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EXPERIMENTAL STUDY OF TRANSVERSE MASS EXCHANGE IN THE

FLOW OF POLYOXYETHYLENE SOLUTIONS IN A ROUND PIPE

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A method is proposed for investigating the transverse mass exchange in the turbulent flow of polyoxyethylene solutions in a pipe using the phenomenon of nuclear magnetic resonance.

Investigations of the influence of polymer admixtures on the reduction of hydrodynamic resistance in the turbulent flow of polyoxyethylene solutions in pipes by traditional methods are described in [1].

However, these methods introduce a disturbance into the investigated medium, which can lead to considerable errors when measuring in pipes of small diameter. As for methods based on recording particle tracks [2], they also are not free of important drawbacks, especially when investigating flows of polymer solutions, since polymers, while effectively reducing resistance, are strong flocculants, distorting the behavior of individual particles in the flow. For example, pulsation velocity components in the boundary region in the turbulent flow of water and polymer solutions in a channel were obtained in [2] which differ considerably from those given in [3], where the intensity of turbulence near the wall was studied using photography of small air bubbles included in the liquid and it was established that under the conditions of a decrease in resistance there is a decrease in the intensity of the axial components of turbulent pulsations in comparison with pulsations in a Newtonian liquid, whereas no noticeable changes take place in the radial component.

In this connection it seems appropriate to develop new methods of investigation of the flow structure of turbulent streams. This is also underlined by the fact that, despite the numerous investigations, none of the existing theories ultimately satisfy the requirements of the practical use of small admixtures of polymers for the reduction of hydrodynamic resistance [4].

To study phenomena of transverse diffusion (transverse mass exchange) in the flow of polyoxyethylene solutions in a round pipe we developed a method based on the use of phenomena of nuclear magnetic resonance [5,6].
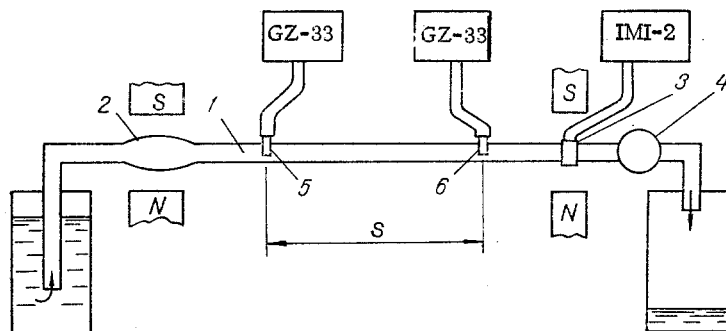
Fig. 1. Block diagram of experimental installation.

A block diagram of the experimental installation is shown in Fig. 1. The pipe 1 consists of a glass tube 700 mm long with an inner diameter of 4.8 mm. Before entering the pipe the liquid is magnetized, passing through a polarizer 2 in which the magnetic moments of the protons in the water molecules are oriented predominantly along the direction of the strong magnetic field (for convenience we will assume that the direction of the magnetic field strength vector is positive), i.e., after passing through the polarizer the liquid has a nonequilibrium positive proton magnetization. This magnetization is preserved for a rather long time, and its decline due to relaxation during flow through the test section does not affect the experimental results. At the end of the pipe there is a detector 3, where the NMR signal, whose intensity is proportional to the proton magnetization M, is recorded with a standard IMI-2 instrument. The liquid is pumped from a volume of 50 liters by a pump 4 placed at the exit from the pipe.

Let us mentally cut the test section of the pipe lengthwise into two equal parts I and II by a plane perpendicular to the direction of the magnetic field. To investigate transverse diffusion we can mark molecules of liquid in one half of a cross section and observe the penetration of the marked molecules into the other half. The marking and the determination of the number of molecules moving into the other half of the cross section are done with special nutation coils of toroidal shape. Two nutation coils 5 and 6 are placed in the same way at a certain distance s from each other in the section of pipe with established flow and are supplied from low-frequency oscillators of type GZ-33. The field of each coil acts only on the first half of the pipe cross section. The liquid flowing through a nutation coil is subjected to the pulsed action of a weak magnetic field oscillating with a frequency equal to the precession frequency of the nuclei. The power of the active signal is chosen as a function of the liquid flow velocity so that after the action of the coil field the magnetization vector is rotated by 180° and becomes negative.

After the polarizer the magnetic moments prove to be directed positively in both halves of a cross section. The field of the first nutation coil, acting on only the first half of the pipe, rotates the magnetic moments by 180°. If only one nutation coil is turned on, then the liquid emerging from it has a zero total magnetic moment and the detector gives a zero signal. The power and frequency of the signal supplied to each of the nutation coils are chosen separately so that the detector signal is equal to zero.

For laminar flow in the section of pipe between the nutation coils movement of the liquid in the transverse direction through the plane separating the first and second halves of the pipe is absent. In such a case with the action of both coils on the flowing liquid the field of the second coil compensates for the action of the first: in the field of the first coil the magnetization of the liquid in the first half of the cross section becomes negative, while in the field of the second coil the direction again changes by 180° and becomes positive. Thus, for laminar flow the signal of the detector when the fields of both nutation coils act on the flow will equal the signal in the absence of a low-frequency voltage on the coils. The intensity of such a signal will not depend on the distance between the nutation coils.
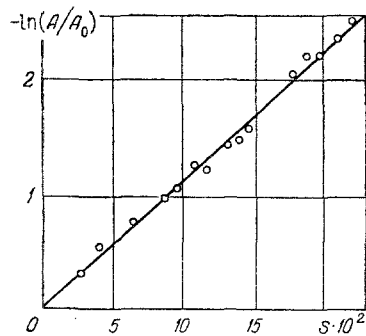
Fig. 2

Fig. 3

Fig. 2. Dependence of logarithm of relative signal intensity on distance between nutation coils $s \cdot 10^2$, m.
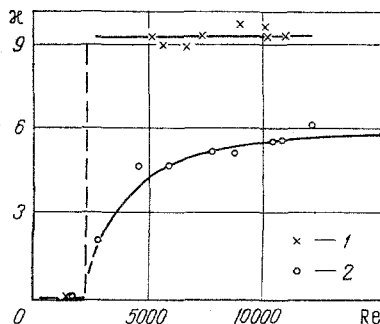
Fig. 3. Dependence of parameter of mixing probability $\varkappa$ (m^{-1}) on Reynolds number Re for water and a polyoxyethylene solution with a concentration of $5 \cdot 10^{-3}$ kg/m^3: 1) water; 2) polyoxyethylene.

If the mode of flow is turbulent, then in the test section of the pipe there is transverse mixing of the liquid, i.e., transverse turbulent diffusion. Let us assume that in the time the liquid flows between the nutation coils a fourth of the liquid with a positive proton magnetization from the second half of the pipe cross section is exchanged with a fourth of the liquid with a negative proton magnetization from the first half. Then after the action of the field of the second coil the proton magnetic moment of a unit volume of liquid decreases by half in comparison with the case when a voltage on the nutation coils is absent, which leads to a decrease in the detector signal by half also. Since the amount of liquid exchanged depends on the distance between the nutation coils, for turbulent flow the intensity of the detector signal will depend on this distance.

Let us treat the diffusion of liquid particles through the partition as the diffusion of gas molecules. The number dN of particles passing through the partition will be proportional to the particle concentration N, the average velocity w_{av} perpendicular to the partition, and the time interval dt:

$$dt = - kNw_{av}dt. \tag{1}$$

We separate the variables and integrate. Then

$$N = N_0 \exp(-kw_{av}t). \tag{2}$$

The entire time interval during which diffusion is observed in our experiment is equal to the time the liquid flows between the two nutation coils, $t = s/v_{av}$, where v_{av} is the average velocity of liquid flow; s is the distance between the coils. Substituting the value of t into (2), we will have

$$N = N_0 \exp\left(- k \frac{w_{av}}{v_{av}} s\right). \tag{3}$$

Since the magnetization M of a unit volume of liquid is proportional to N and the signal intensity I is proportional to M, the dependence of the detector signal intensity on the distance between the nutation coils should be exponential:

$$I = I_0 \exp\left(-k \frac{w_{av}}{v_{av}} s\right) = I_0 \exp(-\varkappa s), \tag{4}$$

where $\varkappa$ is a coefficient having the dimensionality of m^{-1} and equal to $k(w_{av}/v_{av})$, I_0 is the value of I when s = 0.

The dependence of the signal intensity on the distance between the nutation coils was measured on the installation described above for tap water in the turbulent mode of flow ($v_{av} = 1.83$ m/sec, Re $= 8.8 \cdot 10^3$). The data presented in Fig. 2 confirm the exponential character of this dependence, namely,

$$\ln\frac{I_2}{I_1} = \varkappa(s_2 - s_1), \tag{5}$$

where I_1 and I_2 are the signal intensities for distances s_1 and s_2, respectively, between the coils.

For laminar flow the coefficient $\varkappa$ equals zero and the average transverse velocity w_{av} equals zero. For turbulent flow the coefficient $\varkappa$ characterizes the degree of mixing of liquid in the transverse direction and its value can be treated as the fraction of molecules moving through the longitudinal plane separating the two halves of the pipe per unit length of the pipe, which is the probability of transverse mixing per unit length. To determine the value of $\varkappa$ it is sufficient to measure two values of the signal intensity I_1 and I_2 for two respective values of the distance s_1 and s_2 between the coils.

The proposed method of measuring the degree of transverse turbulent diffusion was used to study the flow in a pipe of weak polymer solutions possessing low coefficients of hydrodynamic friction. We used WSR-301 polyoxyethylene. As is known, polyoxyethylene solutions are subject to destruction (disintegration) with time. In order to reduce as much as possible the influence of destruction on the experiment, we adopted a uniform method of preparation of the solution. A weighed amount of powder was dissolved in a volume of 1 liter for 10 min with the help of a small amount of glycerin, and then the concentrated solution was poured into a volume of 50 liters. The measurements were made 2 h after the preparation of the solution, when the dissolving was completed and when the effect of a decrease in resistance was sufficiently stable. The pump was placed at the exit from the pipe to eliminate mechanical destruction of the solution.

Since to obtain $\varkappa$ it is sufficient to measure the signal intensities at two values of the distances between the coils, three nutation coils were mounted in succession on the glass pipe. The distance between the first and second was 10 mm and between the first and third 140 mm. In order to make measurements only in the established mode of flow, the first coil was placed no closer than 20 diameters from the entrance. Each coil was tuned separately so that the signal intensity equalled zero when the low-frequency signal from a GZ-33 oscillator was fed to it. With liquid flowing at a constant flow rate through the pipe successive measurements were made of the intensities of two detector signals: I_1 with the first and second coils turned on; I_2 with the first and third coils turned on. Hence, from Eq. (5) the coefficient characterizing the mixing probability is

$$\varkappa = -\ln \frac{I_2}{I_1} / (s_2 - s_1). \tag{6}$$

The values of I_1 and I_2 were measured on the experimental installation for the cases of the flow of tap water and of a polyoxyethylene solution with a concentration of $5 \cdot 10^{-3}$ kg/m^3. The liquid flow rate was measured by the volumetric method. The dependence of $\varkappa$ on Re is presented in Fig. 3. The Reynolds number was calculated from the pipe diameter and the average flow velocity; the viscosity of the solution was taken as equal to the viscosity of water, since the difference is small and comprises only a few percent.

The accuracy in measuring $\varkappa$ was 8% in the region of values of 5.0 m^{-1} and 2-3% in the region of values of 10.0 m^{-1}. The inconstancy of the turbulent mode of flow introduces some scatter into the values of $\varkappa$.

The quantity $\varkappa$, equal to $k w_{av}/v_{av}$, is proportional to the average absolute value of the liquid pulsation relative to the average flow velocity. The measurement results presented in Fig. 3 show the character of the dependence of the quantity $|w_{av}|/v_{av}$ on Re for water and a polyoxyethylene solution and provide the basis for drawing the following conclusions about the behavior of the average pulsation of the transverse velocity component:

1. For water in the laminar mode of flow transverse pulsations are absent; then at Re = 2300 a sharp transition to the turbulent mode of flow is observed.

2. For water in the turbulent mode of flow the size of the transverse pulsations is proportional to the flow velocity, since the value of $|w_{av}/v_{av}|$ does not depend on Re.

3. Transverse pulsations are also absent in the case of the flow of a weak polyoxyethylene solution at small Re; then, in contrast to water, a drawn-out transition (up to Re $\approx$ 5000-6000) to the turbulent mode of flow is observed.

4. In the turbulent mode of flow the transverse pulsations in a polyoxyethylene solution, as in water, are proportional to the average flow velocity. In contrast to water, however, the transverse pulsations in a solution are considerably smaller. For example, for a

solution with a concentration $c = 5 \cdot 10^{-3}$ kg/m³ the average absolute value of the transverse pulsation is decreased by 1.7 times.

NOTATION

N, particle concentration; w_{av}, average velocity in transverse direction; t, time; s, distance between magnetic marking coils; v_{av}, average velocity in longitudinal direction; M, magnetization per unit volume of liquid; I, intensity of NMR signal; Re, Reynolds number; k, $\varkappa$, proportionality factors.

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BOUNDARY LAYER ABOVE A SEMI-INFINITELY LARGE HOT PLATE IN A MEDIUM WITH PHASE TRANSITION

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A self-adjoint solution in the "boundary layer" approximation is constructed to the problem of streamlining of a hot plate by a medium in which a phase transformation occurs. A longitudinal pressure gradient exists within the region of the liquid phase.

Let a substance in the solid state with density ρ_0 and phase transition temperature T_f move in the direction of the x axis at a constant velocity U_0 in the half-space y > 0. The temperature of the solid at $y \to \infty$ is given and assumed to be $T_\infty < T_f$. At y = 0 there is located a semi-infinitely large stationary flat plate ($0 \leqslant x < \infty$) whose temperature is everywhere the same $T_W > T_f$. Above this plate, moreover, there forms a layer $0 < y < y_f(x)$ (where $y_f(x)$ denotes the phase transition surface) within which the liquid phase of the given substance flows (Fig. 1).

The processes of heat and mass transfer within the region of the liquid phase $0 < y < y_f(x)$, x > 0 are described by the system of equations [1]

$$\frac{\partial \Psi}{\partial y}\frac{\partial \Delta\Psi}{\partial x} - \frac{\partial \Psi}{\partial x}\frac{\partial \Delta\Psi}{\partial y} = \nu\Delta\Delta\Psi, \tag{1}$$

$$\frac{\partial \Psi}{\partial y}\frac{\partial T}{\partial x} - \frac{\partial \Psi}{\partial x}\frac{\partial T}{\partial y} = \varkappa\Delta T + \frac{\nu}{c}\left[4\left(\frac{\partial^2\Psi}{\partial x\partial y}\right)^2 + \left(\frac{\partial^2\Psi}{\partial y^2} - \frac{\partial^2\Psi}{\partial x^2}\right)^2 \right].$$

Here x, y are respectively the longitudinal and the transverse coordinates, $\Psi = \Psi(x, y)$ is the flow function ($u = \partial\Psi/\partial y$, $v = -\partial\Psi/\partial x$ are respectively the longitudinal and the transverse