FORMATION AND DEVELOPMENT OF TURBULENCE DURING MOVEMENT OF A DISPERSE SYSTEM IN A ROUND TUBE

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The experimental results are presented for a study of the turbulence intensity, coefficient of intermittence, and average velocity profile during the transition of the laminar flow of an aqueous dispersion of bentonite clay to turbulent flow. A calculation of the critical value of the Reynolds number is offered.

Great interest is currently displayed in the mechanics of disperse systems, caused both by the development of new technological processes and by the intensification of traditional processes in the chemical, construction, and mining industries. Pulps and washing liquids based on aqueous clay dispersions, which display non-Newtonian behavior, are widely used in these branches.

The investigation of the rheological properties of non-Newtonian systems has led to the development of a large number of phenomenological models, a review of which is given in [1]. The application of the rheological models with experimentally determined parameters for a given material makes it possible to calculate the laminar motion of this material in systems of simple geometry.

The turbulent motion of disperse systems has been studied to a lesser extent. The absence of experimental data on the local structure of the turbulence is connected with difficulties in the use of the popular experimental methods of measuring pulsation velocities in disperse systems and other non-Newtonian liquids. There are studies available in the literature devoted to the determination of the connection between the rheological properties of a material and the integral parameters of a turbulent stream. In such reports [2, 3] functions are developed which give the similarity of friction losses with respect to the Reynolds number.

It is suggested that the generalized Reynolds number

$$\mathrm{Re_g} = \frac{\rho D^n U_0^{2-n}}{k \cdot 8^{n-1}}, \tag{1}$$

based on a power-law dependence presented in [1], which gives satisfactory similarity of the friction losses in laminar flow, be used for the turbulent region. However, the studies conducted in [3] show that the state of a disperse system is determined by the level of development of turbulent velocity pulsations. In order to understand the mechanism of turbulence in a disperse system one must study in detail the interaction of the flocculent particles of the solid phase and the turbulent disturbances.

The transition from laminar to turbulent motion occurs in a certain range of velocities when the critical velocity is exceeded. The analysis made in [2] of the dependence of friction losses on $\mathrm{Re_g}$ led to the conclusion that this transitional mode can be extended to $\mathrm{Re_g} = 50\text{–}70 \cdot 10^3$ when $\mathrm{Re_c} = 2\text{–}3 \cdot 10^3$. In connection with this it is of interest to study how turbulence develops in a tube at velocities exceeding the critical velocity.

We attempted to obtain experimental data on the formation and development of turbulence during the flow of an aqueous dispersion of bentonite clay in a round smooth tube. The disperse systems contained

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TABLE 1. Rheological Parameters of Disperse Systems and Values of Critical Reynolds Numbers

c, %	N/m²	$\mu_p \cdot 10^3$, N·sec/m²	He·10⁻⁶	n	k	$Re_c \cdot 10^{-3}$	$Re_k \cdot 10^{-3}$, exper	$Re_k \cdot 10^{-3}$
2,0	0,165	1,85	0,43				12,5	13,1
2,8	0,6	2,5	0,9	0,16	0,42	2,05	16,8	16,8
2,90	1,08	4,1	0,6	0,18	0,55	2,45	14,4	14,7
3,4	1,7	4,8	0,69	0,16	0,66	2,4	14,1	15,4
3,5	1,6	3,1	1,6	0,15	1,11	2,26	25,1	20,4
4,0	0,93	3,86	0,6	0,2	0,54	2,5	15,3	14,7
4,7	2,53	4,9	1,0				21,0	17,5
5,0	2,5	5,06	0,92	0,18	1,82	1,92	18,7	16,9

from 2 to 5% of the solid phase, more than 90% of which consists of particles with a diameter of less than 10^{-6} m and has a highly developed specific surface of 700-800 m²/g [4]. Therefore the systems studied display marked plastic properties at relatively low concentrations of the disperse phase. A study of such dispersions [5] showed the absence of elastic properties at low concentrations of the solid phase.

The rheological properties of the systems studied were determined on a capillary viscosimeter having tubes with diameters of 4 and 6 mm and lengths of x = 452 and 360, respectively. The flow curves obtained were plotted in the following coordinates, which are consistent, as shown in [1]:

$$\tau_R = \frac{\Delta PD}{4L}; \quad \gamma = \frac{32Q}{\pi D^3}. \tag{2}$$

The study was conducted in a wide range of variation in the variable γ from 10 to $2 \cdot 10^3$ 1/sec. The formation of turbulent pulsations was determined visually from the stability of the effluent jet. The parameters of the Bingham—Shvedov model — the limiting shear stress τ_0 and the plastic viscosity μ_p — were determined from the flow curves. The index of non-Newtonian behavior n and the consistency k were determined by the Metzner—Reed method [2] at the shear velocities corresponding to the critical velocity. The results obtained are presented in Table 1.

The measurement of the local characteristics of the flow was made in a round smooth tube with D = 95 mm and made of insulating material (viniplast). The sections in which the measurements were made were 50 to 100 diameters away from the entrance. According to an estimate based on the experiments of [6] such a length is sufficient for the development of hydrodynamically stable flow.

A system of openings located in the sections with coordinates x = 105, 85, 70, 55, and 40 was used to determine the pressure gradient. The pressure drop was measured relative to the downstream section after washing the system with water. The dynamic velocity U_* was calculated from the known pressure gradients.

The average velocity profile was determined with a microrotor 10 mm in diameter with an electrolytic contact. The number of revolutions of the vanewheel was recorded with a PS-20 counter, making it possible to determine the rotation rate with high accuracy. Some of the measurements of the average velocity profile were made with Pitot—Prandtl tube with an inner diameter of 2.5 mm. The measurement was made after washing the tube with water, when reproducibility of the results was achieved. The data measured by the two methods are in good agreement. An unsystematic scatter of points in the region near the wall at y = 0.2 exists at very low velocities of laminar flow.

A conduction anemometer, for which the principle of operation was described in [7], was used to measure the turbulent velocity pulsations. The electrical signal corresponding to the instantaneous value of the pulsation velocity, was recorded by an N-105 loop oscillograph. The conduction anemometer used as the primary converter has a C-shaped magnet system into the gap of which the channel is placed. A constant magnetic field with induction B_0 = 1 T whose heterogeneity does not exceed 3% is produced in the measurement zone. Two- and three-electrode probes with electrodes of platinum wire 0.4 mm in diameter which were set up at a separation of l = 2.5 mm were used to read the induced potentials.

The instantaneous value of the local velocity between the electrodes was determined from the voltage E at the output of the amplifier of the conduction anemometer from the equation

$$u = \frac{E}{k_b k_a B_0 l}. \tag{3}$$

In our studies (7) the calibration coefficient k_b was equal to 0.5. The noise of the measurement system was determined by two methods: with the magnetic field disconnected and with laminar flow in the tube.

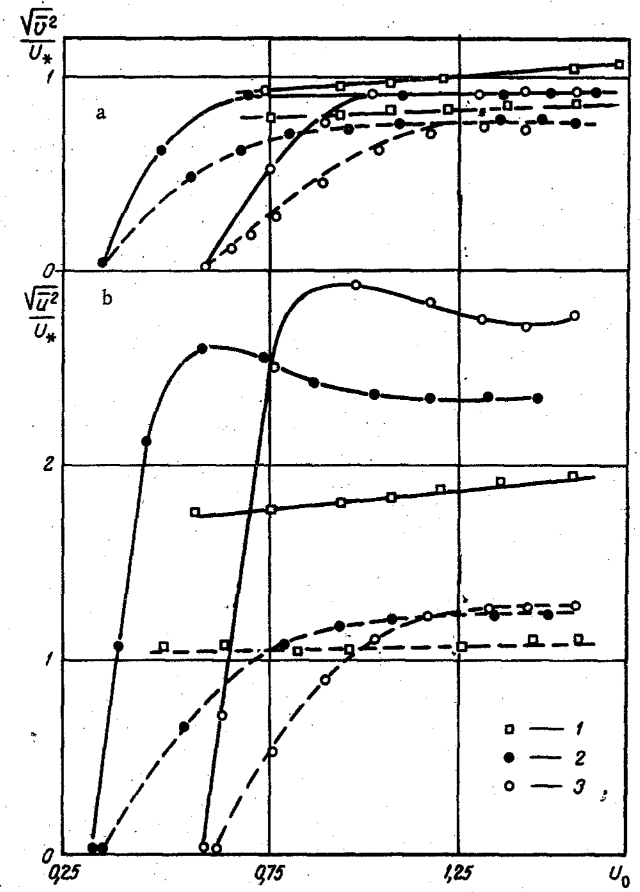

Fig. 1. Dependence of turbulence intensity on velocity U_0(m/sec) in transitional region for different concentrations of solid phase: 1) c = 0; 2) 2.2%; 3) 3.4%; a) solid curves y = 0.22, dashed curves y = 1.0; b) solid curves y = 0.04, dashed y = 1.0.

The rms values and spectral densities of the noise obtained in the two cases were the same. The rms value of the noise reduced to the amplifier input is 4 mW in the transmission band from 1 Hz to 1 kHz.

To distinguish the principal relationships of the formation and development of turbulence the intensity of the longitudinal and transverse components of the pulsation velocity was measured at points of the cross section with the coordinates y = 1 and 0.04 and y = 1 and 0.22, respectively, for different flow rates. The results of the measurements are presented in Fig. 1. Here one can clearly determine the critical velocity U_c of the formation of turbulent disturbances which develop with an increase in the flow rate. This proceeds monotonically for the transverse component and for the longitudinal component at the axis of the tube. The velocity U_t after which the curves change to sloping straight lines can be taken as the start of the region of development of the turbulence. The curves for the longitudinal component have an inflection with a maximum which is reached at a velocity 1.6-1.7 times greater than the critical velocity. Then after some decrease in intensity the turbulence changes little, which also corresponds to the start of the region of development of the turbulence. Having determined the boundaries of the transitional region we established that the ratio U_t/U_c = 1.8-2.5 and that it decreases with an increase in the critical velocity.

In the transitional region the flow in the tube represents an alternation of laminar and turbulent motion. This is well seen in Fig. 2, where oscillograms of the longitudinal component of the pulsation velocity recorded at several points of the cross section are shown. The quantitative characteristic of this process is the coefficient of intermittence ν which was calculated from the oscillograms for several velocities at different points of the cross section.

The measurements were made with a special pickup at all the points at once. A family of curves of the distribution of the coefficient of intermittence over the cross section of the tube for a disperse system

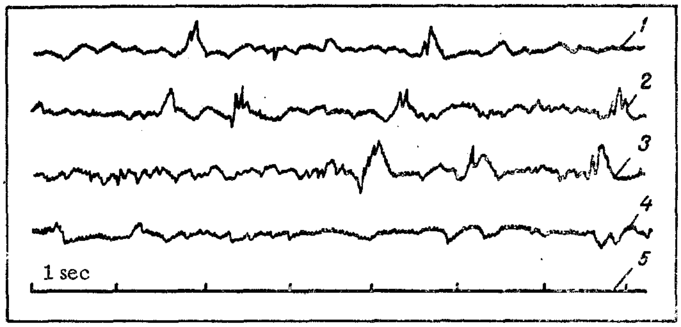

Fig. 2. Oscillograms of longitudinal component of pulsation velocity at different points of tube cross section: 1) y = 0.005; 2) 0.2; 3) 0.3; 4) 1.0; 5) time markings.

with a concentration c = 3.4% is shown in Fig. 3. An interesting property of the curves obtained is the maximum which at close to the critical velocity is located in a region near the wall with the coordinate y = 0.15 and with an increase in velocity spreads toward the axis of the tube. In comparing the graphs of Fig. 3 one can note that the velocity at which $\nu_{max} = 1$ corresponds to the maximum value of the longitudinal component at the point with the coordinate y = 0.04. Up to this velocity the turbulence intensity increases in proportion to the coefficient of intermittence at all points of the cross section.

Profiles of the average velocity were measured in laminar, transitional, and turbulent modes of motion of the disperse system from the axis of the tube to the wall. Three qualitatively different distributions of the relative velocity which correspond to the different modes of motion are presented in Fig. 4. During laminar motion a typical velocity profile exists which has a flat core occupying the central region of the tube and a gradient part, close to a parabola, which is located closer to the wall. When the velocity exceeds the critical value the core is considerably reduced while the profile becomes flatter near the wall. Applying to the analysis the results of the measurement of the coefficient of intermittence we note that at this velocity it reaches a value of 0.4 near the wall, while in the immediate vicinity of the axis of the tube it does not exceed 0.1. Thus, the reason for the flattening of the average velocity profile near the wall is the turbulent transfer of momentum which becomes significant here. In the central part of the tube the individual velocity pulsations can be considered as oscillations of a core which is preserved. A further increase in the velocity leads to a profile qualitatively similar to a turbulent profile for a non-Newtonian liquid, but steeper. Such an average velocity distribution corresponds to a coefficient of intermittence close to 1 at the wall of the tube and close to 0.5 in the central part. An increase in the flow rate leads to filling in and flattening of the profile, which approaches the turbulent profile within the limits of the velocity range investigated.

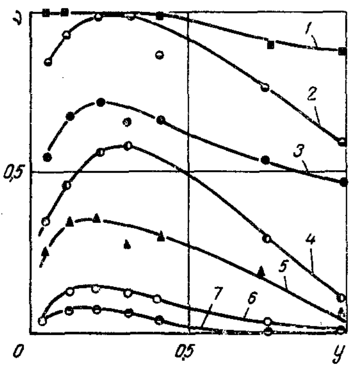

Fig. 3

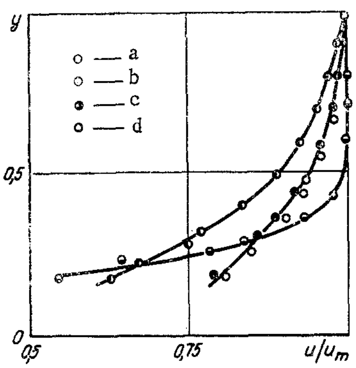

Fig. 4

Fig. 3. Distribution of coefficient of intermittence over tube cross section at different velocities: 1) U_0 = 1.2 m/sec; 2) 1.0; 3) 0.9; 4) 0.75; 5) 0.68; 6) 0.65; 7) 0.62.

Fig. 4. Distribution of average velocity over cross section of tube in laminar (a), transitional (b), and turbulent (c: clay dispersion, d: water) regions of motion.

The choice of the parameter which determines the transition from laminar to turbulent flow and the calculation of its critical value from the rheological characteristics of the system have important significance. Values of the Reynolds number Re_c calculated from the experimentally determined critical flow rate in accordance with Eq. (1) are presented in Table 1. Its average value is 2280 with an rms deviation of 10.5%. However, the determination of the parameters of the rheological model used here for the shear velocities corresponding to the critical velocity in tubes of large diameter is difficult.

A local stability parameter is suggested whose application in terms of the Bingham–Shvedov Model leads to the following equations [9]:

$$Re_k = \frac{1 - \frac{4}{3}\alpha + \frac{1}{3}\alpha^4}{8\alpha} He, \tag{4}$$

$$\frac{He}{8\,Re} = \frac{\alpha}{(1-\alpha)^3}, \quad Re = 2300. \tag{5}$$

These equations make it possible to calculate Re_k, knowing the rheological parameters τ_0 and μ_p, which are relatively easy to determine, and the tube diameter. The coordinate corresponding to the maximum value of the proposed stability parameter is determined by the equation

$$y = 0.423(1-\alpha). \tag{6}$$

For the system studied $y = 0.1$–0.15, which coincides with the coordinate of the maximum value of the coefficient of intermittence.

For the large values of α which were observed in the experiment Eq. (4) can be simplified:

$$Re_k = \sqrt[3]{Re^2 He}, \tag{7}$$

which results in an error of less than 6% for $\alpha \geq 0.75$. The values of Re_k calculated from Eq. (7) and determined experimentally are presented in Table 1. The rms deviation of the experimental values from the calculated values is 13%.

Thus, the use of a conduction anemometer to measure the turbulence intensity allows one to clearly differentiate the regions of laminar, transitional, and turbulent motion of disperse systems. The development of the turbulence and of the average velocity profile in the transitional region is determined by the change in the coefficient of intermittence. For disperse systems it is possible to calculate the critical value of the Reynolds number using Eq. (7).

NOTATION

ρ	is the density;
τ_0	is the limiting shear stress;
μ_p	is the plastic viscosity;
n	is the index of non-Newtonian behavior;
k	is the consistency;
k_b, k_a, ν	are the coefficients of calibration, amplification, and intermittence;
c	is the weight concentration;
D	is the diameter of tube;
x, y	are the distance from entrance to tube and from wall, respectively, dimensionless with respect to the diameter;
$\alpha = \tau_0/\tau_R$	is the relative critical size of core of average velocity profile;
U_0, U_c, U_t, U_*	are the flow rate, velocities at beginning and end of transitional section, and dynamic velocity, respectively;
u, v	are the longitudinal and transverse components of pulsation velocity;
τ_R	is the shear stress at wall;
γ	is the average shear rate;
B_0	is the magnetic field strength;
E	is the voltage at amplifier ouput;
Re_g, Re_c	are the generalized Reynolds number for power-law model and its critical value;
$Re_k = \rho U_c D/\mu_p$	is the critical value of Reynolds number for Bingham–Shvedov model;
$He = \rho\tau_0 D^2/\mu_p^2$	is the Hedstrom number;

Q is the flow rate;

ΔP is the pressure drop.

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