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NOTE

Initial Results of a Flow Birefringence Study of the Hole Pressure for Polymer Melts

INTRODUCTION

The hole pressure (P_H) is defined for flow through a channel as the difference between the pressure measured by means of a transducer mounted flush with the die wall and the pressure measured at the same position but by a transducer mounted at the base of a fluid-filled hole (i.e., P_H is the difference of the pressures measured by transducers T_1 and T_2 in Fig. 1). P_H is of great practical interest because of its apparently simple linear relation to the primary normal stress difference N_1.[1-4] For flow over a rectangular slot placed transverse to the flow direction, the theory of Higashitani and Pritchard (HP)[5] predicts the following relationship between P_H, N_1, and the shear stress σ:

$$P_H = \int_0^{\sigma_w} \left(\frac{N_1}{2\sigma}\right) d\sigma, \tag{1}$$

where σ_w is the wall shear stress. This expression can be differentiated to yield a method for obtaining N_1 directly from P_H and σ_w data as follows:[6]

$$N_1 = 2\sigma_w \left(\frac{\partial P_H}{\partial \sigma_w}\right). \tag{2}$$

Remarkably good agreement has been found between the experimental data and Eqs. (1) and (2) for several polymer solutions[1,6] and Eq. (1) for two polyethylene melts.[4]

In spite of the agreement between the HP theory and experimental data, Han and Yoo[7] have criticized the use of this method for obtaining N_1 from P_H data for polymer melts because of the violation of several key assumptions in the HP theory. In particular, they reported that the stress and flow fields are not symmetric about the slot centerline and that secondary motion in the hole is not negligible. In light of this controversy over the use of HP theory to obtain N_1 from P_H measurements for polymer melts, we have undertaken a

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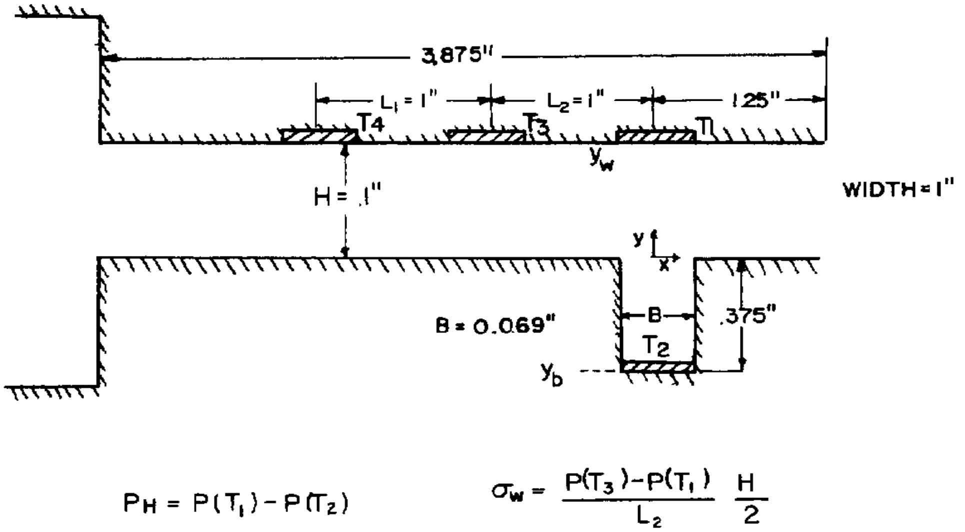

Fig. 1. Schematic diagram of slit showing the pressure transducer arrangement for the determination of the hole pressure and viscosity.

study using flow birefringence to evaluate quantitatively the factors which affect stress field asymmetry and to determine the effects of stress field asymmetry and fluid motion in the hole on the magnitude of P_H and on the validity of the HP theory. In this note we present some of our initial results on a polystyrene melt in which P_H is obtained from direct measurements, from the HP theory [Eq. (1)] evaluated with both flow birefringence and cone-and-plate data, and from an indirect method using flow birefringence which is referred to as the shear difference method.

EXPERIMENTAL

A schematic drawing of the apparatus is shown in Figure 2 and consists of two major components: the slit die with associated polymer pumping equipment and the apparatus for obtaining flow birefringence measurements. The slit die was machined from 316 stainless steel and has the dimensions shown in Figure 1. Three strain gauge pressure transducers (Dynisco PT422A) were mounted flush with the upper wall in order to generate wall shear stress data. A fourth transducer was mounted at the base of a rectangular slot placed perpendicular to the flow direction. This slot was machined into a removable block so that slots with various dimensions could be

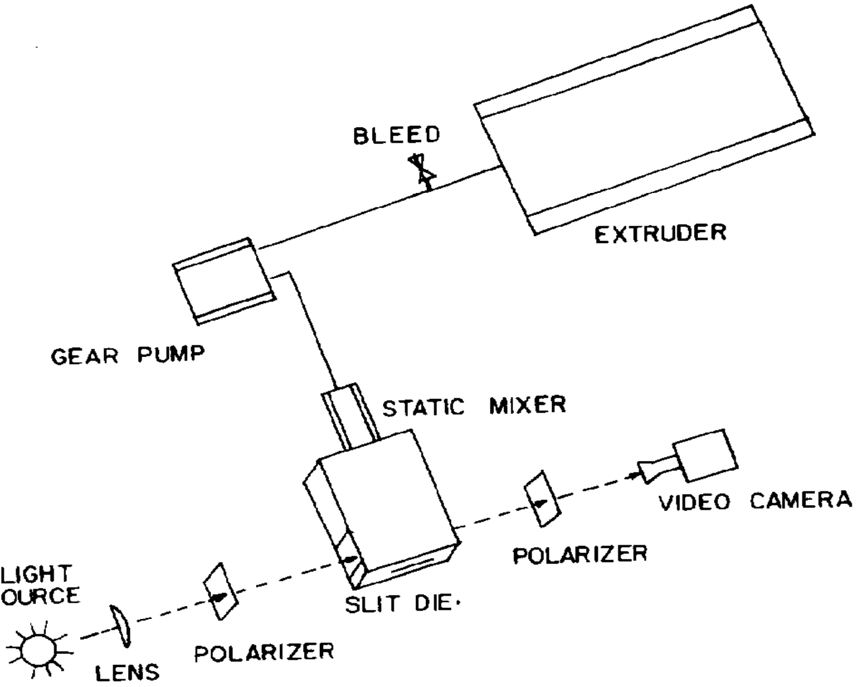

Fig. 2 Schematic diagram of the apparatus used for the flow birefringence study of the hole pressure.

used. Quartz windows were mounted in the die in the region of this slot for flow birefringence studies. The transducers were accurately calibrated in the die at normal operating temperature by sealing the end of the die and pressurizing the die with a dead-weight tester (Chandler Engineering, #23-1). By using this calibration procedure and recording the transducer output on a chart recorder, pressures could be measured with an accuracy of ± 2.5 kPa. The die was insulated by encasing it in a box of 1.9-cm-thick alumina–silica fiber board. The die melt temperature was controlled to within ± 0.5°C by five independently controlled sets of cartridge heaters, including one set inserted in a metal plate bolted to the die exit. The melt temperature uniformity was determined by a thermocouple probe inserted into the slit. Polymer melt was pumped to the die by a Zenith gear pump (HPB 5556,0.16 cm^3/rev) which was fed by a 1-in. Killion extruder. A Kenics ISG motionless mixer placed before the die ensured a uniform temperature distribution in the entering melt.

The apparatus for obtaining the flow birefringence measurements is shown schematically in Figure 2. The isochromatics (lines of constant principal stress difference) were obtained by means of circularly polarized monochromatic light of 632.8-nm wavelength produced by a helium–neon laser (Spectra-Physics model 155). Isoclinics (lines of constant principal stress direction) were determined using plane-polarized white light. Birefringence patterns were recorded via a video camera on a video tape recorder. A more detailed description of this procedure and the birefringence method is presented elsewhere.[8]

P_H was obtained directly by subtracting the pressure recorded by T_2 from that recorded by T_1. Values of P_H were then corrected for misalignment of transducers T_1 and T_2 by measuring P_H generated by a polymer melt (nylon 6) which exhibited negligible normal stresses. Hole pressure measurements using the inelastic melt at low Reynolds numbers should yield negligible values of P_H. When misalignment exists, the measured values of P_H for the nylon 6 melt increase linearly with the pressure gradient, allowing one to calculate the magnitude of the misalignment.[8]

The present measurements were carried out at 190°C using a polystyrene melt (Dow Styron 678). Rheological properties are presented in Figure 3, including viscosity data generated by means of the slit die using well-known methods.[11] Steady shear and dynam-

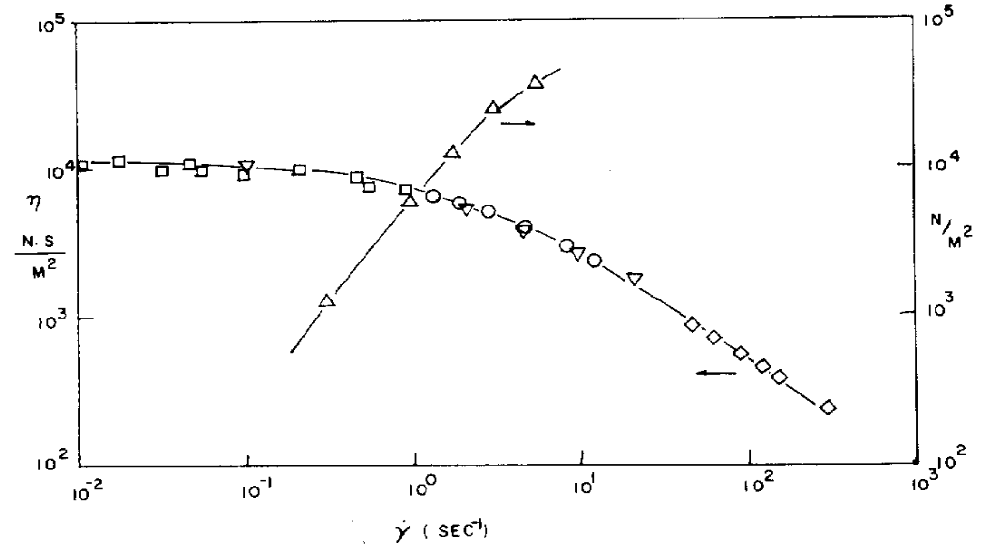

Fig. 3 Rheological properties of Styron 678 at 190°C, including viscosity data generated in the slit die: (△, □) cone-and-plate steady shear, (○) slit die data, (▽) dynamic, (◇) Instron.

ic measurements were carried out in a cone-and-plate device (Rheometrics mechanical spectrometer, model 605), while capillary data were obtained using an Instron capillary rheometer. An inelastic nylon 6 melt (Allied LSB) was used to generate P_H data at 270°C for determining the degree of transducer misalignment. Values of N_1 for this fluid were not observed until a shear rate of 100 s^{-1}, which is above the present experimental conditions and presumably negligible values of P_H would be measured.

RESULTS AND DISCUSSION

In order to provide some confidence in the calibration of the pressure transducers, viscosity values for the polystyrene melt obtained from slit die pressure measurements are compared in Figure 3 with viscosity values obtained by means of the cone-and-plate and capillary rheometers. The excellent agreement observed for the three methods indicates that an accurate measurement of fluid pressure in the die is being obtained, although it is recognized[4] that even small errors in pressure measurements can result in large errors in the measured values of P_H.

Values of σ and N_1 were obtained in the region of the slot using flow birefringence data and the well-known stress-optic law.[9] A representative distribution of values of σ and N_1 across the slot for a constant value of y ($y/H = 0.2$) is presented in Figure 4. Here it is observed that both the shear stress and N_1 are asymmetrically distributed about the slot centerline. The shear stress distribution in Figure 4 agrees qualitatively with the distribution obtained by Arai[10] for a polyethylene melt.

In Figure 5, values of P_H obtained from the HP theory [Eq. (1)] evaluated using both flow birefringence and cone-and-plate data are compared with values of P_H obtained from corrected direct measurements. It is observed that, in spite of the stress field asymmetry, excellent agreement is found between direct P_H measurements and P_H predicted by Eq. (1) evaluated using both cone-and-plate and birefringence data. By substituting a relationship between N_1 and σ of the form $N_1 = a\sigma^n$ (a and n are constants), Eq. (1) was evaluated directly to give the following simple relationship between P_H and N_1:

$$P_H = 0.286 N_1 \qquad (3)$$

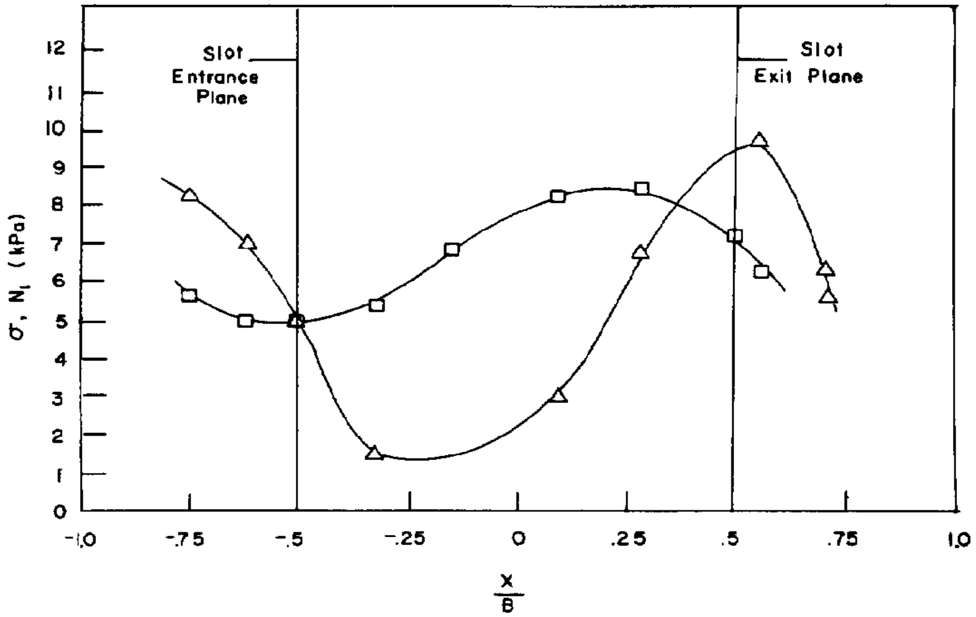

Fig. 4 Distribution of shear stress and primary normal stress difference values across the slot region for Styron 678 at 190°C, a shear rate $\dot{\gamma}$ of 2.14 s^{-1}, and width $y/H = 0.2$: (△) N_1, (□) σ.

P_H was also calculated using flow birefringence data and the so-called shear difference method. From the equation of motion one can derive the following shear difference equation:[10]

$$P_H = \frac{1}{B}\int_{y_b}^{y_w}(\sigma_{\text{ex}} - \sigma_{\text{ent}})dy, \tag{4}$$

where y_w, y_b, and B are defined in Figure 1. σ_{ex} and σ_{ent} are the shear stress values evaluated along the slot exit and entrance planes, respectively, and are determined from flow birefringence data. Therefore, P_H is obtained from Eq. (4) by determining the values of σ along the two planes defined by the two vertical slot walls and integrating the difference $\sigma_{\text{ex}} - \sigma_{\text{ent}}$ from the bottom of the slot to the opposite slit wall. Values of P_H calculated from Eq. (4) are also presented in Figure 5 and are found to lie below the values of P_H determined from the other methods. This disagreement is believed to be a result of the difficulty in accurately obtaining the shear differences ($\sigma_{\text{ex}} - \sigma_{\text{ent}}$) in the regions near the sharp corners of the slot, where the stress gradients vary rapidly in the areas both above

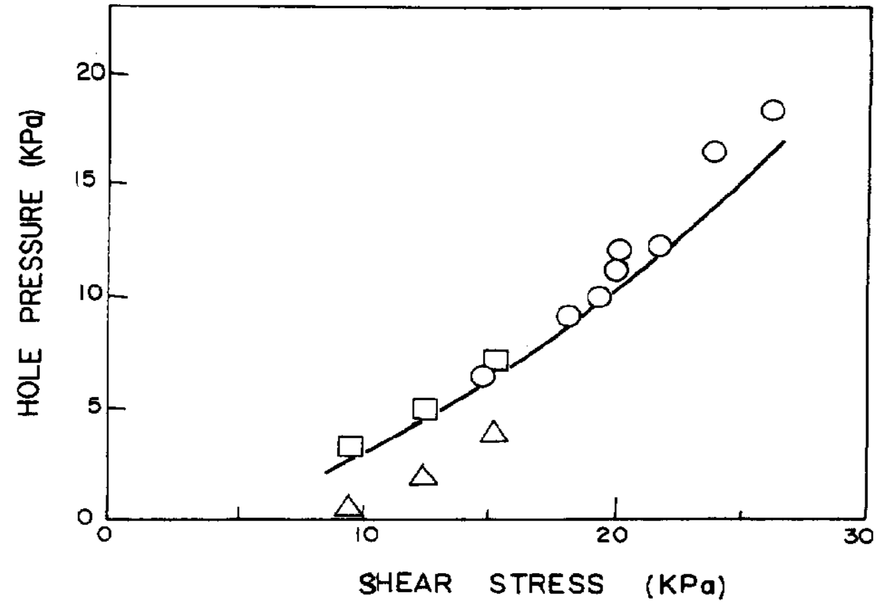

Fig. 5 Comparison of hole pressure values obtained from the (□) HP theory with birefringence data, (—) HP theory with cone-and-plate data, (○) direct transducer measurements, and the (△) shear difference equation for Styron 678 at 190°C.

and below the corners of the slot. Since the shear differences evaluated near the corners of the hole contribute as much as 50% to the value of P_H calculated from Eq. (4), errors in these values of $\sigma_{ex} - \sigma_{ent}$ will result in a large error in the calculated value of P_H. Arai[10] found similar disagreement between the values of P_H obtained from Eq. (4) and values of P_H obtained from the HP theory [Eq. (1)] for two polymer melts. However, it is likely that his analysis was subject to the same difficulty described above. In addition, he found that the shear differences evaluated inside the slot provide a negligible contribution to P_H obtained from Eq. (4), while our results indicate they may contribute as much as 20% to this value of P_H. Further studies of the shear difference method must be completed before any definitive conclusions can be drawn concerning the disagreement of this method with the other methods of determining P_H.

Finally, we compare in Figure 6 values of N_1 obtained from Eq. (2) evaluated using directly measured values of P_H and σ_w with measurements of N_1 obtained from the cone and plate. Again, excellent agreement between theory and experiment are found.

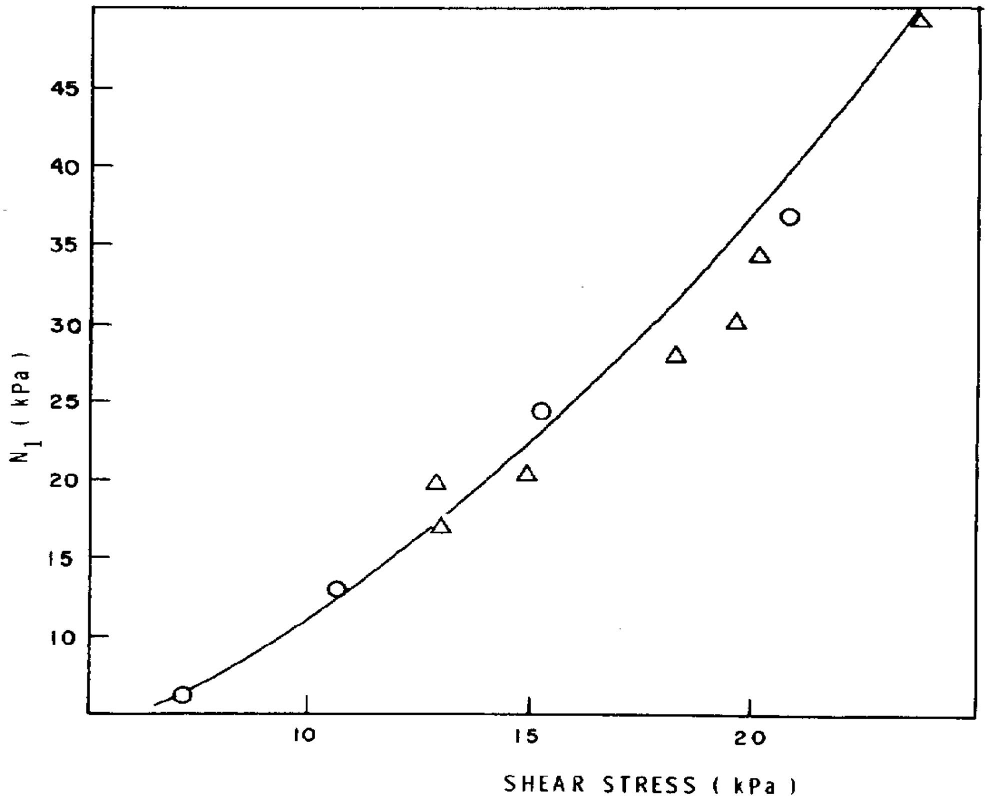

Fig. 6 Comparison of primary normal stress difference values for Styron 678 at 190°C obtained from the HP theory and (○) corrected hole pressure data with values obtained from cone-and-plate measurements, $N_1 = 2\sigma\ (dP_H/d\sigma)$.

CONCLUDING REMARKS

The initial results of this study on a polymer melt shows that, for the present experimental conditions, stress field asymmetry has a negligible effect on the validity of the HP theory and that the theory may be extended to yield a method [i.e., Eq. (2)] by which values of N_1 may be calculated directly and accurately from slit die P_H and σ_w data. Additional work is needed, however, to determine the range of conditions for which this is true. Current research efforts are being directed toward determining the effects of slot dimensions, rounding of slot corners, and melt rheological properties on stress asymmetry and the corresponding effect on the magnitude of P_H and the predictions of the HP theory.

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