Single-Screw Extrusion
THE EXTRUDER CHARACTERISTIC
A. W. Birley, B. Haworth and J. Batchelor, Physics of Plastics:
Processing, Properties and Materials Engineering, Hanser
(on reserve in Deike Library)

Figure 1: Definitions of Symbols

Barrel Diameter $D = 2R$
Screw Helix Angle $\theta$
Screw Pitch $B + b$
Screw Rotation Speed $N$ (RPM)

Channel Depth $H = R - R_i$
Screw Clearance $h = R - R_o$
Channel Width $W$
Flight Width $w$
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DRAG FLOW — the Couette flow between the rotating screw and the stationary barrel

![Figure 2: Drag Flow Mechanism](image)

**Down Channel Velocity Component**

\[ V_z = V \cos \theta \]  \hspace{1cm} (4.1)

**Volumetric Flow Rate from Drag**

\[ Q_D = W \int_0^H v(y) dy \]  \hspace{1cm} (4.2)

For a Newtonian fluid, the velocity profile is linear:

\[ v(y) = V_z \frac{y}{H} \]

\[ Q_D = \frac{W V_z}{H} \int_0^H y dy = \frac{W V_z H^2}{2} = \frac{W V_z H}{2} \]  \hspace{1cm} (4.3)
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Figure 3: Unrolled Single Turn of the Extruder Screw Helix

The tangential velocity at the barrel surface is determined from the rotation speed of the screw:

\[ V = \pi DN \]  \hspace{1cm} (4.4)

Down Channel Velocity Component \[ V_z = \pi DN \cos \theta \]  \hspace{1cm} (4.5)

\[ Q_D = \frac{\pi}{2} WHDN \cos \theta \equiv \alpha N \]  \hspace{1cm} (4.6)

The drag flow effectively pumps the polymer through the extruder. 
\( Q_D \) is proportional to the rotation speed \( N \).
Proportionality constant \( \alpha \) only depends on screw geometry.
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PRESSURE FLOW — the Poiseuille flow suppressing flow through the extruder

Extruders usually have some FLOW RESTRICTION (like a die) at the end of the extruder. This creates a pressure gradient along the screw that works against the flow through the screw:

\[ Q_P = -\frac{WH^3 \Delta P}{12\mu L} \equiv -\frac{\beta}{\mu} \Delta P \]  \hspace{1cm} (4.7)

Again, the proportionality constant \( \beta \) only depends on screw geometry.

The NET VOLUMETRIC FLOW RATE is the sum:

\[ Q = Q_D + Q_P \]  \hspace{1cm} (4.8)

Example 1: OPEN DISCHARGE
No flow restriction at the end of the extruder (remove die)

\[ Q_P = 0 \quad \text{and} \quad Q = Q_D \]

Example 2: CLOSED DISCHARGE
No flow out of the extruder (plug die)

\[ Q = 0 \quad , \quad Q_P = Q_D \quad \text{and} \quad \Delta P = \alpha \mu N / \beta \]
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In general the die restricts the flow somewhat, but not completely. Combining equations 4.6, 4.7, and 4.8, we get the EXTRUDER CHARACTERISTIC:

\[ Q = \alpha N - \frac{\beta}{\mu} \Delta P \]  

(4.13)

Figure 4: The Extruder Characteristic for a Newtonian Fluid is a linear relation between \( Q \) and \( \Delta P \).

- y-axis intercept ⇒ OPEN DISCHARGE (\( \Delta P = 0 \))
- x-axis intercept ⇒ CLOSED DISCHARGE (\( Q = 0 \))

More Flow Restriction ⇒
Larger Pressure (larger \( \Delta P \)) ⇒
Smaller Throughput (lower \( Q \))
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THE DIE CHARACTERISTIC

There is a simple relation between pressure drop and volumetric flow rate in the die.

\[ Q = K \frac{\Delta P}{\mu} \]  \hspace{1cm} (4.21)

Circular Die: \[ K = \frac{\pi R^4}{8L} \]  Hagen-Poiseuille Law

Slit Die: \[ K = \frac{WH^3}{12L} \]

Figure 5: The Operating Point is the Intersection of the Extruder Characteristic and the Die Characteristic.
Figure 6: (a) Effect of Screw Speed \( (N_3 > N_2 > N_1) \).
(b) Effect of Screw Channel Depth \( (H_1 > H_2) \)
and Metering Section Length \( (L_2 > L_1) \).
(c) Effect of Die Radius \( (R_2 > R_1) \).
(d) Effect of Viscosity \( (\eta_2 > \eta_1) \).