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EXPERIMENTAL INVESTIGATION OF LONGITUDINAL MASS TRANSFER IN THE FLOW OF POLYOXYETHYLENE SOLUTIONS IN A ROUND PIPE

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A method is described for studying longitudinal mass transfer in the turbulent flow of polyoxyethylene solutions in a pipe using nuclear magnetic resonance effects.

This study of longitudinal mass transfer is a continuation of [1]. The phenomenon of nuclear magnetic resonance (NMR) in a flowing liquid [2] makes it possible to study the hydrodynamics of the flow with magnetic marking. Compared to other methods, use of magnetic labelling has such advantages as lack of contact with the flow, an adequate lifetime, and the possibility of studying flows in thin tubes [3].

The improved Taylor method [5] was used in [4]. Longitudinal mass transfer in a pipe with a flow of water and aqueous solutions of polyoxyethylene was studied by introducing NaCl and recording the distribution of the electrical conductivity of the water along the pipe at a certain distance from the site of the labelling. Data was obtained for different concentrations of polyoxyethylene.

Figure 1 shows a block diagram of the experimental unit for studying longitudinal mass transfer by the NMR method. The pipe 1 is a glass tube 700 mm long with an inside diameter of 4.8 mm. The liquid is magnetized beforehand by passing it through a polarizer 2, where the magnetic moments of the protons in the water molecules were preferentially oriented in the direction of the strong magnetic field.

Located at the end of the tube is a detector 3, where, with the aid of a standard IMI-2 magnetic inductometer, an NMB signal is recorded. The signal strength here is proportional to the total magnetic moment of the protons in a unit volume of the liquid M. The liquid is pumped from a 50-liter tank by a pump 4 placed at the tube outlet. The section of tube investigated was a portion of length L = 380 mm located between the nutation coil 5 and the coil of the detector 3.

The molecules were marked by means of the coil 5, which creates a weak variable magnetic field directed along the dynamic velocity of the flow and perpendicular to the vector of the external magnetic field **B**. The nutation coil is fed from a G4-26 generator, which creates an alternating electric field with a frequency of 100 kHz — equal to the frequency of precession of the nuclei in the field **B** — and a power corresponding to a 180° rotation of the magnetization vector. The signal is modulated by rectangular pulses with a frequency ν = 2-40 Hz. The NMR signal is observed and the signal strength read from an oscillograph screen.

In studying longitudinal diffusion, liquid particles to one side of a cross section of the stream perpendicular to the flow direction must be marked and the number of marked particles which turn up on the other side of this cross section after a certain period of time has to be determined.

We will assume that all of the particles move at the same velocity v_{av}. After the field of the nutation coil has acted on the liquid, alternating volumes of positive and negative magnetization separated by sharp boundaries appear in the fluid. The length of each volume

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$l = v_{av}\tau/2$, where τ is the modulation period, equal to $1/\nu$. After the liquid has traversed the test section of the tube L, its magnetization is recorded in the detector coil. Since the intensity I of the signal seen on the oscillograph screen is proportional to the magnetization of the unit volume of liquid M passing through the detector, it may change from a maximum positive value I to a maximum negative value $-I$ with a period τ over the rectangular screen. The maximum value of the signal $I_{max} = I_0$ will be independent of τ.

In actuality, the liquid particles move at different velocities (with a certain velocity distribution). As in the above case, alternating sharply defined volumes of positive and negative magnetization appear in the liquid passed through the nutation coil. However, this situation no longer obtains after the liquid has passed the test section of length L. The boundary between the volumes will be blurred in equal measure as a result of both retarding and acceleration of the liquid particles, and the magnetization of the liquid passing through the detector coil will vary with time in accordance with a smooth curve, rather than according to a rectangular law. Examining the averaged motion, we reason that the center of the boundary between regions of different magnetization moves at the mean flow velocity v_{av}, and the eroded boundaries are the result of differences in the velocities of the liquid particles from the mean velocity. We will call the velocities of the liquid particles relative to the section moving at the mean velocity longitudinal pulsations. The proposed method is insensitive to the sign of the pulsations and allows us to judge the absolute magnitude of the pulsations relative to the mean velcoity. We will here introduce the quantity of relative particle-velocity pulsations, equal to $w = |v - v_{av}|/v_{av}$, where v is the actual velocity of a liquid particle. Then the width of the boundary erosion will be

$$l_0 = 2\, w_{max} v_{av} T, \tag{1}$$

where w_{max} is the maximum longitudinal pulsation; T is the time of flow over the test section. Since

$$T = L/v_{av}, \tag{2}$$

then

$$l_0 = 2\, w_{max} L. \tag{3}$$

A boundary of length l_0 will pass through the detector coil in the time

$$\frac{\tau_0}{2} = \frac{l_0}{v_{av}} = 2\, w_{max}\, \frac{L}{v_{av}}. \tag{4}$$

If the frequency of modulation of the magnetization of the liquid at the marking site is sufficiently low (i.e., if the period τ is large), then the peak value of M will be equal to the magnetization in the absence of a velocity distribution M_0. If we increase ν, i.e., decrease the period τ, then the value of the magnetization M will begin to decrease beginning with a certain frequency ν_0.

In modulating the nutation-coil signal with a frequency ν_0 and period τ_0, the time of passage of the boundary through the detector coil will be equal to half the nutation period, i.e.,

$$\frac{\tau_0}{2} = \frac{1}{2\,\nu_0}. \tag{5}$$

Using Eq. (4) and substituting for the quantity $\tau_0/2$, we find the maximum value of the pulsations relative to the mean velocity:

$$w_{max} = \frac{v_{av}}{4\, L \nu_0}. \tag{6}$$

With an increase in the modulation frequency, the signal I begins to fade at $\nu = \nu_0$. Having measured the flow rate of the liquid $q = v_{av}S$ (S is the cross section of the tube), we find that all of the quantities in the right side of Eq. (6) are known and that we can find w_{max}. The higher the modulation frequency, the lower the peak magnetization of the liquid passing through the detector.

The reduction in magnetization $\Delta M = M_0 - M$ depends on the distribution of the particles with respect to the pulsations. The value of ΔM is affected by the particles moving fast

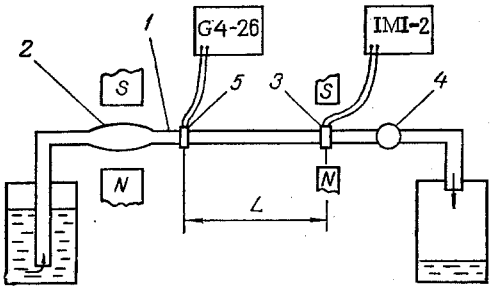

Fig. 1

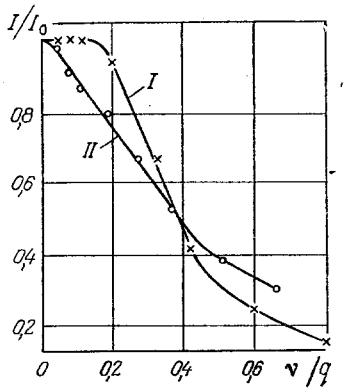

Fig. 2

Fig. 1. Block diagram of experimental unit for studying longitudinal mass transfer in the flow of a liquid in a tube.

Fig. 2. Experimental dependence of strength of NMR signal I/I_0 on ratio of modulation frequency to flow rate ν/q (10^{-6} m^{-3}) for water (I) and for a polyoxyethylene solution of concentration $1 \cdot 10^{-1}$ kg/m^3 (II).

enough to reach the middle of the volume with positive magnetization from the volume with negative magnetization during their passage over the test section.

The derivative of the dependence of I/I_0 on w will give us a curve depicting the particle distribution with respect to the longitudinal pulsations.

Given a test section of constant length, the minimum velocity at which the particles will affect the signal depends only on the quotient from the division of the mean flow velocity by the frequency of the nutation signal. To obtain the distribution with respect to the pulsations, it is sufficient that we determine the dependence of the NMR signal on the value of ν/q.

The experimental unit was used to measure the strength of the NMR signal in relation to the modulation frequency at different flow rates for tap water (Fig. 2). The flow rates were 1.5-2.5 m/sec, which correspond to Reynolds numbers Re = 7200-12,000.

To analyze the empirical data, we replotted it in the coordinates I/I_0 and w (curve I in Fig. 3), where w was calculated from the measured flow rate q and modulation frequency ν by means of Eq. (6).

The decrease in I/I_0, beginning at w = 0.3, in the direction of lower pulsation values indicates that the maximum difference from the mean velocity in turbulent flow of the water is 0.3 of the mean velocity, i.e., $w_{max} = 0.3$ for the water. Due to the overlapping of adjacent pulses in the region of pulsations below $w_{max}/3$, we introduced corrections (curve II in Fig. 3). The experimental measurement possibilities were limited by the minimum pulsation rate, equal to $w_{lim} = 0.1$.

The derivative of the dependence of I/I_0 on w gives us the distribution with respect to longitudinal pulsations (curve I in Fig. 4). The beginning of this curve was plotted with a dashed line for $w < 0.1$ on the assumption of a Gaussian velocity distribution.

A solution of WSR-301 polyoxyethylene was studied to determine the effect of small polymer additions on the distribution of longitudinal velocity pulsations. To avoid breakdown of the polymer, the solution was prepared in exactly the same way, with a concentration of $1 \cdot 10^{-1}$ kg/m^3.

The dependence of the signal strength I/I_0 on w was plotted for the solution of $q = 6 \cdot 10^{-5}$ m^3/sec, Re = 17,000 (curve II in Fig. 2). This dependence is shown in the coordinates I/I_0, w by curve III in Fig. 3. We should point out the fact that the reduction in the signal for the solution begins at relatively low frequencies compared to water (Fig. 2). It follows from this that the maximum longitudinal pulsations at Re = 17,000 are significantly greater in the solution flow than in the water flow. Since the above experiment is sensitive to the absolute values of the pulsations, the distribution curve can be asymmetrical relative to the mean velocity. As in the case of the water flow, we have introduced corrections into

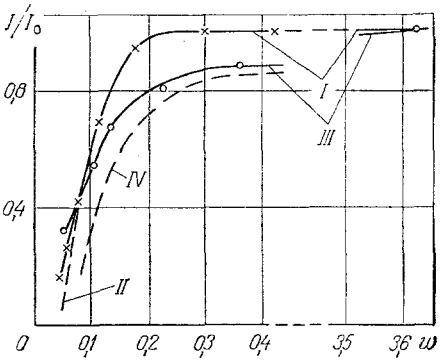

Fig. 3

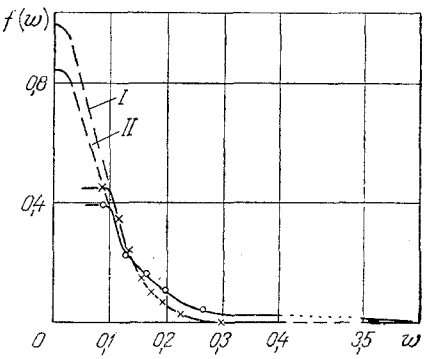

Fig. 4

Fig. 3. Dependence of NMR signal I/I_0 on longitudinal pulsation w for water (I, II) and a $1 \cdot 10^{-1}$ kg/m^3 solution of polyoxyethylene (III, IV).

Fig. 4. Curves of particle distribution with respect to longitudinal pulsations for water (I) and a $1 \cdot 10^{-1}$ kg/m^3 solution of polyoxyethylene (II).

the empirical data to account for the effect of adjacent pulses (curve IV, Fig. 3). The derivative of the curve yields the particle distribution with respect to longitudinal velocity pulsations for the solution (curve II, Fig. 4). The path of the distribution curve for the solution deviates from the Gaussian curve. Thus, in plotting the curve in the region of small pulsations, we made use of the fact that the signal reduction is the same as in the experiment with water.

Thus, Fig. 4 shows curves of longitudinal pulsation distribution in turbulent flows of water and the polyoxyethylene solution ($c = 1 \cdot 10^{-1}$ kg/m^3). The integrals of the areas bounded by both curves are equal.

The results obtained here agree with the data in [4], despite the fact that different methods of measurement were used. The NMR method has the advantage of noncontact marking over the method used in [4]. The NMR method can be used to measure concentrations as low as 10^{-3} kg/m^3; study of flow in thinner tubes makes it possible to judge the effect of the surface on the structure of solution flows.

NOTATION

L, length of investigated section of tube; T, time of flow over section L; τ, modulation period; ν, modulation frequency; v_{av}, mean velocity; w, longitudinal velocity pulsation; l, marker length; M, magnetization of a unit volume of the liquid; I, intensity of NMR signal; q, flow rate; c, solution concentration.

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