductance of the Layer [7]

In the case of fluidization with a liquid, the void fraction of the layer can be determined on the basis of the conductance of the layer [7]. The method is based on the fact that the conductance of the layer depends on the magnitude of the space between the particles, because any changes in the voidage also cause the useful cross section to be changed. Having established a calibration curve, the metnod is applicable both in the case of electrically insulating and of electrically conducting solid particles.

An experimental apparatus was constructed, its schematic drawing is shown in Fig.4. This differs from the apparatus already

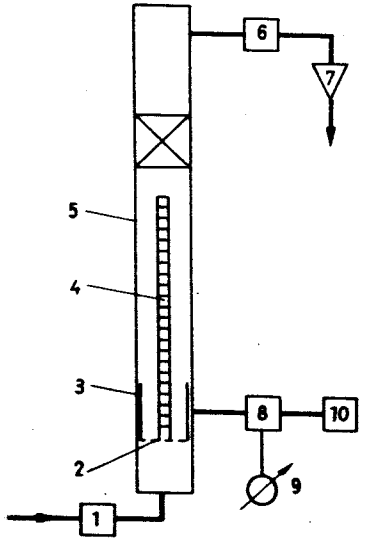

Fig.4.

1 - flow meter
2 - support plate
3 - platinum electrodes
4 - scale, subdivided in mm
5 - Perspex glass apparatus
6 - cyclone
7 - effluent
8 - conductivity meter
9 - meter
10 - potentiometric recorder

described [7] inasmuch as instead of the conductivity meter operating at 2000 c.p.s. frequency, a special conductivity meter of exceptionally wide measuring range, operated at 50 c.p.s. frequency was used. The Perspex glass apparatus was of 5 x 5 cm^2 cross section and there were platinum electrodes placed on the opposite sides in order to measure the conductance of the fluidized layer.

Experiments were carried out with sand and porous burnt clay fluidized in tap-water. The conclusion was reached that the current proportional to the conductance of the fluidized layer (I) divided by the current proportional to the conductance of the liquid (I_o) gives, to a good approximation, the void fraction of the layer:

$$\varepsilon_v' = \frac{I}{I_o} \qquad (13)$$

The differences between the respective void fraction values determined by the layer height measurement on the basis of Equation (2) and by conductivity measurement on the basis of Equation (13) plotted against void fraction values determined from layer height determinations are shown in Fig.5. As it is apparent from the Figure, the values determined with the two methods show a very good agreement and even the highest difference is below ± 10 %.

Accordingly, this method can be applied for void fraction determination in measurements carried out with fluidization with a liquid. An advantageous property of the method is that it can also be used with an opaque-walled apparatus, and the result of the measurement can easily be recorded. Moreover, if more than one pair of independent electrodes is placed into the apparatus at different levels, the distribution of the void fraction can also be determined. The dependence of the void fraction on place (along the height and radius) can also be determined in such a way that an adequately shaped, movable probe is brought into the layer and used for conductivity determination. For example, COEURET and LE GOFF [4] used for such experiments, in an apparatus for fluidization with a liquid, 10 cm in diameter, a conductivity probe movable in the layer and comprising electrodes of

5 mm diameter and 20 mm length, fastened at a distance of 15 mm from each other. In this way, they determined - among others - variations in the void fraction along the axis of the apparatus.

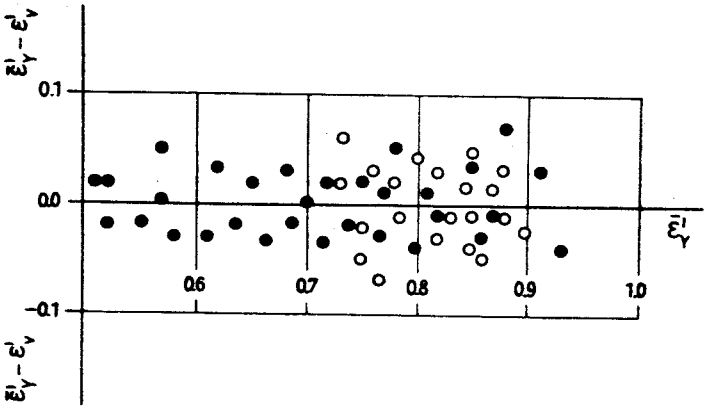

Fig.5. o - burnt clay - water system; • - sand - water system.

Despite its numerous advantages, the method can rarely be applied, because the particles fluidized in a liquid frequently release components which are soluble in the liquid and alter its conductance. Furthermore, every change which tends to alter the conductance of the liquid or the particles - such as adsorption, ion exchange, and change in temperature, etc. - naturally interferes with the method and affects its accuracy to a high degree.

c) Void Fraction Determination Methods in the Case of Fluidization with a Gas

Determination of the Void Fraction on the Basis of X-ray Absorption [8]

GROHSE [8] proposed a method for the determination of the void fraction based on X-ray absorption. The basic principle of the technique is similar to that using the absorption of γ-rays emitted by a radiation source. The X-ray absorption method cannot be easily realized in practice because it necessitates an expensive apparatus. In addition to the above, the place requirement of the method is high, and due to the radiation hazard it requires a separate laboratory to be established. These factors contribute to the difficulties of sprending of the technique.

Void Fraction Determination Based on the Measurement of Layer Capacity

The void fraction at various places of a layer fluidized with a gas can be determined in the following way: small pairs of capacitor plates are placed into the layer and the capacity of these condensers is determined [9]. If the capacitor plates are sufficient small, the distribution of the void fraction along the radius and the height can also be determined.

Void fraction determination technique based on the capacity measurement was improved so as to make it possible to determine the void fraction of the whole layer [10]. The essence of the method is as follows: capacitor plates were placed on two opposite walls of the Perspex glass apparatus of rectangular cross-section and an overflow tube was applied over the capacitor plates. The capacity determinations were carried out according to a definite

Table I. Measuring Methods for the Determination of the Void Fraction of Fluidized Layers

Method	The fluid is		Applicable		The walls are		The method is	
	liquid	gas	$\bar{\varepsilon}$	$\varepsilon' = f(Y,r)$	transparent	opaque	simple	cumbersome
based on layer height determination	+	+	+	-	+	-	+	-
based on the measurement of the pressure drop in the fluid	+	+	+	+	+	+	+	-
based on γ-ray absorption	+	+	+	+	+	+	-	+
based on layer density	+	-	+	-	+	-	+	-
based on the conductance of the layer	+	-	+	+	+	+	-	+
based on X-ray absorption	-	+	+	-	+	+	-	+
based on the capacity of the layer	-	+	+	+	+	+	-	+

system, but the details will not be dealt with here. The results of the capacity measurements enabled the void fraction of the fluidized layer to be calculated, as well as the height and void fraction of the dense and the thin layers, respectively [10, 11]. It was found that the relative error of the experimental void fraction determinations was ± 5 %.

It is easier to carry out the technique based on capacity measurement in the laboratory than either of those based on γ-ray or X-ray absorption. The capacitive method can also be used with apparatus whose walls are opaque. Despite the advantages detailed in the foregoing, this method is rarely applied, partly because it requires instrumentation and partly because the measurement is rather cumbersome and time-consuming.

The conditions and possibilities of the application of the different void fraction determination methods are summarized in Table I.

Used symbols

d particle diameter (m)

F cross section of apparatus (m^2)

G weight of solid particles present in the layer (kp)

I current in the case of a fluidized layer (amperes)

I_o current in the case of pure liquid (amperes)

I_γ intensity of γ-radiation after absorption (counts/sec)

I_{γ_o} intensity of γ-radiation before absorption (counts/sec)

u' linear velocity of fluid as referred to the total cross section of the apparatus (m/sec)

V volume of solid particles present in the layer (m^3)

V_r volume of the layer (m^3)

y given distance along the height of the layer (m)

Y Height of the layer (m)

α mass absorption coefficient ($m^3/kp.sec^2$)

γ density of solid particles (kp/m^3)

γ' density of fluid (kp/m^3)

Δp_y pressure drop of fluid across a length y of the layer (kp/m^2)

Δp_Y pressure drop of fluid across the total height (Y) of the layer (kp/m^2)

ε' value of voidage at a given place of the layer (dimensionless)

$\bar{\varepsilon}'$ calculated mean void fraction of the layer (dimensionless)

ε'_v void fraction calculated on the basis of the conductance of the layer (dimensionless)

$\bar{\varepsilon}'_Y$ mean void fraction determined on the basis of the measurement of the layer height (dimensionless)

ε'_γ void fraction determined on the basis of γ-ray absorption (dimensionless)

$\varepsilon'_{\Delta p}$ void fraction determined on the basis of the pressure drop measurement in the fluid (dimensionless)

$\varepsilon_{\rho r}$ void fraction determined on the basis of the layer density measurement (dimensionless)

ρ density of solid particles ($kp\ sec^2/m^4$)

ρ' density of fluid ($kp\ sec^2/m^4$)

ρ_r density of fluidized layer ($kp\ sec^2/m^4$)

ρ_F "surface density": mass of the solid particless with reference to a unit surface area ($kp\ sec^2/m^3$)

References

1. BLICKLE, T., Theoretical and Experimental Studies on the Realization of Some Material Transfer Processes by Fluidization. Dissertation. Budapest, 1967.

2. ORMÓS, Z., Studies on the Extension of Fluidized Layers. Dissertation. Vegyipari Egyetem, Veszprém, 1968.

3. ORMÓS, Z., Proceedings of the 2nd Conference on Applied Physical Chemistry. Akadémiai Kiadó. Budapest, 1971.Vol.2. p.143.

4. COURET, F., LE GOFF, P., I.Conference on Some Aspects of Physical Chemistry. Budapest, 1966. Publication No.2. Vol. III. p. 323.

5. HODANY, L., ORMÓS, Z., Conference of Intensive Chemical Technological Processes, Kecskemét, 1964. Proc. p. 225.

6. HODANY, L., BLICKLE, T., I. Conference on Some Aspects of Physical Chemistry, Budapest, 1966. Publication No.2. Vol. III. p. 335.

7. BLICKLE, T., BORLAI, O., Vortragstagung des Fach-Verbandes Verfahrenstechnik Halle 1961.

8. GROHSE, E.W., A.I.Ch.E. Journal, 1, 358 (1955)

9. JOTTRAND, R., Chem. Eng. Sci. 1, 81 (1951)

10. BLICKLE, T., Studies on Fluidized Systems. Dissertation, Budapest, 1958.

11. BLICKLE, T., Apparatus, Applications and Calculations in Connection with Fluidization. Akadémiai Kiadó, Budapest, 1963.

РЕЗЮМЕ

Знание распространения псевдоожиженных слоев является важным с точек зрения как расчета процессов передачи тепла и материалов, так и проектировки установок. Распространение слоя — между прочим — можно характеризовать долей свободного объема. Методы, подходящие к измерению доли свободного объема можно подразделить в три группы:

а/ применимые при флюидизации как с жидкостью так и газом,
б/ применимые только при флюидизации с жидкостью,
в/ применимые только при флюидизации с газом.

Находимые в литературе методы измерения описаны авторами в указанной группировке, далее дан ими отчет о результатах исследовательской работы, выполненной по испытанию применимости методов измерения, по разработке новых методов измерения и усовершенствованию известных методов. Условия и возможности применения методов определения доли свободного объема составлены в таблице.