BEHAVIOR OF POLYMER MELTS IN ROTARY INSTRUMENTS OF THE PLANE—PLANE AND CONE—PLANE TYPE

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The qualitative flow pattern of polyethylene melts in rotary instruments of the plane—plane and cone—plane type is examined. It is shown experimentally that in these instruments the flow lines are Archimedes spirals, which indicates the presence of radial mass transport.

Rotary instruments of the plane—plane and cone—plane type are widely used to determine different properties of viscoelastic liquids, typical representatives of which are polymer solutions and melts. Unfortunately, it must be stated that the behavior of polymer melts during shear flow in these instruments has not been experimentally studied thoroughly enough. Moreover, there is no single opinion at present on questions dealing with the formation and development of normal stresses in a deforming medium. This in turn prevents the creation of a rigorous theory of the viscoelastic behavior of materials on the basis of which the Weissenberg effect [1] could be studied.

In recent years a number of works [2-5] have appeared in which the possibility of the development of circulation flows in rotary instruments is indicated. However, the authors assert that circulation flows can develop only in instruments of the cone—plane type having cone angles of less than 170°, and attribute the origin of this phenomenon to inertial effects. The question of the behavior of viscoelastic media in instruments of the plane—plane type remains open at present.

In connection with the above, we have attempted to study experimentally the shear flow of a viscoelastic material in instruments of the plane—plane and cone—plane types.

An apparatus [6] which made it possible to create a model of a rotary instrument and to conduct not only visual observations but also photography and filming was used to conduct the experiments. Plane disks and conical disks with apex angles of 170, 160, 150, and 120° were used as the working organs. The diameters of the disks and bases of the cones were 0.115 m. The range of shear velocities was $\dot{\gamma}=20$–400

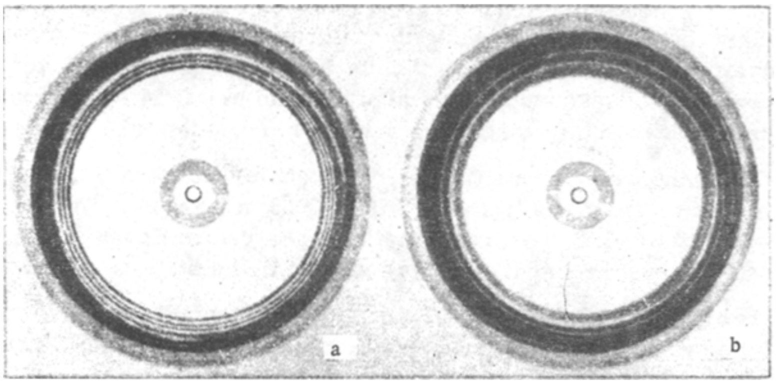

Fig. 1. Flow of polymer melt in a plane parallel gap (γ = 20–400 sec^{-1}).

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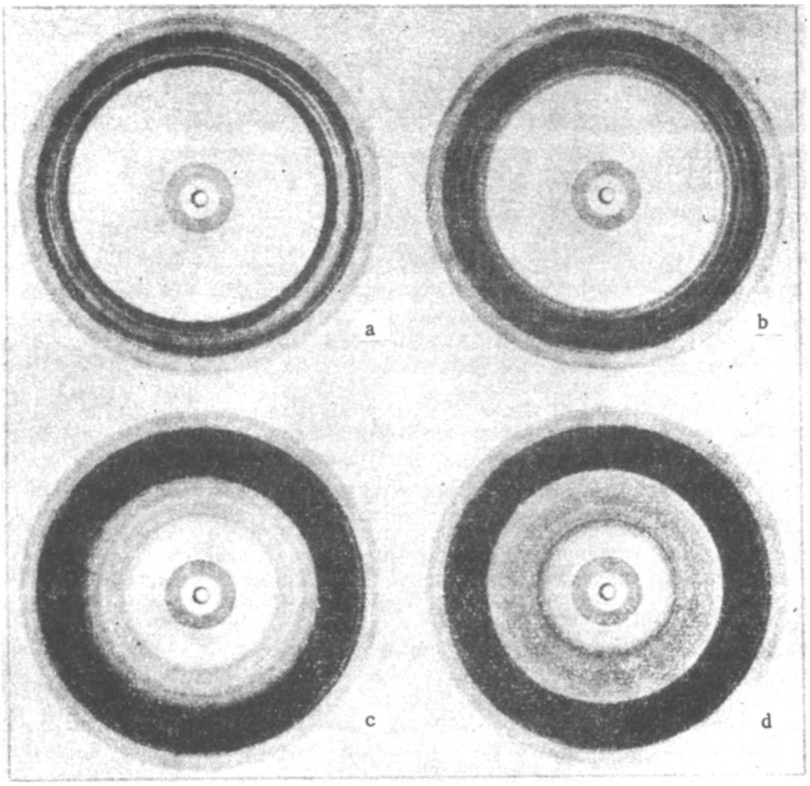

Fig. 2. Flow of polymer melt in a plane parallel gap (γ = 15-90 sec^{-1}).

sec^{-1}. The experimental material, P2020-T brand polyethylene of low density, in the form of a melt at a temperature of 453°K was loaded into the working gap and completely filled it.

The construction of the working unit permitted the introduction of a tracer material (a colored granule of polymer) during the operation of the instrument at any depth with respect to the height of the gap and the radius of the working surfaces. Here it should be mentioned that there was no thermostatic control of the material during the operation of the apparatus since the main purpose was to study the qualitative flow pattern of the polymer melt.

We have made analytical studies confirming the nature of the flow of a viscoelastic liquid in the batching zone of a disk extruder (the presence of the discharge of liquid through the central opening in the stationary disk) earlier [6, 7]. These studies can also be valid in a first approximation for the qualitative flow pattern of a polymer melt in rotary instruments which is considered below.

In the first version of the experiments the colored granule was located near the periphery of plane parallel disks with gaps of H = 0.003 m (Fig. 1) and H = 0.006 m (Fig. 2). The colored material traveled along an Archimedes spiral toward the center of rotation and a return flow was observed simultaneously, as in the presence of a discharge through the central opening in the stationary disk.

As a result of this a gray ring is formed at some distance from the center after sufficiently long rotation as a result of the overlapping of the two opposing flows. This is illustrated in Fig. 1, in which the development of an Archimedes spiral is shown, and in Fig. 2, in which the development of an Archimedes spiral and the indicated gray ring are seen. The inner diameter of the region of spread of the colored material depends on the shear velocity and decreases as the shear velocity increases.

The zone of spread of the colored material after 65 revolutions of the disk is shown in Fig. 1a and after 130 revolutions in Fig. 1b. Here the rotation rate of the disk was constant and equal to 20 rpm.

Figure 2a was made after 25 revolutions of the disk and Fig. 2b after 100 revolutions at a rotation rate of 15 rpm. Hardly any advancement of the colored material toward the center was observed during further operation at this speed so the rotation rate was increased to 45 rpm and Fig. 2c was made after 270 revolutions of the disk. Figure 2d shows the maximum zone of spread of the colored material at a disk rotation rate of 90 rpm. In the second version of the experiments two colored granules were placed in the gap.

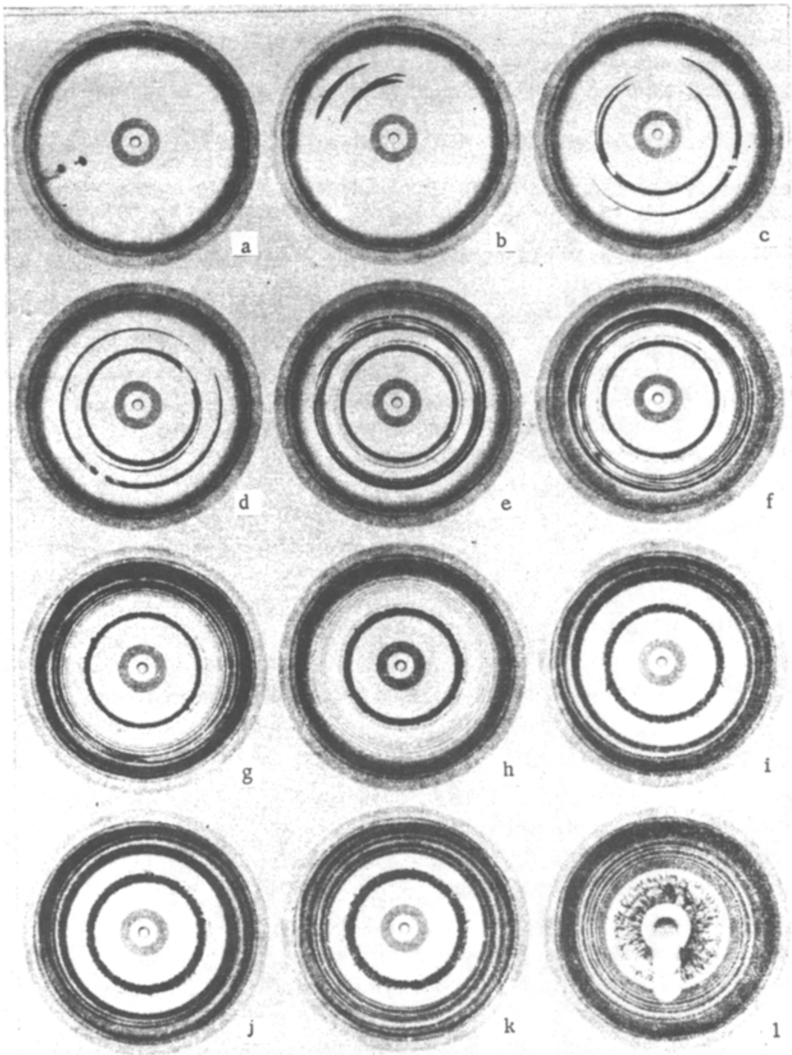

Fig. 3. Flow of polymer melt in conical gap (γ = 2-240 sec^{-1}).

Figure 3 illustrates the behavior of these two granules introduced into a polyethylene melt which is in a conical gap (ε = 10°) at a cone rotation rate N = 50 rpm. While the particles of granule I, located closer to the periphery of the cone, undergo intensive displacement along the radius of the gap, granule II during the same time is smeared out into a concentric ring whose area does increase but remains small.

Figure 3 reflects the state of the system at the time the rotation of the cone started (b: after one revolution of the cone; c: after three; d: after 10; e: after 20; f: after 30 revolutions of the cone). The successive photographs show the change in the pattern of displacement of the colored material after each 2.5 min. In Fig. 3k after 655 revolutions of the cone we see the maximum zone of spread of the colored material at the rotation rate indicated above.

The change in the intensity of the color of the zone of granule I (Fig. 3, g-k) shows how it is displaced, gradually smears out, and colors the main polymer mass.

Thus, it is clearly seen in which zone of the conical gap at these cone rotation rates the secondary flows have an important effect on the flow of the polymer melt and in which zone they prove to be unimportant. Nevertheless, with sufficiently prolonged rotation of the cone one would expect the merging of the zones formed by granule I and granule II. This indicated that the intensity of the secondary flows differs at different points of the conical gap and is in direct dependence on the shear velocity. After the moving cone was stopped and the opening of the forming head was uncovered the spontaneous extrusion of the melt from the working gap was observed (Fig. 3*l*), with the distension of the stream of extrudate reaching two to three diameters of the forming opening and 4-8 cm^3 of polymer melt flowing out. This can be considered as the realization of reversible (elastic) deformations. The intensity of discharge of the melt from the working gap increases during rotation of the cone. However, it was repeatedly noted that not all the melt is extruded from the working gap.

This indicates that the velocity field both in a plane parallel gap and in a conical gap is nonuniform and a zone exists in the gap where the Weissenberg effect is vanishingly small.

It must be remarked that the opinion which has been expressed [5, 8] concerning the possibility of the development of secondary (circulation) flows in rotary instruments of the cone–plane and plane–plane types due only to inertial effects was not confirmed experimentally for polymer melts. Secondary flows, which are the consequence of the effect of normal stresses (the Weissenberg effect), occur both in plane parallel gaps and in conical gaps independently of their size.

It should also be noted that the assumption [8] that the creeping out of the polymer melt along the periphery from the gap of a rotary instrument because of inertial effects along the rotating surface was not confirmed. It follows from the results presented above that the creeping out of the melt is connected with secondary flows and can occur only along the stationary disk (if, of course, the rotation rates of the working organ are not so great that inertial forces have a substantial magnitude).

Thus, summing up the results of the discussion of the experimental studies obtained on the qualitative flow pattern of polyethylene melt in rotary instruments it must be emphasized that secondary flows exist both in instruments of the plane–plane type and in instruments of the cone–plane type and their nature depends on the geometrical parameters of the working gaps and the shear velocity (the rotation rate of the moving working organ). It can be concluded from all the aforementioned that not only simple shear but also a complex stress state is realized in rotary instruments of the type studied.

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