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THE VELOCITY FIELD IN A VERTICAL GAS–SOLID SUSPENSION FLOW

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Abstract—The distribution of velocity in the entry region of a gas–solid suspension flow was measured by means of a two-thermistor anemometer. Air was employed as the carrier gas and the dispersed phase was five individual fractions of polypropylene particles. Experiments were carried out by the method of planned experiment design. The measured velocity profiles were correlated by a universal distribution equation of flow velocity. The length of the entry region and the distribution of velocity in the steady flow region were estimated by the analysis and statistical treatment of experimental velocity profiles in the entry region of the flow.

Key Words: vertical gas–solid suspension flow, velocity field, entry region of the flow

THEORY

The simplest method of obtaining basic information concerning the inner structure of a flow is the experimental determination of velocity profiles. The velocity profile of a flowing fluid is defined as the dependence of the local time-averaged axial velocity component upon the distance from the wall and/or the equipment axis. The shape of the velocity profile of the fluid behind its entry into the equipment changes with the axial distance from the entry. After a certain distance from the entry, the shape of the velocity profile is no longer a function of the axial distance from the entry into the equipment. This state of fluid flow is called "fully developed flow". The axial distance from the entry along which the flow of fluid becomes fully developed is called the length of the entry region.

If the fluid enters a pipe, an increase in pressure drop (Bogue 1959), due to a change of kinetic energy and increment of pressure drop due to friction, is observed. Experimentally it was found that the length of the entry region depends upon the geometric arrangement of the entrance of the pipe, the level of turbulence of the entering fluid flow, Re and the rheological behaviour of the fluid. The length of the entry region can be determined experimentally in the following way:

(1) on the basis of the distance necessary for the velocity profile to be formed;
(2) on the basis of the distance over which the pressure gradient along the column becomes constant.

For the reason that about 95% of the total value of the increment of pressure drop (Bogue 1959) corresponds to the first half of the entry region, the first method is used more often. This explains why the length of the entry region, determined by various authors on the basis of achievement of a constant pressure gradient, is substantially smaller than the length calculated on the basis of the development of the velocity profile.

With regard to experimental problems, only a few sets of data concerning the velocity field in a gas–solid suspension flow are available in the literature. Moreover, these data are inconsistent. For illustration, the following examples can be presented: according to Soo *et al.* (1964; Soo & Terzek 1966; Soo 1967) and Kolonsky *et al.* (1976) the presence of particles does not cause a change in the velocity profile of the carrier medium. Peskin & Dwyer (1965). Boothroyd & Walton (1973) and Varga (1978) observed a flattening of the velocity profiles. According to Doig & Roper (1967), Drozdová (1980), Drozdová & Lodes (1986) and Lodes *et al.* (1986a), the distribution of velocity in the gas phase is more convex in the core region in comparison with the velocity profiles of the pure carrier medium at the same Re; Lodes & Breský (1977) and Drozdová & Lodes (1986) have shown the thickness of the boundary layer to be two- or three-fold greater due to the latter observations.

Authoritative reviews about the interaction between solid particles and the turbulence of the carrier fluid in two-phase flow appear at regular intervals (e.g. Soo 1967; Govier & Aziz 1972; Hetsroni 1989). These and later reviews are the best source for relatively concise descriptions of research on turbulence in two-phase flow. It is well-recognized that data concerning the laws of the velocity field are not convincing enough. These results arise from the fact that from the viewpoint of the kind of the carrier gas flow and flow past solid particles there can exist almost 12 various two-phase (solid particles–gas) systems.

EXPERIMENTAL

Velocity profiles in the gas–solid suspension flow were measured in a 0.05 m i.d. vertical glass column. The working part of the column consisted of an assembly of glass columns of various length, whose combination enabled velocity profiles at various heights from the bottom of the column to be measured. The local velocities were measured by a two-thermistor anemometer, which was developed by Lodes *et al.* (1986b). The two-thermistor probe for simultaneous measurement of temperature and velocity fields was located in the measuring supporting device. The latter was fixed between two flange joints and ensured a radial shift of the thermistor detector along the cross-section. The turning of the measuring supporting device through an angle of 90° enabled a measurement of the velocity profile in two mutually perpendicular directions to be made.

Air fed from a one-stage air blower through the feed pipe to the bottom of the column was employed as the carrier gas. The particles were separated in a cyclone and fed through a control and checking system into the inlet air flow. This system enabled the mass flow rate of solid particles to be adjusted and checked during the experiments.

The dispersed phase was five individual fractions of polypropylene particles with equivalent diameters of $115 \cdot 10^{-6}$, $167 \cdot 10^{-6}$, $216 \cdot 10^{-6}$, $261 \cdot 10^{-6}$ and $368 \cdot 10^{-6}$ m. These fractions were screened on sieves and, in addition, treated by the air flow in the classification column. The equivalent diameter refers to the equivalent spherical diameter.

In the laminar region i.e. at $\mathrm{Ly} < 55$ the polypropylene particles have a dynamic shape factor of value 1. In the region $55 \leqslant \mathrm{Ly} \leqslant 240$, the value of the dynamic shape factor is given by the equation

$$\psi = \mathrm{Ly}(-17.1 + 1.32\mathrm{Ly})^{-1}.$$

In this region the equation $\mathrm{Ly}_p = \psi^3\mathrm{Ly}$ holds, where Ly_p is the Lyaschenko number of the irregular particles and Ly is the Lyaschenko number with the equivalent diameter of particles d_e.

This means, that in the transient and turbulent region of flow around the particles the particle shape is significant. At values of $\mathrm{Ly} > 240$ one can consider the value of the dynamic shape factor constant and equal to 0.8.

The experimental equipment used in the investigation of the velocity profile in a gas–solid suspension flow is depicted in figure 1.

The requirement of resistance against both abrasion and vibration in the suspension and the ability to make almost spot measurements supported the application of a thermistor anemometer. The main disadvantage of this detector is the requirement of an isothermic system. However, an anemometer which might be used also as a resistive sensing unit for temperature would eliminate the necessity for an environment of constant temperature. Modifying the method published by Murphy & Sparks (1968), and starting from temperature balances in the surroundings of a thermistor anemometer, the dependence

$$u = f\left(\frac{R_t}{\ln\dfrac{R_{t,a}}{R_t}} - \frac{R_{t,0}}{\ln\dfrac{R_{t,a}}{R_{t,0}}}\right) \qquad [1]$$

can be obtained, in which u is the local velocity of the suspension flow, f is the function, R_t is the thermistor resistance in the flowing fluid heated by a current of the order of mA, $R_{t,0}$ is the

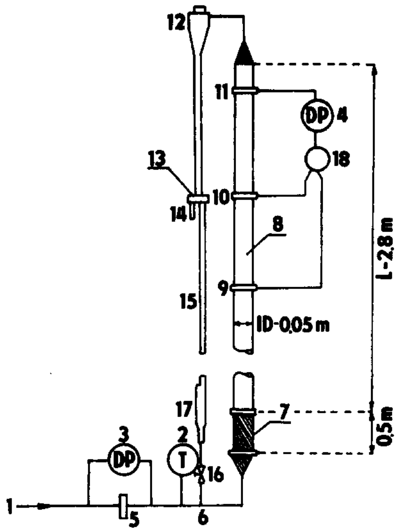

Figure 1. Experimental equipment: 1—inlet of air flow; 2—thermometer; 3—differential manometer for the orifice; 4—Ascania differential manometer for measuring the pressure drop; 5—orifice gauge; 6—inlet of particles into the air flow; 7—equalizing part of the column, $L = 0.5$ m; 8—glass pipe, $L = 2.8$ m, i.d. $= 0.05$ m; 9–11—pressure taps; 12—cyclone; 13—three-way equipment; 14—solid sampling; 15—connecting pipe, i.d. $= 0.01$ m; 16—clamp for solid flow control; 17—solids feed tank, i.d. $= 0.03$ m; 18—two-way cock.

thermistor resistance in the flowing fluid heated by the same current as R_t, $R_{t,a}$ is the thermistor resistance measured at the heating current of the order of μA (for such a small heating current the thermistor resistance is not a function of the flow velocity, but only of the temperature of the surroundings).

The disadvantage of the method proposed by Murphy & Sparks (1968) is an alternating loading of the thermistor anemometer by a small and a large heating current. This procedure, negatively influences the stability of the thermistors' resistance and also causes a significant hysteresis of their resistance. For this reason, two thermistors heated by a steady unidirectional current were used in the measurement of velocity fields (Lodes *et al.* 1986b). The thermistor heated by a small current measured the temperature of the medium, while the resistance of the second thermistor enabled an estimate of the value of the local velocity according to [1] to be made. The resistances $R_{t,0}$ and $R_{t,a}$ were determined on the basis of the known temperature with regard to the following calibration equation:

$$R_T = A \exp\left(\frac{B}{T}\right). \qquad [2]$$

The second thermistor anemometer was calibrated by means of a laser-Doppler anemometer in non-isothermic conditions. In order to form the Doppler effect in the measurement of the local velocity of air by means of LDA, tracing particles, such as polypropylene powder (fraction $160 \cdot 10^{-6}$ and $250 \cdot 10^{-6}$ m), polydisperse fractions of polypropylene, silicagel, a narrow fraction of water particles ($5\text{–}10 \cdot 10^{-6}$ m) etc., were added into the air. From the shape of the dependence of type [1] for individual tracing particles the dependence [1] was recognized not to be a function of the temperature of the environment and physical properties of the dispersed phase, which corresponds to expectation.

Due to the time-consuming experiments in the investigation of the development of velocity profiles in gas–solid suspension flow, a statistical method of planned experiment design was used. The obtained mathematical description of the experimental model offers information on the influence of particle variables and enables us to quantify the values of the response function and, at the same time, it can also serve as a support for the optimization of the process. Experiments were carried out by the method of central composition rotatabular planning design which is described in detail by Nalimov & Cucupcrcernova (1965) and Saumin (1975). The range of experimental conditions was as follows: $4000 \leqslant \mathrm{Re} \leqslant 15{,}000$, $0.05 \leqslant X \leqslant 0.4$, $26 \leqslant L/D \leqslant 60$.

RESULTS AND DISCUSSION

According to the planned experiment design, for each fraction, 20 velocity profiles with 16 measuring points along the diameter of pipe were measured at the given values of Re, the relative mass fraction of solid particles, X, and the relative distance from the entrance of the vertical pipe, L/D. The measured values of voltage drop on thermistors, obtained in the estimation of local velocities along the cross-section of the column, were statistically treated. For the calculation of these velocities account was taken only of the value of voltage drop belonging to the 95% confidence interval.

Table 1 summarizes only the values of the relative velocities along the axis measured according to the planned experiments design. However, with regard to the equality

$$\frac{\int_0^R 2\pi r \frac{u(r)}{w}\,\mathrm{d}r}{\pi R^2} = 1,$$

on the basis of the values of u_m/w, given in table 1, one can appreciate the shape of particular velocity profiles. It is evident that flatter velocity profiles correspond to lower values of u_m/w.

The influence of the individual investigated quantities involved in Re, the relative mass fraction of solid particles and the geometric simplex L/D upon the distribution of velocity in the gas–solid suspension flow was studied on the basis of the experiments, in which only the influence of the quantity that was changed was examined. From the detailing of the matrix of the planned experiment design, given on the l.h.s. of table 1, it is apparent that the investigation of the influence of individual independent variables is possible on the basis of three systems composed of four couples and one trio of velocity profiles. Within the framework of each system only one and the same variable is changed in particular couples and in the corresponding trio. The influence of the equivalent diameter of dispersed solid particles was judged by a mutual comparison of velocity profiles of individual fractions measured under equal experimental conditions.

The influence of Re on the shape of the velocity distribution in the gas–solid suspension flow was studied by comparing the velocity profiles in the following couples: 1 and 2; 3 and 5; 4 and 6; 7 and 8; and in the trio 9, central point and 10. On the basis of mutual comparison of the above-mentioned velocity profiles for all investigated fractions of polypropylene powder it was found that, with an increase in Re, the relative velocity along the axis decreases while at the wall it increases. This means that the velocity profile becomes flatter with an increase in Re. A similar phenomenon was observed in the flow of one-phase Newtonian fluids.

Table 1. Relative velocities along the axis of the pipe

Expt No.	Re	X	L/D	u_m/w values for $d_e \cdot 10^6$(m): 115	167	216	261	368
1	8540	0.123	25.5	1.269	1.239	1.291	1.212	1.249
2	4630	0.123	25.5	1.617	1.331	1.434	1.478	1.407
3	8540	0.327	25.5	1.310	1.269	1.301	1.270	1.329
4	8540	0.123	48.3	1.275	1.315	1.337	1.220	1.335
5	4630	0.327	25.5	1.494	1.430	1.492	1.543	1.482
6	4630	0.123	48.3	1.404	1.454	1.457	1.427	1.450
7	8540	0.327	48.3	1.326	1.361	1.341	1.318	1.341
8	4630	0.327	48.3	1.552	1.615	1.593	1.550	1.585
9	12000	0.225	36.4	1.236	1.201	1.253	1.257	1.265
10	4000	0.225	36.4	1.688	1.387	1.531	1.667	1.431
11	6000	0.050	36.4	1.352	1.288	1.324	1.458	1.328
12	6000	0.400	36.4	1.559	1.356	1.433	1.676	1.373
13	6000	0.225	18.1	1.319	1.223	1.251	1.375	1.222
14	6000	0.225	55.5	1.426	1.372	1.376	1.381	1.323
15	6000	0.255	36.4	1.410	1.327	1.395	1.383	1.447
16	6000	0.225	36.4	1.358	1.419	1.278	1.369	1.383
17	6000	0.225	36.4	1.403	1.342	1.368	1.458	1.400
18	6000	0.225	36.4	1.396	1.297	1.395	1.381	1.326
19	6000	0.225	36.4	1.355	1.378	1.382	1.456	1.360
20	6000	0.225	36.4	1.332	1.343	1.280	1.477	1.440

The influence of the relative mass fraction of solid particles on the velocity distribution in the vertical suspension flow was estimated by comparing the velocity profiles in the following couples: 1 and 3; 2 and 5; 4 and 7; 6 and 8; and in the trio 11, central point and 12. From the comparison of the above-mentioned profiles for all five fractions it arises that the relative velocity in the vicinity of the walls increases with an increase in the concentration of solid particles. Exceptions are the following couples of velocity profiles: 2 and 5; 12 and the central point for the fraction with $d_e = 115 \cdot 10^{-6}$ m; and 11 and the central point for the fraction with $d_e = 261 \cdot 10^{-6}$ m. Hence, an increase in the concentration of solid particles causes a more convex velocity profile. According to Razumov's (1979) conclusion, this can be attributed to deturbulization effect of the dispersed phase in the investigated two-phase system.

The influence of the simplex L/D upon the development of the gas–solid suspension flow was examined by comparing the velocity profiles in the following couples: 1 and 4; 2 and 6; 3 and 7; 5 and 8; and in the trio 13, central point and 14. From the comparison of the foregoing velocity profiles it follows that, according to expectation, an increase in the simplex L/D causes an increase in the values of the relative velocities in the core region and a decrease in these values in the vicinity of the wall. Exceptions are the following couples of velocity profiles: 2 and for the fraction with $d_e = 216 \cdot 10^{-6}$ and $115 \cdot 10^{-6}$ m; and central point and 14 for the fraction with $d_e = 261 \cdot 10^{-6}$ m.

The influence of the equivalent diameter upon the velocity distribution in the entry region of the suspension flow was studied on the basis of a comparison of the velocity profiles measured in the presence of individual fractions of the dispersed phase under equal experimental conditions. From the comparison it follows that in the majority of cases an increase in the equivalent diameter of the dispersed phase causes an increase in the local velocities in the region of the axis, and their decrease in the vicinity of the walls. An opposite trend is characteristic of about one-third of all the profiles. This can be ascribed to the fact that, on the one hand, the increase in the equivalent diameter of the dispersed phase causes an increase in its relaxation time and, in this way, also increases its deturbulization effect (Razumov 1979), which leads to more convex velocity profiles. On the other hand, an increase in the equivalent diameter of the dispersed phase results in a more profound non-Newtonian pseudoplastic character of the flowing system (Lodes *et al.* 1985), which leads to flatter velocity profiles. From the foregoing conclusions it results that the two influences of an increase in the equivalent diameter act in opposite directions. Which one will prevail depends upon concrete conditions of flow of the system.

In the estimation of the entry region of the flow the starting assumption was that the relative velocity along the equipment axis, expressed by the ratio u_m/w, does not change behind the entry region, i.e. the condition

$$\frac{\partial\left(\frac{u_m}{w}\right)}{\partial\left(\frac{L}{D}\right)} = 0 \qquad [3]$$

holds.

An equation for the calculation of the dependent variables corresponding to the experimental data of the planned experiment design may be expressed as

$$Y = b_0 + \sum_{i=1}^{3} b_i x_i + \sum_{j=1}^{3} \sum_{i=1}^{3} b_{ij} x_i x_j, \qquad [4]$$

in which b_0, b_i and b_{ij} are regressive coefficients and x_i and x_j are coded independent variables. The values of the regression coefficients in [4] were estimated by the regression analysis of the measured relative velocities in the equipment axis. Combining [3] and [4], the length of the entry region in the gas–solid suspension flow was obtained from the standpoint of the development of the velocity field. By statistical treatment of lengths calculated in this way, the following equation was obtained:

$$\left(\frac{L}{D}\right)_k = 78.7 \cdot \mathrm{Re}^{0.05}(1+x)^{0.53}\left(\frac{d_e}{D}\right)^{0.03}. \qquad [5]$$

From [5], it follows that similar to the turbulent character of the flow of a one-phase Newtonian fluid an increase in the value of Re causes a decrease in the length of the entry region. On the contrary, due to an increase in the value of both the relative mass fraction and the equivalent diameter of solid particles the value $(L/D)_k$ increases. This can be explained by the phenomena that an increase in both the equivalent diameter and concentration of solid particles will lead to a more profound pseudoplastic behaviour of the investigated systems (Lodes *et al.* 1985), which will cause an increase in the length of the entry region.

In accordance with previous experience, the experimental velocity profiles were correlated by the equation of the universal distribution of velocity in the form given by Rothfus & Monard (1955):

$$U^+ = K_1 \ln Y^+ + K_2, \qquad [6]$$

in which

$$U^+ = u^+ \frac{w}{u_m} = \frac{u}{u^*}\frac{w}{u_m} \qquad [7]$$

and

$$Y^+ = y^+ \frac{u_m}{w}. \qquad [8]$$

The non-dimensional distance from the wall of the equipment y^+ was expressed with regard to the pseudoplastic character of the investigated system (Lodes *et al.* 1985) as

$$y^+ = \frac{y^n u^{*2-n} \rho_m}{8^{n-1} K}. \qquad [9]$$

In the estimation of the dynamic velocity u^* involved in [7]–[9] for the calculation of u^+ and y^+, we started from the expermentally measured pressure drops in the vertical gas–solid suspension flow (Lodes *et al.* 1986a).

The coefficients K_1 and K_2, determined by linear regression of the experimental velocity profiles, were treated statistically and yielded regression dependences of type [4]. On the basis of these equations and [6] we calculated the distribution of velocities along the cross-sections of the equipment for the individual fractions of polypropylene particles investigated depending upon Re, the relative mass fraction of solid particles and various distances from the entrance into the equipment. It is evident that after introducing the entry length, velocity profiles for the suspension behind the entry region were obtained.

Figures 2 and 3 show the velocity profiles behind the entry region of flow for Re = 6000 at various values of the relative mass fraction of solid particles and for $X = 0.225$ at various values of Re, for fractions with an equivalent diameter of $216 \cdot 10^{-6}$ m. Figure 4 depicts local velocity distributions in the steady flow region at Re = 6000 and $X = 0.225$ for all the fractions of polypropylene particles investigated.

From analysis of the estimated velocity profiles behind the entry region of the gas–solid suspension flow it follows that:

—With an increase in the value of Re the velocity profiles become flatter, similar to that in the flow of a one-phase Newtonian fluid.

—With an increase in the relative mass fraction of solid particles, the local velocities in the vicinity of the equipment axis increase and, on the contrary, the local velocities in the vicinity of the walls decrease. A similar conclusion was made by Razumov (1979). This influence of the dispersed phase upon the shape of the velocity distribution can be ascribed to the deturbulization phenomenon of solid particles.

—An increase in the equivalent diameter of the dispersed phase causes, as mentioned earlier, on the one hand, a deturbulization of the flow and, on the other hand, a more profound pseudoplasticity. As can be seen in Figure 4, the influence of pseudoplasticity prevails and in this case is manifested by the flattening of the velocity profiles with an increase in the equivalent diameter of solid particles.

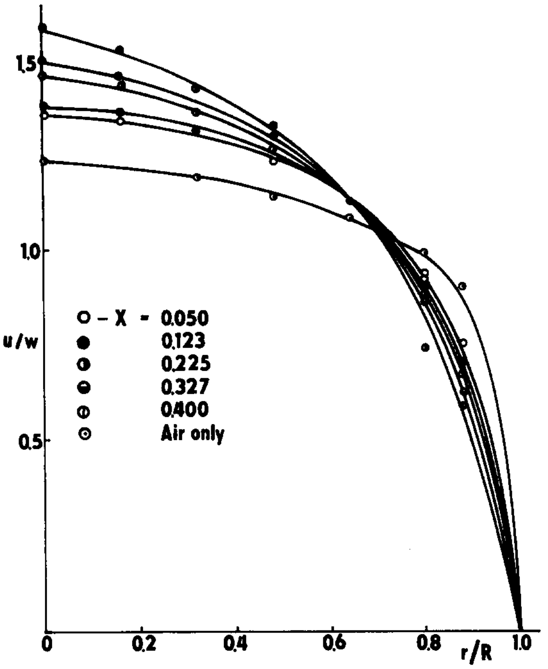

Figure 2. Estimated velocity profiles behind the entry region of the suspension flow for the polypropylene particles fraction with $d_e = 216 \cdot 10^{-6}$ m and Re = 6000 for various values of X.

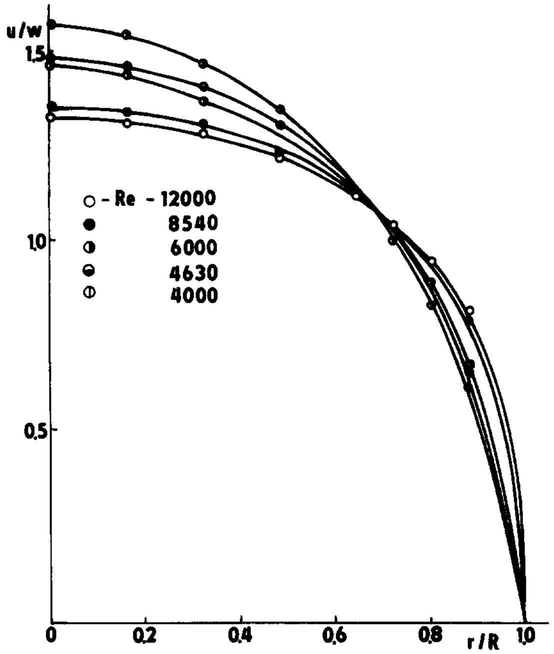

Figure 3. Estimated velocity profiles behind the entry region of the suspension flow for the polymer particles fraction with $d_e = 216 \cdot 10^{-6}$ m and $X = 0.225$ for various values of Re.

CONCLUSIONS

On the basis of experimental data of velocity profiles the entry length in vertical co-current gas–solid suspension flow has been estimated. The entry length decreases with an increase in Re and increases with an increase in both the relative mass fraction and the equivalent diameter of solid particles.

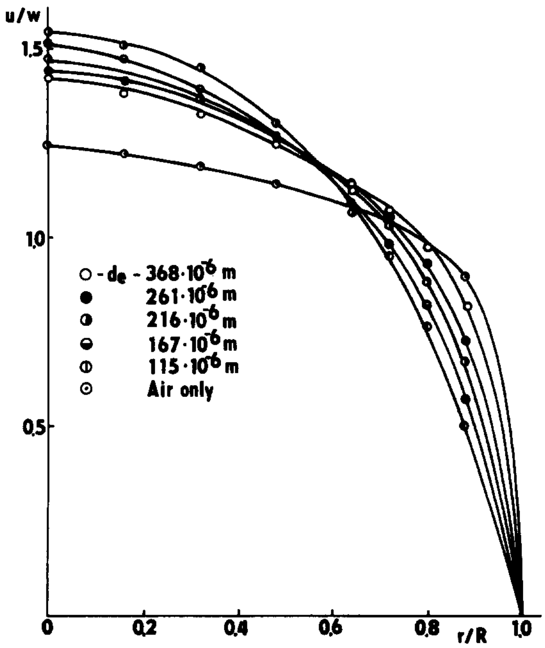

Figure 4. Estimated velocity profiles behind the entry region of the suspension flow at $X = 0.225$ and Re = 6000 for all the fractions of polypropylene particles investigated.

By statistical treatment of data concerning the distribution of velocity in the entry region of the flow and on the basis of estimated values of the entry length, the velocity profiles in the steady flow region were estimated. Behind the entry region, the velocity profiles of the investigated two-phase system become flatter with an increase in Re, while the influence of both the equivalent diameter and equivalernt mass fraction of solid particles is the opposite.

NOMENCLATURE

Standard SI units apply.

A—Coefficient in [2]
B—Exponent in [2]
b_0, b_{ij}, b_i—Coefficients in [4]
D—Diameter of the equipment
d_e—Equivalent diameter of solid particles
K—Rheological parameter, consistency coefficient
L—Distance from the equipment entrance
Ly—Lyaschenko number, $u_t^3\rho^2/g(\rho_s-\rho)\mu$
$\mathrm{Ly_p}$—Lyaschenko number of irregular particles
$(L/D)_k$—Relative length of the entry region
n—Rheological parameter, flow index
R—Equipment radius
Re—Reynolds number, $Dw\rho/\mu$
R_T—Thermistor resistance for the measurement of the temperature at a heating current of the order of 10^{-6} A
$R_{t,a}$—Thermistor resistance for the measurement of velocity at a heating current of the order of 10^{-3} A at zero flow velocity
R_t—Thermistor resistance for the measurement of velocity
r—Radial distance from the pipe axis
T—Absolute temperature of the surrounding flow
U^+—Non-dimensional velocity, [7]
u—Local velocity of the flow
u_m—Flow velocity along the axis
u^+—Non-dimensional velocity
u^*—Dynamic velocity of the flow, $w\ (\lambda/8)^{0.5}$
u_t—Particle falling velocity
w—Mean velocity of the flow
X—Relative mass fraction of solid particles in gas
x_i, x_j—Independent coded variables in [4]
y—distance from the wall, $R-r$
Y^+—Non-dimensional distance from the wall of the pipe, defined by [8]
y^+—Non-dimensional distance from the wall, defined by [9]
λ—Friction factor
ρ—Density of the continual phase
ρ_m—Suspension density
ρ_s—Particles density
ψ—Shape factor of irregular particles
μ—Viscosity

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