SECONDARY FLOWS IN THE GAP BETWEEN A ROTATING CONE AND A STATIONARY DISK

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The flow of an elastic–viscous incompressible liquid (polyethylene melt) in the batching zone of a disk extruder is examined. It is shown experimentally that a state of complex stress exists in the conical gap independent of its angle.

In recent years a number of reports have been published [1-5] in which the possibility of the formation of secondary flows has been indicated in the study of polymer solutions in rotary instruments of the cone–plane type. The authors state that secondary flows can arise in systems having apex cone angles of less than 170° and attribute the appearance of this phenomenon to inertial effects.

The question of the behavior of polymer melts in such systems remains open at present.

The disk extruder [6] is a promising type of instrument which is finding ever wider application in the industry of processing plastic masses.

Since a working gap of conical configuration is very characteristic for the disk extruder, the flow of a polymer melt between a rotating cone and a stationary disk which has a central opening is examined in the present report.

A combination worm–disk extruder, for which a schematic diagram is shown in Fig. 1, was used to conduct the experimental studies. Conical disks with apex cone angles of 174, 170, 160, and 120° were used; the rotation rate of the working element 2-3 was regulated in the range of 10-200 rpm. The stationary disk 1 was made from heat-resistant glass in order to conduct visual observations and motion picture photography.

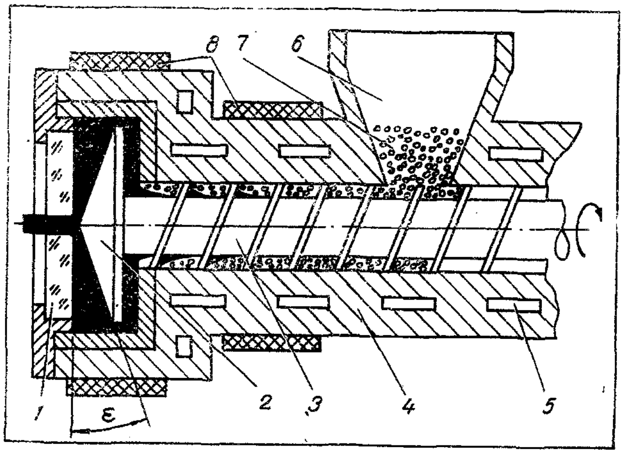

Fig. 1. Schematic diagram of combination extruder: 1) stationary disk; 2) moving cone; 3) worm; 4) body of extruder; 5) cooling channels; 6) hopper; 7) polymer; 8) heaters.

A more detailed description of the experimental apparatus is given in [7, 8].

A melt of low-density polyethylene of brand P2020-T was used as the experimental medium. The running index of the melt was 2 g/10 min. The temperature of the melt in the working gap was 180°C.

Let us examine the results of a visualization of the qualitative flow pattern of a polymer melt in the conical gap of the batching zone of a disk extruder.

As seen from the motion picture record (Fig. 2, a-i), the polymer melt, preliminarily prepared in the intake-plasticizing zone (worm 3, Fig. 1), reaches the working gap ($\varepsilon = 5°$) in the form of separate bunches, which are not ground between the working surfaces but stretch out along the radius in the direction of the exit opening as

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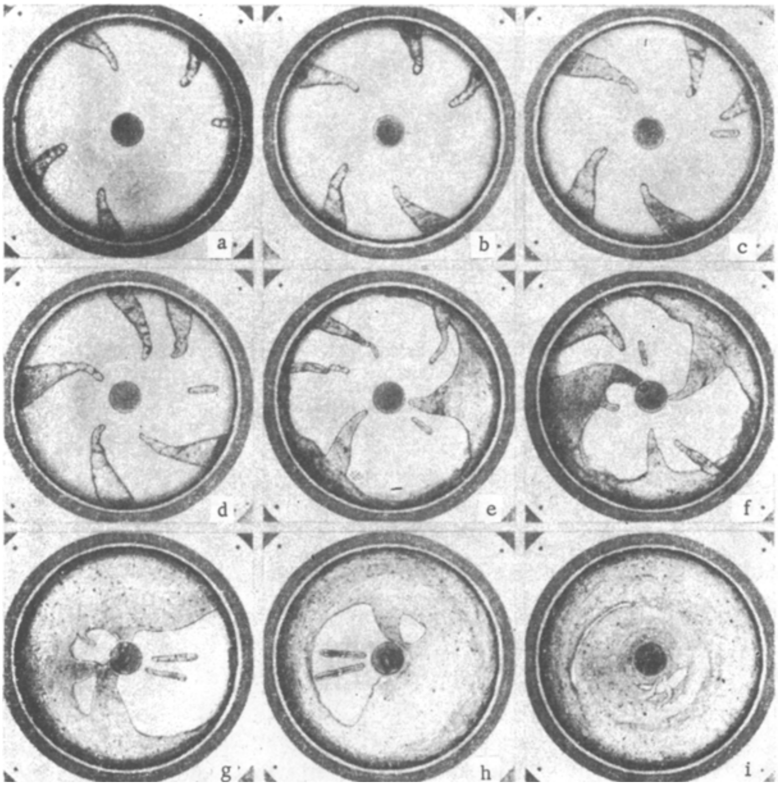

Fig. 2. Process of filling of conical gap ($\varepsilon = 5°$) with polymer melt.

new portions of polymer are supplied. The bundles, rolling between the working surfaces, are twisted around their own axis. The result of this is that the heads of the bundles, because of the difference in circular velocities in different parts of the bundles along their length, are torn off from the main mass and perform independent "planetary" motion in the gap, gradually approaching the output opening (Fig. 2c, h). When the torn off parts make contact with the main mass of the bundles they are merged (Fig. 2e, f). The development of the flow is characterized by the fact that the discharge of the melt through the output opening begins even when the working gap is partially filled (Fig. 2f, i). Bridges and joints are formed at the bases of the separate bundles (Fig. 2e, f) which, gradually expanding, fill the working gap and stabilize the flow. The flow enters into a steady state.

This pattern of development of the flow in a conical gap is also characteristic for a plane parallel gap when its height is less than 5-6 mm.

The development of the flow takes place differently in conical gaps with an angle $\varepsilon > 5°$. The polymer melt fills the working gap with a continuous flow whose front has the form of a concentric circle directed along the rotating cone from the periphery toward the center. The filling of a plane parallel gap proceeds analogously when its height is more than 6 mm. It should be mentioned that the dimensions given above for the working gaps in which the described pattern of flow of polyethylene melts is observed depend on the elastic–viscous properties of the polymer and can be smaller or larger depending on the latter.

One or more colored granules were introduced into the polymer melts to study the flow lines in the developed and steady flow. Flow lines of steady flow are shown in Fig. 3.

The visual observations and an analysis of the motion picture materials showed that secondary (circulation) flow develops in the working gap whose magnitude depends on the geometrical parameters and rotation rate of the cone, the size of the conical gap, and the resistance of the forming instrument [9]. The flow lines are Archimedes spirals whose pitch depends on the parameters enumerated above. With high enough rotation rates of the cone and large angles ε two (or more) circulation streams can develop in the working gap, which indicates the complicated nature of the flow of the polymer melt.

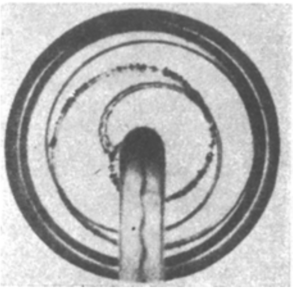

Fig. 3

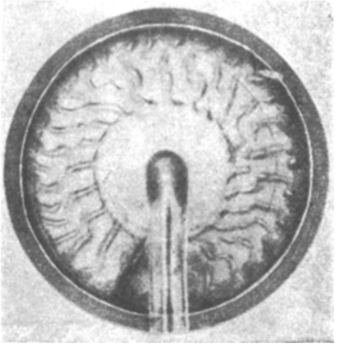

Fig. 4

Fig. 3. Flow lines during flow of polyethylene melt in conical gap ($\varepsilon = 5°$).

Fig. 4. Pattern of quasi-turbulent flow in conical working gap.

The presence of circulation flows confirms the theoretical conclusions that the velocity field changes sign in the batching zone of a disk extruder, i.e., there is a boundary along the height of the conical gap between the direct and reverse flows where the velocity vector has a zero radial component [7].

The formation of circulation flows can be explained on the basis of the following considerations. For conical gaps with small angles the influence of the Weissenberg effect on the melt particles in the immediate vicinity of the rotating cone is sufficiently great and the flow produced by it is directed from the periphery toward the center. As the angles ε increase the influence of the Weissenberg effect on the melt particles in the zone of the moving cone remains as before and the flow produced by it has the same direction. At the same time, for the melt particles located near the stationary disk the circular velocity is decreased thanks to retardation in the layers of the melt owing to forces of viscous friction, which in turn reduces the influence of the Weissenberg effect and slows the flow. However the radial pressure gradient which develops in the process of motion of the melt and increases from the periphery to the center of the disk remains constant over the height of the gap and positive in the direction of flow, as a result of which radial flows develop near the stationary disk directed from the center to the periphery.

Experimental studies were made of the stability of the flow of polymer melts. It was found that the fully developed laminar flow is stable in the range of rotation velocities of the cone studied (for $\gamma = 2\text{-}400$ $\sec^{-1}$). This is apparently explained by the rather high viscosity of the melts. Nevertheless the laminar flow can break down, producing a "starved" process of supply of the working gap. In this case quasi-turbulent flow develops (Fig. 4) whose nature is identical to that shown in Fig. 2. At the periphery of the working gap the continuous flow is replaced by bundles of melt which are the means of supply to the central zone in which the laminar flow is preserved.

A detailed study of the mode of processing of polymers represented in Fig. 4 showed that it has great significance for the mixing of polymers and compositions based on them to obtain a product of high quality. The composition based on a polymer is mixed intensively upon arriving in the gap in the form of bundles. The central zone, in which laminar flow is preserved and the melt completely fills the working gap, plays the role of a hydraulic valve which does not transmit into the molding head the volatile substances, moisture, etc. given off by the bundles. The latter are removed from the working gap through openings located in the peripheral zone. The studies showed that the achievement of the process described in a gap of conical or plane parallel configuration even without additional devices for mixing makes it possible to obtain high-quality compositions with very different contents of filler or dye.

When a stable process of "starved" supply is achieved the pattern of flow remains unchanged and the diameter of the central zone depends on the rate of drift, decreasing when the drift rate increases. Thus, the ratio of the dimensions of the zones of quasi-turbulent and laminar flow can be regulated through variation in the rotation rate of the cone (flat disk) and the size of the working gap. An increase in the rate of drifting deformation can lead to disruption of the laminar flow, i.e., to an unstable mode of operation. Therefore a stable supply has paramount importance for the operation of a disk extruder. Such supply can be accomplished by forced means, for example, using a worm feeder [10].

The analysis presented above shows that in rotating instruments of the cone–plane type and also of the plane–plane type secondary flows must develop independently of the size and configuration of the working gap, which indicates the state of complex stress in the polymer studied.

LITERATURE CITED

1. D. V. Sokh, Nature, 193, 4816 (1962).
2. W. H. Hoppmann and C. N. Baronett, ibid., 201, 1205 (1964).
3. H. Giesekus, Rheologica Acta, 4, No. 2, 85 (1965).
4. S. Middleman, Polymer Flow [Russian translation], Mir, Moscow (1971).
5. V. G. Litvinov, Gidroaéromekh. i Teoriya Uprugosti, No. 6, 44 (1967).
6. B. Maxwell and A. J. Scalora, Modern Plastics, No. 10, 107 (1959).
7. V. L. Kocherov, Yu. E. Lukach, É. A. Sporyagin, and L. A. Tsitsankina, Mekhan. Polim., No. 2, 351 (1972).
8. V. L. Kocherov and Yu. E. Lukach, Summaries of Reports of All-Union Scientific Technology Conference on Procedures and Apparatus for Production of Polymers and Methods and Instruments for Their Processing into Products [in Russian], MIKhM, Moscow (1970), p. 93.
9. V. L. Kocherov, Yu. E. Dukach, and É. A. Sporyagin, Technology and Organization of Production [in Russian], UkrNIINTI, Kiev (1971), No. 4, p. 104.
10. I. K. Yartsev, I. P. Knyaz'kin, and É. A. Sporyagin, Plastmassy, No. 9, 44 (1968).