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INVESTIGATIONS OF THE FLUID MECHANICS IN LIQUID-SPOUTED BED SYSTEMS

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Fluid mechanics in spouted bed processes are dealt with. In an air-water model the pressure drop, the liquid content and the recirculation rate of the system are studied as a function of the gas flow rate and the design characteristics of the apparatus. In addition to the description of the experimental apparatus, test methods, and characteristic results are given. On the basis of the estimated data, the derivation of equations for the pressure drop, recycling rate and liquid fraction in the apparatus are aimed at. The numerous data show that the measured values agree well with the values calculated by the derived equations.

INTRODUCTION

Many kinds of the two-phase gas-liquid flow are known in practice. The flow of gas-liquid systems can be varied depending upon the direction of the flow, and the physical state of the gaseous phase, etc. In the present work, such a liquid-gas flow was investigated that was directed from the bottom to the top of a tube where the liquid is drawn in an inserted tube by a gas flowing with high velocity through a nozzle and where the relatively small residence time of the two-phase flow can be set practically at any value by an internal liquid recirculation. In contrast to the two-phase flow in a tube, where the feed rates and the ratio of the phases are freely selected for both phases, in the studied liquid--spouted bed system the flow of the liquid phase was determined by the system itself, i.e. it depends upon the amount and velocity of the liquid drawn in, the geometrical circumstances and the gas velocity. From this important difference it follows that the relationships derived for the calculation of the flow characteristics of gas-liquid systems cannot be applied without the relationships for the liquid amount and the velocity of the liquid, even if they are also valid for the spouted bed system.

Several equations were derived on the basis of the main variables for the calculations of the characteristics of the two--phase flow [1, 2]. All of these have the inadequacy that they refer only to a certain type of flow, to gases of a given density, some liquid flow rate interval, and a given tube diameter, etc. There is no general relationship such as the coefficient of friction and Reynold's Number diagram which is so useful at the calculation of the single phase flow. Provided the flow processes and all the physical and geometric properties of the system are known, even the best correlations provide a pressure drop with an error of about 25 % and this problem is solved inadequately in the case of volume fractions.

EXPERIMENTAL APPARATUS AND MEASURING TECHNIQUE

The scheme of the apparatus built for the investigation of the fluid mechanics of liquid-spouted bed systems is shown in Fig. 1. The apparatus consists of two concentric cylinders (3, 4). The controlled amount of air (1) is introduced into the inner cylinder (3) through the nozzle (2). The gas flowing with high velocity

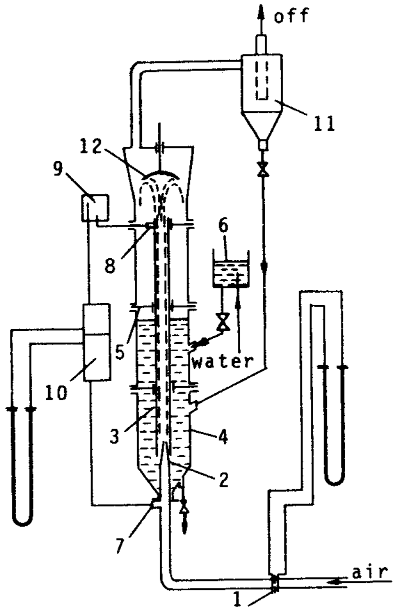

Fig. 1. Liquid-spouted bed. 1 - metering orifice; 2 - nozzle; 3 - inserted tube; 4 - column; 5 - clamping lever; 6 - water tank; 7-8 - pipe end; 9 - liquid separator; 10 - buffer vessel; 11 - cyclone; 12 - baffle plate

draws in the liquid from the space between the two cylinders and carries it away. The gas-liquid mixture proceeds through the inserted tube (3) in a certain type of flow and after bumping into the plate placed at the top of the apparatus (12) the liquid falls back into the space between the two cylinders. In the outer space of the apparatus the liquid moves downwards countercurrently to the flow in the inner cylinder and it once again enters the inner tube at the nozzle. The liquid droplets left in the gas are separated in a cyclone (11) and the gas is carried off into the air.

The pressure drop of the system can be measured as the pressure difference between the (7) and (8) pipe ends. This is the sum of the pressure drops on the nozzle and on the inner cylinder and it is measured after the liquid separator (9) and damper vessels (10).

The liquid amount in the inserted tube was measured by the frequently applied intermittent method well known in literature. In the lower part of the inserted tube, above the nozzle, a lock was built in which allowed the free flow when open. The measurement consisted of the abrupt closure of the bottom of the system, the liquid collected above the lock was withdrawn and its volume was measured. The standard deviation of the parallel measurements was less than $\pm$ 3 %.

The outer cylinder of the apparatus was assembled from column elements, so the recycling rate of the liquid was measured by separating the column into two parts with a plate built in between two adjacent column elements, which had an opening in the middle, with a diameter corresponding to that of the inserted tube. The liquid collected above the plate was continuously withdrawn, while liquid was added in an amount that corresponded to that of the withdrawn liquid. It was not the volume of the withdrawn liquid that was measured - although some controlling measurements were also carried out in that manner - but the amount of the added water fed under the plate into the bottom of the column via a rotameter, needed to maintain a constant liquid level. Since the identity of the pressure at either side of the plate was ensured, the rotameter directly showed the recirculation rate.

THE EXPERIMENTAL CIRCUMSTANCES AND RESULTS

For the study of the fluid mechanics in liquid-spouted bed systems, the overall pressure drop of the system, the pressure drop of the empty apparatus, the liquid content of the inserted tube, and the liquid recycling rate were measured as a function of the gas velocity, the diameter and length of the inserted tube and the diameter of the nozzle, in the air-water model system. The pressure drop of the empty apparatus can be measured as the pressure difference between the (7) and (8) pipe ends, provided that only air flows through the apparatus. During the measurements the volume of the water in the apparatus, and the diameter and length of the outer cylinder were constant (1.5 litres, 90 millimetres and 1.5 metres). The gas velocity was varied in such a way that it embraced the 0-90 metres per second interval.

The dimensions of the apparatus were selected for the experiments from the following values:

the length of the inserted tube (millimetres)	400; 600; 800; 1000;
the diameter of the inserted tube (millimetres)	10; 15; 24; 29;
the diameter of the nozzle (millimetres)	2; 4; 6; 8; 10; 12; 14; 16; 18; 20.

The relationships derived between the studied characteristics of flow and the variables will be summarized (the detailed experimental results were published in a Doctor Technicus thesis [3]):

The pressure drop of the empty apparatus increases in a quadratic manner with the increase of the gas velocity and decrease of the nozzle diameter, and is independent of the diameter and length of the inserted tube. The latter seemingly contradicts the accepted relations known in literature, but taking into account the pressure drop of the empty apparatus is the sum of the pressure drops established on the nozzle and on the inserted tube, and the latter is in general smaller by several orders of magnitude, then this contradiction is solved.

Between the overall pressure drop of the system and the independent variables, a relation similar to that of the empty apparatus was found; because of the appearance of the second phase the values of the pressure drop were naturally far greater.

The recirculation rate of the liquid transfer by the gas grows proportionally at the beginning, later it approaches a limit. The growth of the length and diameter of the nozzle decreases, while the increase of the diameter of the inserted tube increases the recirculation rate.

The liquid content decreases and tends to zero when increasing the gas velocity, while an increase in the length of the inserted tube increases it. The decrease of the nozzle diameter and the increase of the diameter of the inserted tube increase the liquid content.

CALCULATION AND EVALUATION OF THE FLOW CHARACTERISTICS OF LIQUID-SPOUTED BED SYSTEMS

On the basis of the experimental results, efforts were made to attain the derivation of such relationships for the main flow characteristics (pressure drop, recirculation rate, and liquid fraction) that contain only the feed data and the data of the apparatus, and do not contain parameters that are difficult to measure, e.g. the liquid content.

To calculate the liquid fraction the adaptation of a relation previously derived in this Institute was tried. On the basis of the theory of dynamic foams, SASVÁRI [4] derived the following equation for the determination of the liquid fraction:

$$\varepsilon_f = \frac{k}{u_g + k} \tag{1}$$

The reciprocal of Equation (1) is:

$$\frac{1}{\varepsilon_f} = \frac{1}{k}\,(u_g + k) \tag{2}$$

It is obvious that there is a linear relationship between the reciprocal of the liquid fraction and the gas velocity (u_g). The value of k was determined from the following measured data.

The liquid fractions were calculated from the measured liquid contents by the following equation, derived on the basis of the definition of liquid fraction:

$$\varepsilon_f = \frac{4\ V}{H_B d_B^2 \pi} \tag{3}$$

According to the experimental results since the liquid content (V) not only depended upon the gas velocity, but also on the dimensions of the apparatus, the reciprocals of the liquid fractions were plotted against the gas velocity having these variables as parameters. Straight lines with nearly the same slopes were derived and this confirmed that the value of k is independent of the diameter of the nozzle (d_f) and of the diameter and lenth of the inserted tube (d_B and H_B). From the slope the value of k was found to be 1.7 and so the liquid fraction was calculated by the following equation:

$$\bar{\varepsilon}_f = \frac{1.7}{u_g + 1.7} \tag{4}$$

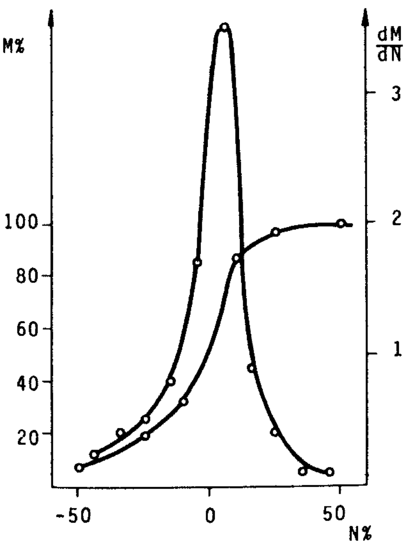

Figure 2. The distribution and frequency of the liquid fraction data

The comparison of the measured and calculated data showed that below a gas velocity of 4 - 5 metres per second the calculated values were invariably smaller than the measured ones. The difference decreased with the decrease of the length of the inserted tube. Above a gas velocity of 5 metres per second the agreement between the two values is good not only in foam, but also in film and mist flow. In Figure 2 the distribution and frequency curves of the differences between the measured liquid fraction values and those calculated by Equation (4) are shown. It can be seen that the deviations have a nearly normal distribution and their absolute majority is within the ± 10 % deviation range.

At the calculation of the overall pressure drop of the system it was assumed that apart from the outer recirculation space the system can be regarded as a sieve plate column with only one opening on the plate for the distribution of the gas in the liquid. In the sieve plate column the pressure drop consists of the pressure drop on the dry plate, the hydrostatic pressure of the liquid on the plate and the dynamic pressure drop necessary to overcome the surface tension. This latter can be neglected since it is smaller than the others by an order of magnitude.

The overall pressure drop of the system (ΔP_t) was plotted against the sum of the pressure drop of the dry apparatus (Δp) and the hydrostatic pressure (ΔP_h). The hydrostatic pressure was calculated from the measured liquid content by the following equation:

$$\Delta P_h = \frac{4\ V}{d_B^2 \pi} \gamma_f \qquad (5)$$

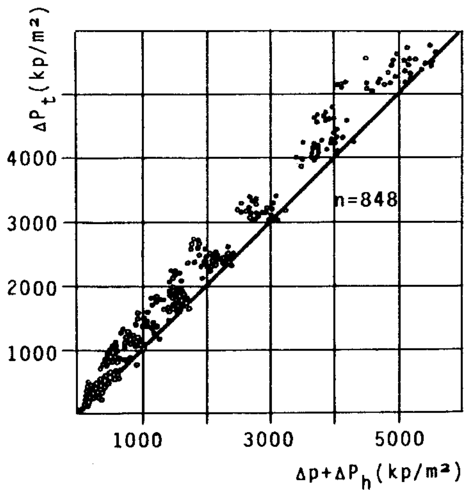

Figure 3

In Figure 3 it is shown that the sum of the pressure drop of the dry column and the hydrostatic pressure is some what less than the overall pressure drop of the system. The measured values are scattered around a straight line of the slope of 1.2. So the overall pressure drop can be calculated by the following Equation:

$$\Delta P_t = (\Delta p + \Delta P_h)\ 1.2 \qquad (6)$$

The pressure drop on the dry column depends upon the gas velocity and on the diameter of the nozzle. So it can be expressed as:

$$\Delta p = a_2 d_f^{a_1} u_{gf}^2 \tag{7}$$

where

d_f is the diameter of the nozzle (metres)

u_{gf} is the gas velocity in the nozzle (metres per second).

The constants were determined from following the measured data.

The pressure drop of the dry column was plotted against the square of the gas velocity in the nozzle, the diameter of the nozzle was the parameter. Straight lines were obtained:

$$\Delta p = a_3 u_{gf}^2 \tag{8}$$

$$a_3 = a_2 \ d_f^{a_1} \tag{9}$$

Which means that there is a linear relationship between the variables and a_3 can be determined from the slopes. The logarithm of the determined a_3 was plotted against the logarithm of the diameter of the nozzle and according to Equation (9) the intercept of the straight lines was a_1 and their slope gave a_2.

It was found that

$$a_2 = 0.00576$$

$$a_1 = -\ 0.5$$

With these values Equation (7) becomes:

$$\bar{\Delta} p = 0.00576 \ d_f^{-0.5} u_{gf}^2 \tag{10}$$

The comparison of the pressure drops of the dry column calculated by Equation (10) and those measured showed a discrepancy less than ± 10 % in 70 % of the 1200 data.

The hydrostatic pressure drop was calculated on the basis of Equation (5):

$$\Delta P_h = \frac{4\ V}{d_B^2\ \pi}\gamma_f = \varepsilon_f H_B \gamma_f \qquad (11)$$

In Equation (11) the only unknown parameter is the liquid fraction, so it can be calculated. If Equations (4) is substituted into Equation (11) an equation is derived for the hydrostatic pressure drop:

$$\Delta P_h = \varepsilon_f H_B \gamma_f = \frac{k}{u_g + k} H_B \gamma_f = \frac{1.7}{u_g + 1.7} H_B \gamma_f \qquad (12)$$

The comparison of the values calculated by Equation (12) and those measured showed that their discrepancies were less than ±10% in about 50 % of the data. In real foam flows the calculated values were higher, in film-mist transition flows the values were lower than those measured, which means that the best fit was observed in film flows.

The substitution of the relationships for the pressure drop of the dry column and the hydrostatic pressure drop Equation (10) and (12) into Equation (6) gives an equation for the pressure drop of the spouted bed system:

$$\bar{\Delta}P_t = (0.00576\ d_f^{-0.5}\ u_{gf}^2 + \frac{1.7}{u_g + 1.7} H_B \gamma_f)\ 1.2 \qquad (13)$$

In Equation (13) the variables are the length of the inserted tube, and the gas velocity calculated on the diameters of the inserted tube and nozzle. This means that without the knowledge of the liquid feed rate the pressure drop can be calculated in advance. The comparison of the measured and calculated values showed discrepancies that were less than ±25 % in about 80 % of the data.

An equation was derived for the recycling rate (u_f) on the basis of the definition of the volumetric rate:

$$w_f = u_f \varepsilon_f A_t \cdot 3600 \qquad (14)$$

In Equation (14) the liquid fraction is known from Equation (4) so the unknown variable is the actual linear velocity of the liquid (u_f) which can be calculated using the relation between the recirculation rate and the following measured parameters.

The linear velocity of the liquid can be calculated by Equation (15) from the measured liquid content and recirculation rate:

$$u_f = \frac{w_f}{A_t \varepsilon_f \cdot 3600} = \frac{w_f H_B}{V \cdot 3600} \tag{15}$$

The determined liquid velocity was plotted against the gas velocity having the data of the apparatus as parameters. Straight lines with different slopes and intercepts were obtained.

The equation of the line:

$$u_f = a_4 u_g + a_5 \tag{16}$$

If $u_f = 0$ then:

$$a_5 = - a_4 u_g^* \tag{17}$$

where u_g^* is the gas velocity where the liquid recycling starts.

The substitution into Equation (16) yields:

$$u_f = a_4 u_g - a_4 u_g^* = a_4 (u_g - u_g^*) \tag{18}$$

a_4 and u_g^* in Equation (18) depend upon the following parameters:

$$a_4 = f(H_B, d_B, d_f) \tag{19}$$

and

$$u_g^* = f(H_B, d_B) \tag{20}$$

The Equation (19) and (20) were solved with the following measured data.

u_g^* was plotted against the length of the inserted tube, at constant values of the diameter of the inserted tube. The relationship between the two variables is nearly linear, so the equations for the derived lines are:

If $d_B = 29$ mm; $u_g^* = 5.4(H_B - 0.24) = 5.4\,H_B - 1.3$ (21)

$d_B = 24\text{-}19$ mm; $u_g^* = 4(H_B - 0.25) = 4\,H_B - 1$ (22)

$d_B = 15\text{-}10$ mm; $u_g^* = 2.6(H_B - 0.18) = 2.6\,H_B - 0.5$ (23)

A relationship having both variables simultaneously could not be obtained for u_g^*.

The experimental data showed that a_4 is directly proportional to the length and diameter of the inserted tube and it is inversely proportional to the diameter of the nozzle. So the following equation was derived:

$$a_4 = a_6 \frac{d_B}{d_f} + a_7 \frac{H_B}{d_f} + a_8 \frac{r_h}{d_f} \tag{24}$$

a_6 can be obtained if the $a_4 d_f$ product is plotted against the diameter of the inserted tube with the length of the inserted tube as parameter. The slope of the parallel straight lines obtained gives a_6 and if the intercepts are plotted against the length of the inserted tube, straight lines are obtained once again, where the slope is a_7 and the intercept is a_8.

The following values were obtained for the constants:

$$a_6 = 0.054, \quad a_7 = -10^{-3}, \quad a_8 = 0.57\times10^{-3}.$$

With these constants Equation (24) yields:

$$\bar{a}_4 = 0.054 \frac{d_B}{d_f} - 10^{-3} \frac{H_B}{d_f} + 0.57\times10^{-3} \frac{r_h}{d_f} \tag{25}$$

Having $\bar{a}_4$ and $\bar{u}_g^*$ Equation (14) is solved on the basis of Equation (18):

$$\bar{u}_f = \bar{a}_4(u_g - \bar{u}_g^*)\varepsilon_f A_t \cdot 3600 \tag{26}$$

where $\bar{u}_g^*$ can be calculated by Equations (21), (22) or (23) depending upon the diameter of the inserted tube,and $\bar{a}_4$ and ε_f by Equations (25) and (4).

The comparison of the experimental recycling rate and those calculated by Equation (26) showed that their discrepancies were less than ± 10 % in more than 50 % of the 900 data.

To briefly summarize the results, empirical equations (Equations 4, 13, 26) were derived for the calculation of the flow characteristics of the liquid-spouted bed systems (pressure drop, volume fraction and recycling rate) on the basis of nearly 1000-1000 experimental data, which sufficiently describe the system. In these equations, parameters that are easy to determine were employed (gas velocity, and design data), there are no variables that are difficult to measure.

SYMBOLS USED

A_t the cross section area of the inserted tube (m^2)
a_1 a_2 ... a_8 constants
a_2 (kg force.sec^2/m^5) a_3 (kg force.sec^2/m^4) a_5 (m/sec)
d_B the diameter of the inserted tube (m)
d_f the diameter of the nozzle (m)
H_B the length of the inserted tube (m)
k constant
M the distribution of the data in percentage
N the differences between the measured and calculated data in percentage
n the number of measurements
ΔP_h hydrostatic pressure drop (kg force/m^2)
ΔP_t the overall pressure drop of the liquid-spouted bed system (kg force/m^2)
ΔP the pressure drop of the dry column (kg force/m^2)
r_h hydraulic radius (m)
u_f actual liquid velocity (m/sec)
u_g gas velocity calculated on the cross section area of the inserted tube (m/sec)
u_{gf} gas velocity calculated on the cross section area of the nozzle (m/sec)
u_g^* minimum gas velocity needed for the start of the recirculation (m/sec)

V liquid content (m^3)

w_f volumetric liquid feed rate or recirculation rate (m^3/h)

γ_f liquid density (kg force/m^3)

ε liquid fraction

π 3.1415

Variables with a bar are calculated data; those without any bar are measured ones.

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РЕЗЮМЕ

Авторами изучаются гидродинамические условия гейзерового способа. Изучают падение давления, содержание жидкости и скорость циркуляции в зависимости от скорости газа и заданных конструктивных параметров. Авторы описывают экспериментальную установку, методы измерения, характерные экспериментальные данные и далее на основе экспериментальных данных пытаются составить уравнения для вычисления падения давления, скорости циркуляции и объемной доли жидкости. Применяя экспериментальные данные большого числа опытов авторы показывают совпадение измеренных данных с данными, вычисленными по составленным соотношениям.