Wall Normal Stresses and Die Swell Behavior of Viscoelastic Polymeric Melts in Flow Through Converging Ducts

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In recent years some theoretical studies which dealt with the flow of viscoelastic fluids through a converging channel bounded by two nonparallel planes (Kaloni, 1965a; Schümmer, 1968; Wissler, 1971) and through a conical duct (Kaloni, 1965b; Schümmer, 1967; Ramacharyulu, 1967) have been reported in the literature. Interestingly enough, these studies predict velocity profiles with superposed secondary circulatory motion. Unfortunately, however, little experimental study which supports such a theoretical prediction has been published. Adams et al. (1965) measured the stress-birefringent patterns for a viscoelastic polymer solution (12% polyisobutylene in decalin) flowing through a converging-diverging channel. These investigators showed quantitative stress distributions in a converging channel with no evidence of the existence of secondary circulatory motion.

From a practical point of view, on the other hand, a better understanding of the flow behavior of viscoelastic fluids, in particular, polymer melts, in converging ducts is very important to the polymer processing industry which is concerned with, for instance, the fiber spinning and film extrusion. It has long been known, also, to polymer processing engineers that the entrance geometry of an extrusion die plays an important role in maintaining stable operation and sometimes in increasing productivity.

Very recently, the author has measured wall normal stresses (sometimes referred to as wall-tap pressures) to better understand polymer melt flow in a converging channel bounded by two nonparallel planes and in a conical die. In view of the previous studies which were concerned with the wall normal stress measurements in straight circular tubes (Han et al., 1969; Han et al., 1971) and in straight rectangular ducts (Han, 1971a; 1971b), the results obtained in this study were quite unusual in both the distributions of wall normal stress and extrudate swell behavior. In this paper some of the results will be presented that seem worth reporting.

EXPERIMENT

The apparatus consists of an extruder, a reservoir section, and a die section. Polymer melt flows from an extruder into a reservoir section. From there, melt flows into the die section. The arrangement of these pieces of equipment is essentially the same as that described in a recent paper by Han (1971a).

In the present study, however, new dies were constructed. Figure 1 gives the detailed layout of the converging channel die having three pressure tap holes (0.099 cm in diameter and 0.508 cm in length) along the center line of the upper plane. Note that pressure transducers (Dynisco, Model PT422) were mounted perpendicular to the wall of the upper plane. Also, a conical die was used having a half-angle of 15°. According to Han (1972), the presence of pressure tap holes should not affect the wall pressure measurements insofar as polymer melt is concerned. It should be noted, however, that there can be substantial pressure-hole errors in the flow of polymer solutions over a certain range of concentration (Han and Kim, 1972).

Details of the experimental procedure of wall pressure measurements and the estimation of measurement errors are referred to in previous papers by the author (Han et al., 1969; Han, 1971b).

Materials used for the study were high density polyethylene (DMDJ 5140, Union Carbide Corp.) and polypropylene (Resin E115, Enjay Chemical Company). Extrusion temperature was 200°C. The volumetric flow rates were determined by collecting the extrudate samples over predetermined intervals of time.

RESULTS AND DISCUSSION

Figure 2 shows representative pressure distributions along the converging channel wall for high density polyethylene (HDPE) and polypropylene (PP) melts, respectively, at 200°C. Two things are worth noting in Figure 2. First, as the melt flows from the entrance to the exit of the die, wall pressures (more correctly stated, the total normal stresses perpendicular to the channel wall) go through a minimum. Second, in the case of polypropylene the minimum wall pressure at a low flow rate ($Q = 14.2$ cc/min) is seen to lie below the ambient atmospheric pres-

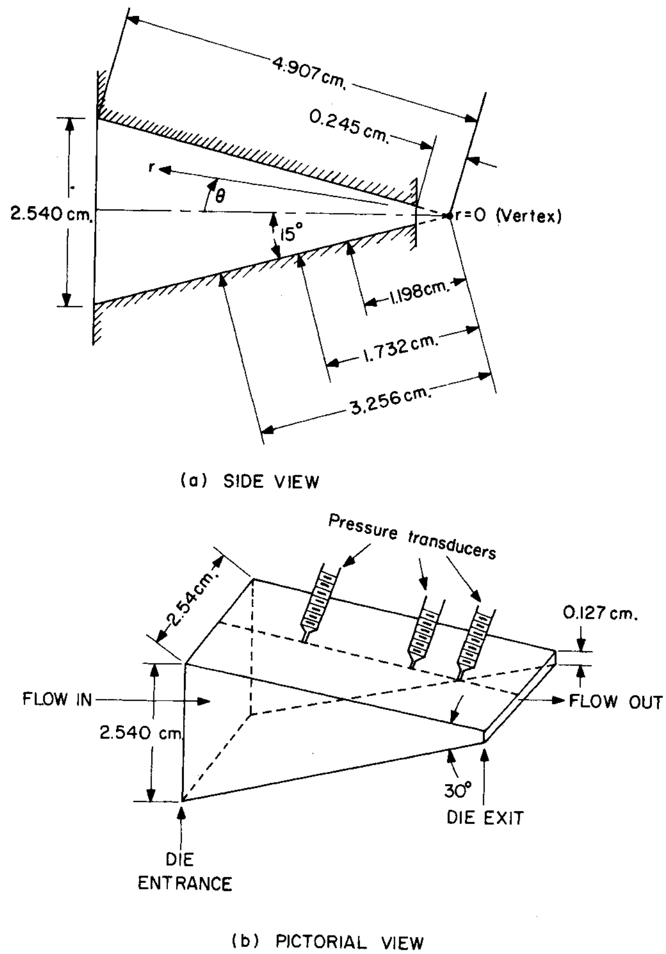

Fig. 1. Details of the converging channel die design: (a) side view; (b) pictorial view.

sure! (Note that 1 atm. = 1.033 Kg/cm²). The two interesting observations presented above were speculated on earlier by Metzner et al. (1968).

It should be noted, however, that there are some important differences between the present study and the work of Metzner et al. (1968). Namely, the latter measured local velocities of a viscoelastic polymeric solution (0.5% Separan AP30) in flow from a large reservoir into a small tube and then presented an analysis, with some simplifying assumptions, predicting that the profile of isotropic pressure $-p$ along the axial distance would exhibit a minimum near the inlet to the small tube. On the other hand, the present study directly measured the θ-directed total normal stress $S_{\theta\theta}$ at the channel wall (see Figure 1a), which is related to the isotropic pressure by

$$S_{\theta\theta}(r, \theta = \alpha) = -p(r, \theta = \alpha) + \tau_{\theta\theta}(r, \theta = \alpha) \quad (1)$$

in which α is the half-angle of the channel and $\tau_{\theta\theta}$ is the deviatoric stress component.

Strange though they may look at a first glance, the profiles of wall normal stress given in Figure 2 can be explained with the following consideration. It is a well-established fact that the wall normal stress decreases as a melt flows through a duct of uniform cross section (Han et al., 1969; 1971; Han, 1971a; 1971b). Therefore, although the cross section of the converging channel changes from the die entrance, there would be a region in the die which is still influenced by the upstream flow regime which gives rise to a gradual drop in pressure. Now, as the melt flows further into the channel, it will reach another region where the fluid gets rapidly accelerated, giving rise to an increase in wall pressure.

Based on the reasoning given above, one may surmise

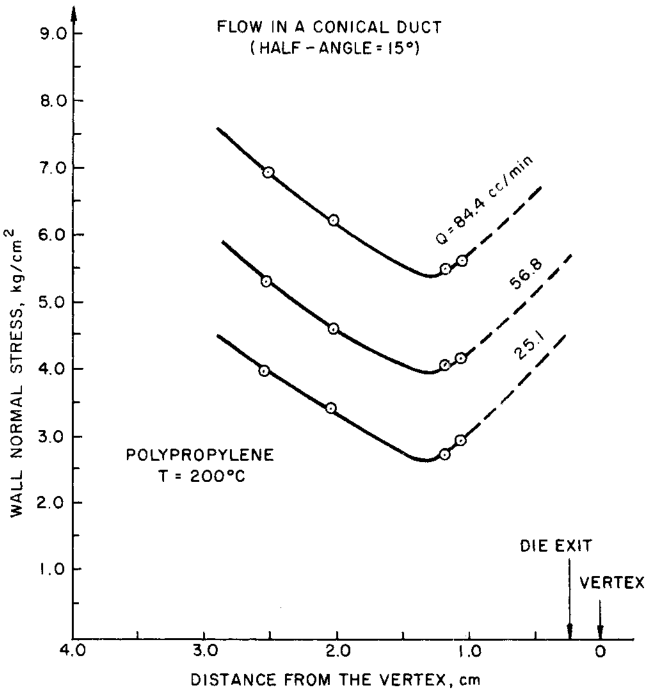

Fig. 3. Plots of wall normal stress distributions of polypropylene melts in the conical duct having a half-angle of 15° (T = 200°C).

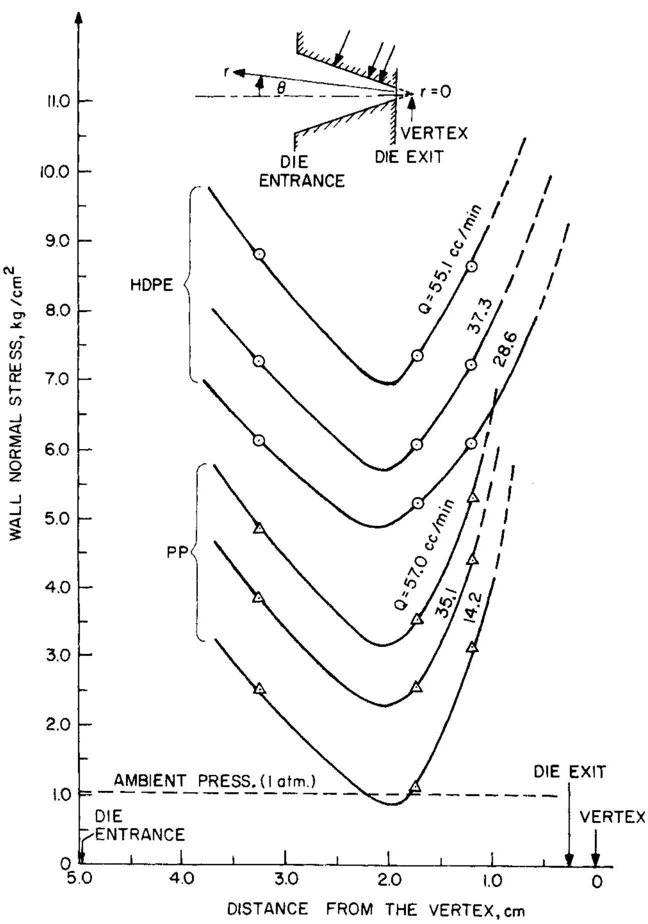

Fig. 2. Plot of wall normal stress distributions of high density polyethylene and polypropylene melts along the center line of the upper plane of the converging channel (T = 200°C).

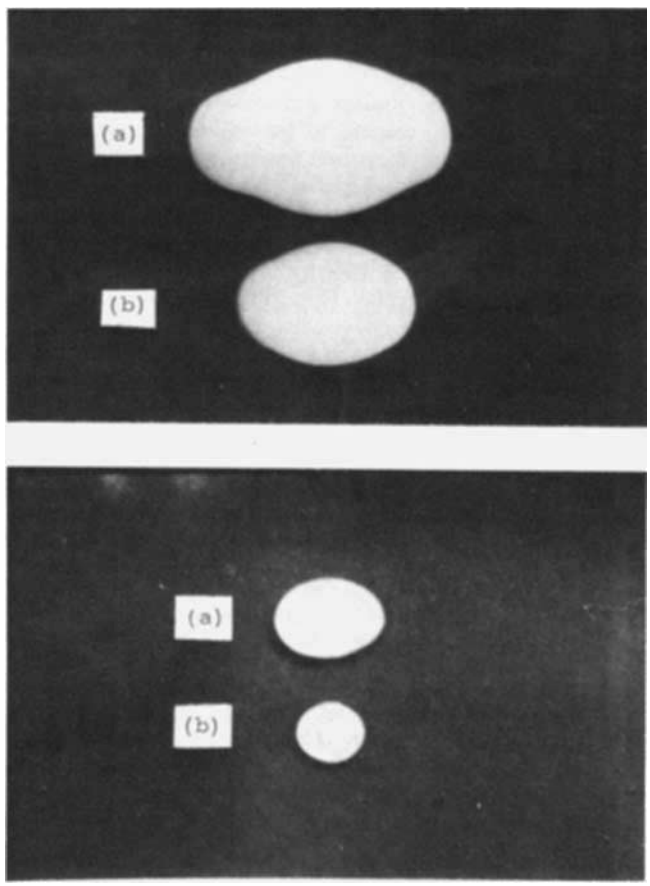

Fig. 4. Extrudate swell behavior from the converging channel: (top) high density polyethylene, (a) at Q = 55.1 cc/min.; (b) at Q = 28.6 cc/min.; (bottom) polypropylene, (a) at Q = 57.0 cc/min.; and (b) at Q = 14.2 cc/min.

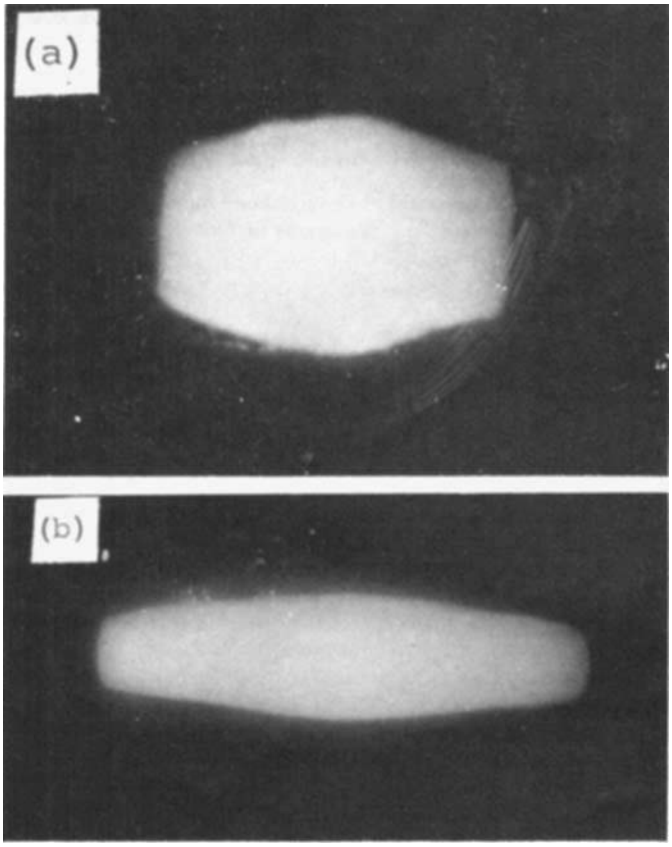

Fig. 5. Extrudate swell behavior from rectangular ducts of uniform cross sections: (a) polypropylene at Q = 41.3 cc/min.; (b) polystyrene at Q = 41.4 cc/min.

that both the position where the minimum wall pressure occurs and the values of the pressure gradients will depend on the viscous and elastic properties and also on the velocity of the fluid. It is seen also in Figure 2 that the polypropylene melts have higher pressure gradients in the accelerative flow field than polyethylene melts over the range of flow rates investigated. This can be attributed to the more elastic nature of polypropylene melts compared to polyethylene melts.

Figure 3 gives representative pressure distributions for polypropylene at 200°C in the conical die having a half-angle of 15°. It is seen that, as the melt flows from the entrance to the exit of the die, wall normal stresses first decrease and then increase. This increase in wall normal stress near the die exit is attributed to a rapid acceleration of the melt. Note that the distributions of wall normal stress observed in the conical die is very much the same as those observed in the converging channel. Space limitation does not permit us to present other results here.

Another very unusual observation made in the present study was the swelling behavior of extrudate from the converging channel. Figure 4 shows photographs of the extrudate cross section of high density polyethylene (top) and polypropylene (bottom) melts at 200°C. What is most interesting in these pictures is the roundedness of the extrudate cross section.

In order to offer explanations for the observed extrudate cross section in Figure 4 let us, for comparison purposes, look at the swelling behavior of extrudates from straight rectangular ducts of uniform cross section. Figure 5 shows photographs of the extrudate cross section of polypropylene melts (top) at 200°C, extruded through a rectangular duct of an aspect ratio of 2 (width = 1.016 cm, thickness = 0.508 cm, length = 5.791 cm), and polystyrene melts (bottom) at 200°C, extruded through a rectangular duct of an aspect ratio of 6 (width = 1.524 cm, thickness = 0.254 cm, length = 15.240 cm). It is seen in Figure 5 that the extrudates swell most at the center of the long side of the rectangle. An explanation for it has been advanced in a previous paper by Han (1971b), who then measured distributions of wall normal stresses also, on both the long side and short side of a rectangular duct of an aspect ratio of 6.

Now then, we can attribute the unusual swell behavior of extrudate from a converging channel to the fact that, as the melt approaches the die exit, wall normal stresses are more rapidly changing on the short side than on the long side of the cross section. This is because in flow through a converging channel the short side of the cross section decreases continuously along the flow direction whereas the long side of the cross section is kept constant (See Figure 1b). Furthermore, as may be seen in Figure 2, as the melt approaches the die exit the wall normal stresses increase very rapidly which in turn implies a very rapid buildup of elastic energy in the melt. The stored elastic energy, upon exiting from the die, will become recoverable, giving rise to extrudate swell. Therefore it can be said that the shape of extrudate cross section in Figure 4 represents the distribution of the elastic energy density at the exit plane of the die.

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