SINGLE-SCREW EXTRUDER
EXPERIMENT

1. Introduction.

Extrusion is a widely used method of forming certain polymeric materials into useful shapes. Extrusion involves transport and melting of the feed and pressure build-up and transport of the melt. It is applied to thermoplastic polymers: those which deform when heated and resume their earlier "no-flow" properties when cooled.

The material, usually in the form of small pellets about 5 to 10 mm in size, is fed from a hopper by gravity into the extruder. The extruder is comprised of a hollow chamber with heating zones outside and a threaded shaft (the screw) which can rotate along the center-line inside. The shaft is narrow at the feeder end with the diameter increasing along the length, reaching its maximum near the other end and tapering off at the extruder tip [see Fig 1]. In addition to the changing diameter, screw flights also change along the length of the shaft. The extruder is designed to: (a) ensure steady transport from the feeder to the melting zone; (b) allow for reduction in volume occurring as the pellets melt; (c) build up pressure; and finally, (d) transport the melt through the die attached to the extruder tip. Dies for extrusion are designed to produce the final desired form of the polymer. Depending on the desired shape and number of layers of extrudate required, dies can be machined into complicated shapes. For this experiment, the die is a simple cylindrical tube (Fig. 2).

The behavior of a polymer melt changes with the operating conditions, namely, shear rate, temperature and pressure. The fluid viscosity is not constant, but varies with the shear rate as well as with temperature. This property is important in terms of processing and design. References on fundamentals of viscoelastic behavior are Transport Phenomena by Bird, Stewart, and Lightfoot (ch. 2-3) and Process Fluid Mechanics by Denn (ch. 2, 8, 19), as well as any ChE Polymers textbook.

2. Theory.

For a non-Newtonian, viscoelastic fluid, the shear stress is a function of the shear rate, and viscosity is dependent on both temperature and shear rate. Several models exist which are applicable to such fluids. The flow behavior of polymer melts is sometimes described by a Power Law model, which in cylindrical coordinates is:

\[ \tau_{rs} = -m \frac{dV_r}{d\gamma} \frac{dV_s}{d\gamma} \]  

(1)
The model contains two empirical constants, \( m \), the modulus of viscosity, and \( n \), the Power Law index. The above relation holds for a given temperature. The parameter \( m \) is a strong function of temperature. The parameter \( n \) may vary with temperature. The parameters can also vary with shear rate, and for the range of shear rates developed in this experiment they may not be true constants. Note that for \( n=1 \), the Power Law model reduces to Newton's Law where \( m \) is exactly the same as the viscosity of the fluid.

### 3. Assignment

For this experiment, a typical thermoplastic polymer such as polypropylene (PP), low-density polyethylene (LDPE), or linear low-density polyethylene (LLDPE) is used. The operating temperature for the die and zone temperatures (zone 1 and zone 2) of the extruder depend on the material. Typical die temperatures are: PP, 180-220°C; LDPE, 150-210°C; LLDPE, 170-210°C. The zone 1 temperature should be 5-20°C above the polymer melting temperature; zone 2 temperature is set between zone 1 and the die temperatures. Melting points and other properties for LDPE, PP, or LLDPE can be found in Modern Plastics Encyclopedia, Polymer Handbook (3rd ed., Brandrup and Immergut, 1989, or earlier editions), or any standard handbook on polymers.

**Part I**

Determine the values of \( m \) and \( n \) that best characterize the material. Given the above discussion, \( n \) may be a constant (determine yes/no), and \( m \) a function of temperature. Assuming that the extruder near the die may be approximated as a cylinder of uniform radius \( R \), and the polymer melt maintains a constant fluid density, a differential momentum balance yields Eq. 2:

\[
Q = \left( \frac{m n R^2}{1 + 3 n} \right) \left( \frac{\Delta P}{2 m L} \right)^{\frac{1}{n}}
\]

\( Q \) is the volumetric flow rate of extrudate, \( L \) the length of the die, and \( P \) the pressure drop in the die. Derive this relationship beginning with a differential balance written in cylindrical coordinates (HINT: consult Ch. 2 of Transport Phenomena or Ch. 8 of Process Fluid Mechanics). Show how the shear stress and shear rate at the wall arise naturally in the derivation, and how shear stress is independent of the constitutive equation of the fluid.

The data you collect should consist of volumetric flow rates and die pressure drop for varying values of die temperature (at least 4 different \( T \)’s) and screw RPM (from the lowest measurable RPM to the highest). You should critically examine your data to see how well they are fitted by the power-law model, and whether portions of the data are in fact even consistent with the model. Major deviations from the model should be explained. You should also compare your results to results for a similar polymer from the vast literature on polymer rheology.

**Part II**
Another aspect of the experiment is to examine the flow/displacement behavior of the screw extruder. The amount of polymer melt delivered per rotation (the flow rate $Q$) varies with the operating conditions; the screw does not function as a constant discharge device. Using $Q$ vs. screw RPM data, this relationship can be examined. Since the polymer is virtually incompressible, a deviation from the correct relationship will provide a measure of the degree of slippage and back-mixing in the extruder. Explain why the amount of slippage varies in the manner observed.

**Part III**

Compare the diameter of the extrudate with the die diameter (the ratio is the "die swell ratio") at the lowest temperature you use. Is there correlation between operating conditions (e.g., shear stress at wall) and the *die swell ratio*? Does the character (shape, texture) of the extrudate change at high shear rates? What do you think are the reasons for these changes, if any? Consulting ch. 19 of *Process Fluid Mechanics* may be useful.

![Diagram of the die with dimensions and a pressure transducer](image)
Fig. 4 Schematic of the extruder assembly