The University of Nottingham

Polymer Engineering

(MM3POE)

MELT RHEOLOGY & PROCESSING

http://www.nottingham.ac.uk/~eazacl/MM3POE

Contents

- Introduction to polymer processing
  - *Basic principles*
  - *Common manufacturing methods*
- General properties of polymer melts
- Flow properties
  - *Power law fluid model*
  - *Temperature & pressure effects*
- Measurement of flow properties
- Melt flow calculations
  - *Pressure shear flow*
  - *Drag flow*
  - *Tensile flow*

1. Introduction

Principles of Polymer Processing:

1. Melting
2. Mixing & Homogenisation
3. Melt Transport
4. Primary Shaping
5. Secondary Shaping
6. Stabilisation of Shape
7. Finishing Operations

Manufacturing methods

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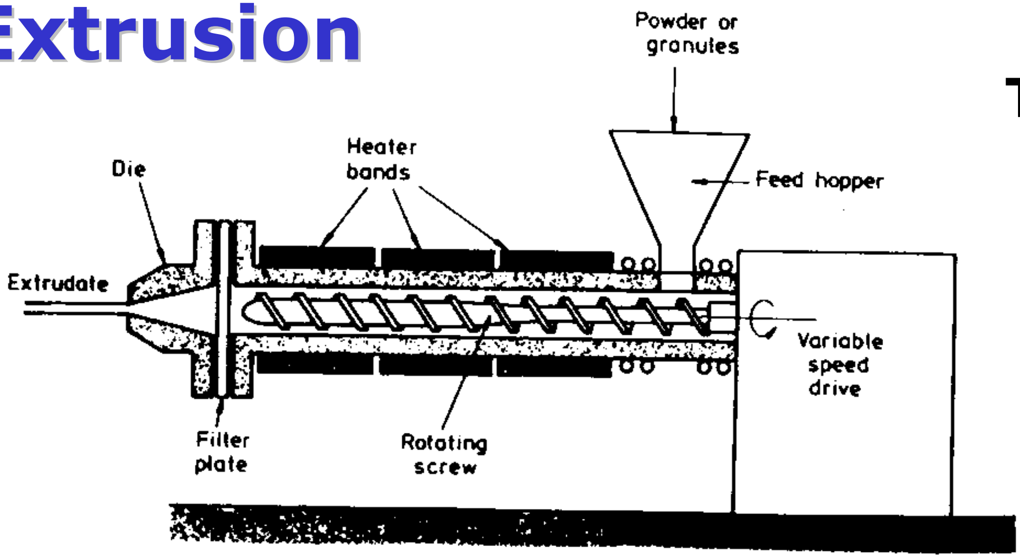
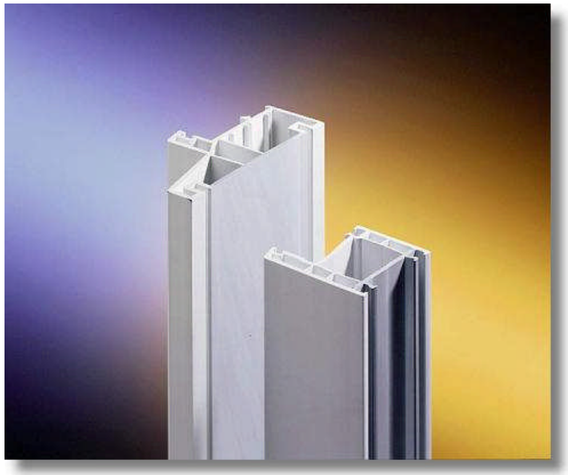
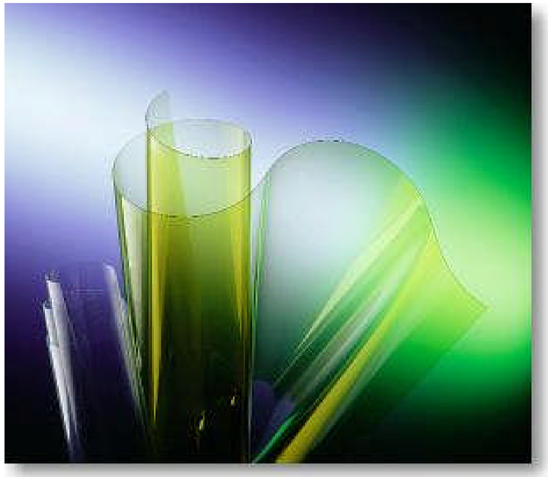
Extrusion



Typical products:

Pipes & tubes
Profiles (eg. window frames)
Seals and liners
Sheet/film
Insulation for cables

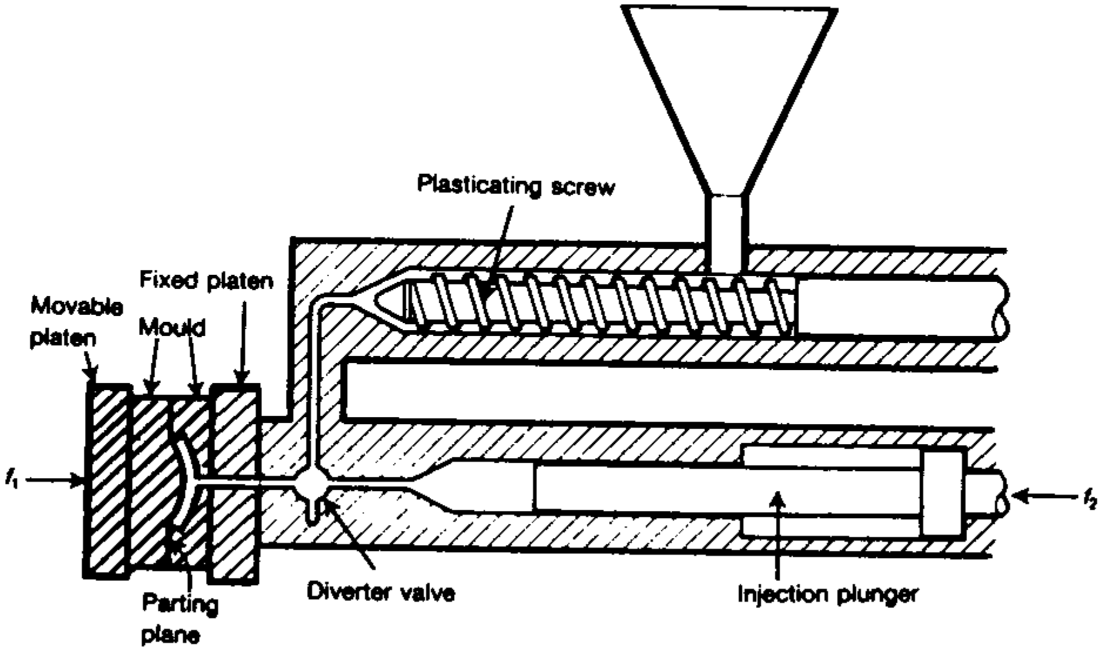




www.vuk.battenfeld.com

Manufacturing methods

Injection Moulding



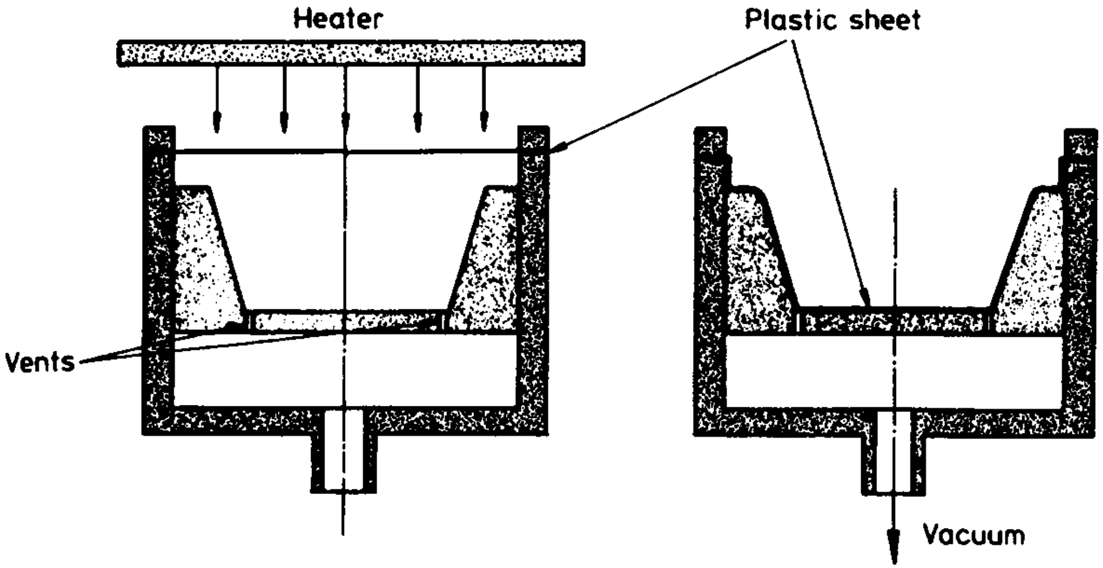
Typical products:

Automotive components
Power-tool housings
Safety helmets
Telephone handsets
Television cabinets
Washing-up bowls

www.bpf.co.uk

Animation from: www.bpf.co.uk

Thermoforming

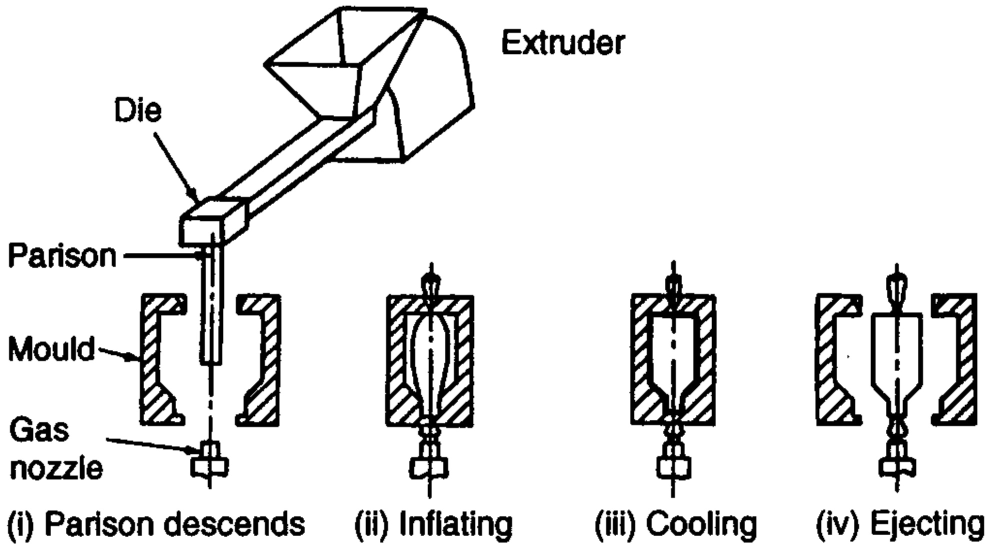


www.bpf.co.uk

Animation from:
www.bpf.co.uk

Manufacturing methods

Blow Moulding



www.plastics-car.com

Animation from:
www.bpf.co.uk

Manufacturing methods

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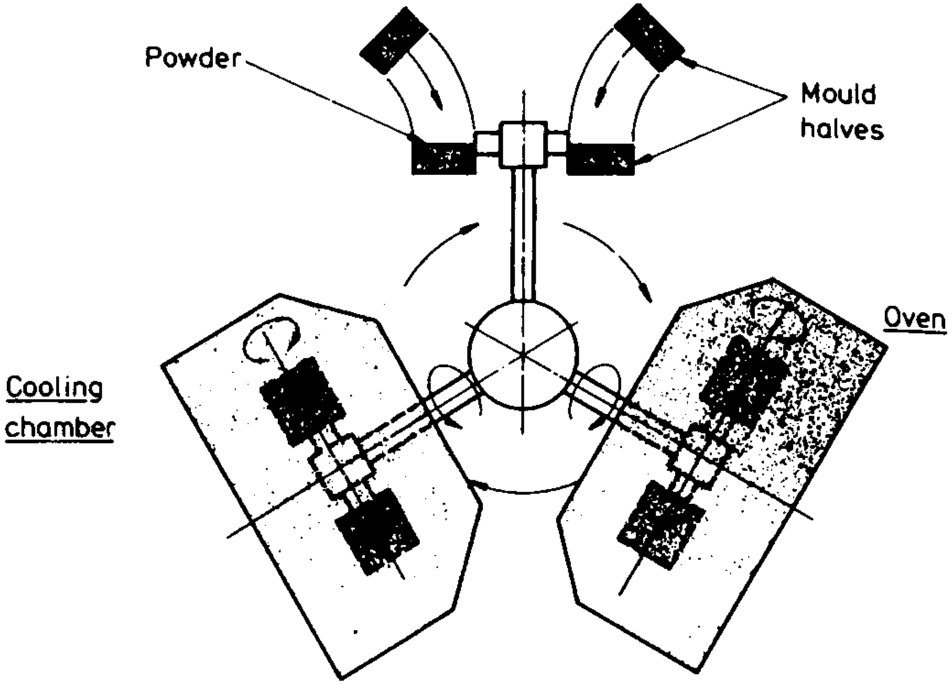
Rotational Moulding



www.bpf.co.uk

www.bbc.co.uk

Animation from: www.bpf.co.uk

2. Flow Properties of Polymer Melts

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General properties of polymer melts:

(i) Low density ($\rho \approx 10^3$ kg/m^3)

(ii) Low thermal conductivity ($K \approx 0.1$ W/mK)

(iii) High shear viscosities ($\eta \approx 10^2 - 10^4$ Ns/m^2)

(iv) NON-NEWTONIAN flow properties

(i) & (ii) $\Rightarrow$ low thermal diffusivity

$\alpha = K/\rho\, c_p \sim 10^{-7}$ m^2/s

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t}$$

Low $\alpha \Rightarrow$ long heating/cooling times ($\propto$ thickness^2)

(i) & (iii) $\Rightarrow$ laminar flow

$Re = \rho\, l\, u / \eta < 0.1$

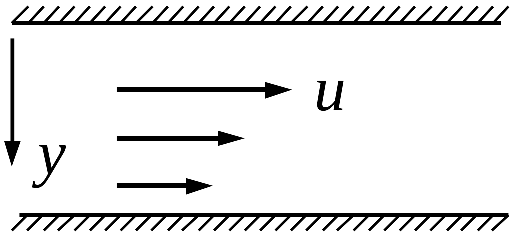
(water = 1000
critical ~ 2000)

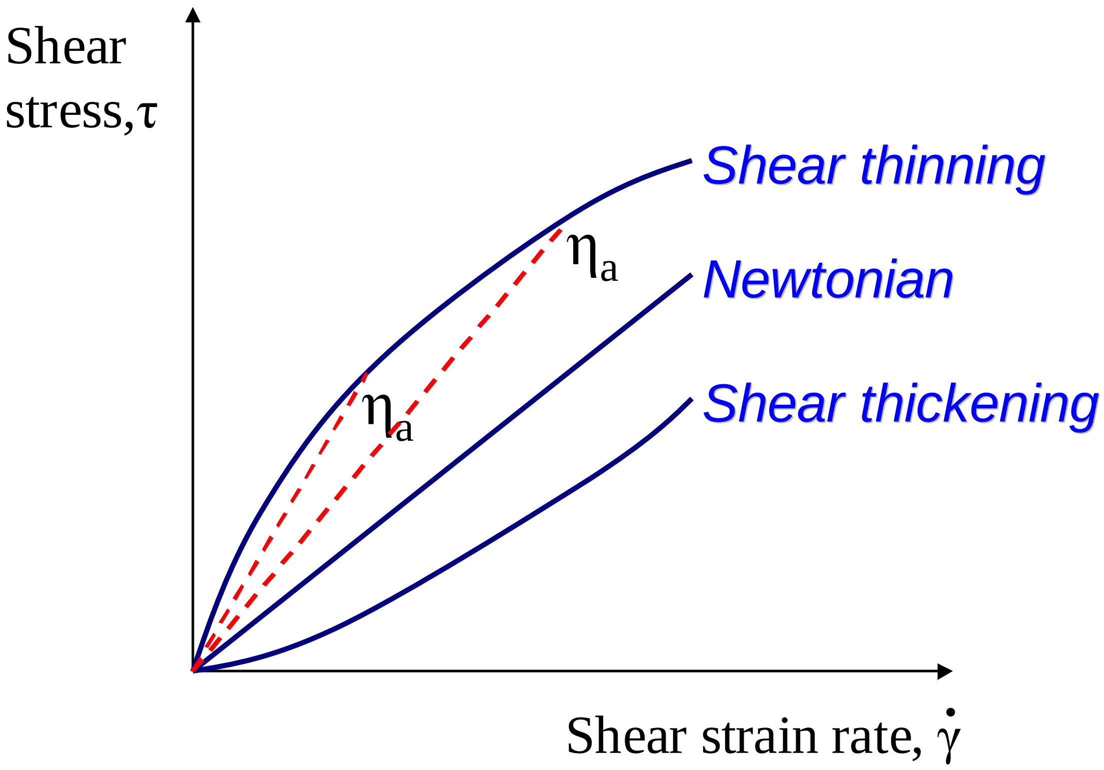
2.1 Non-Newtonian Flow

- Newtonian fluids:

$$\tau = \eta \dot{\gamma}$$

$$\frac{du}{dy}$$



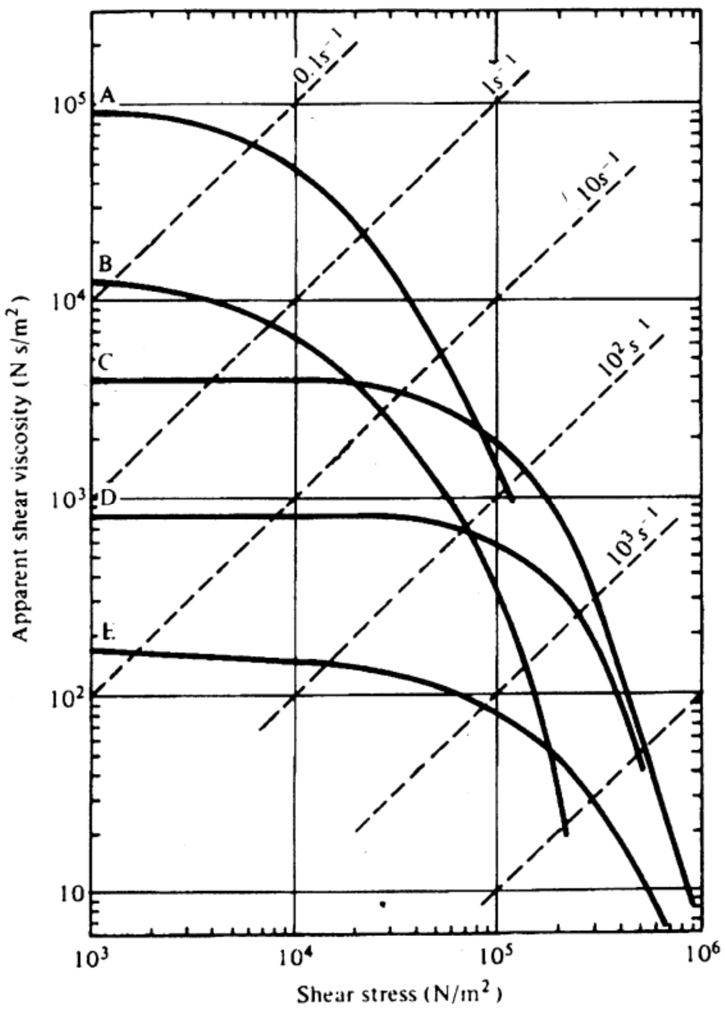


Apparent viscosity

$$\eta_a = \tau / \dot{\gamma}$$

2.1 Non-Newtonian Flow

Typical experimental data:



Viscosity data for polymer melts:

A – LDPE (170 °C)
B – Propylene-ethylene copolymer (230 °C)
C – Acrylic (230 °C)
D – Acetal copolymer (200 °C)
E – Nylon 6,6 (285 °C)

From P C Powell, A Jan Ingen Housz (1998) Engineering with polymers, Stanley Thornes (Publishers) Ltd.

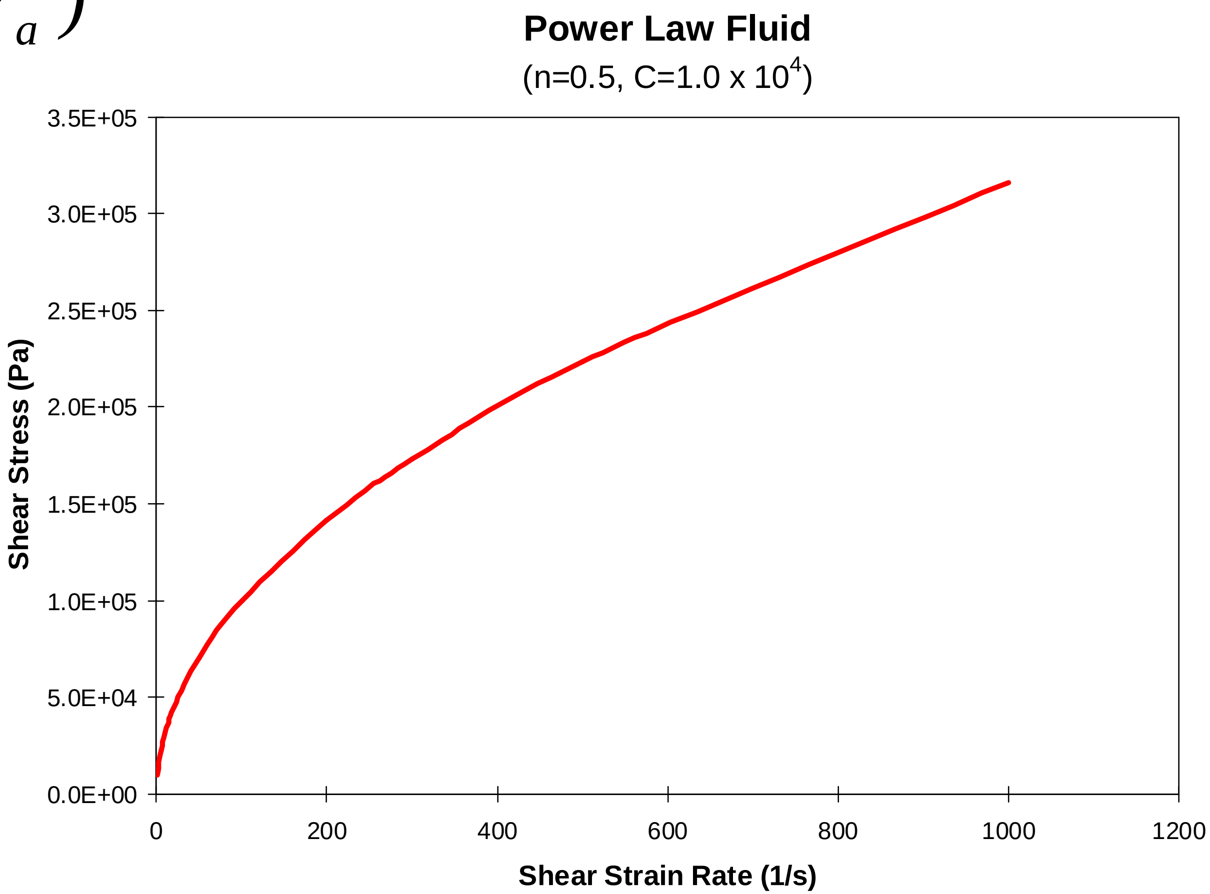
2.2 Power Law Fluid Model

- Over a small range of shear rates, shear thinning can be represented by:

$$\tau = C(\dot{\gamma}_a)^n$$

power law index

consistency



2.2 Power Law Fluid Model

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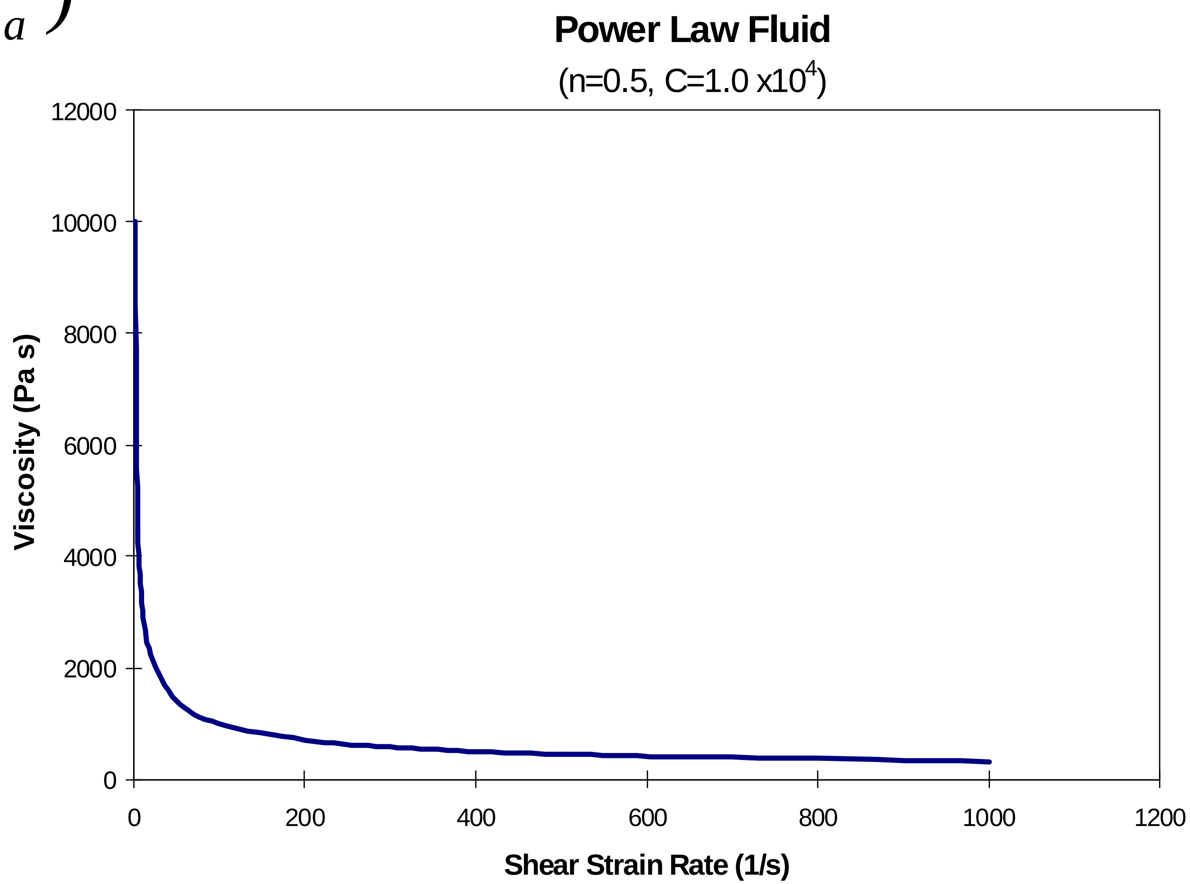

2.2 Power Law Fluid Model

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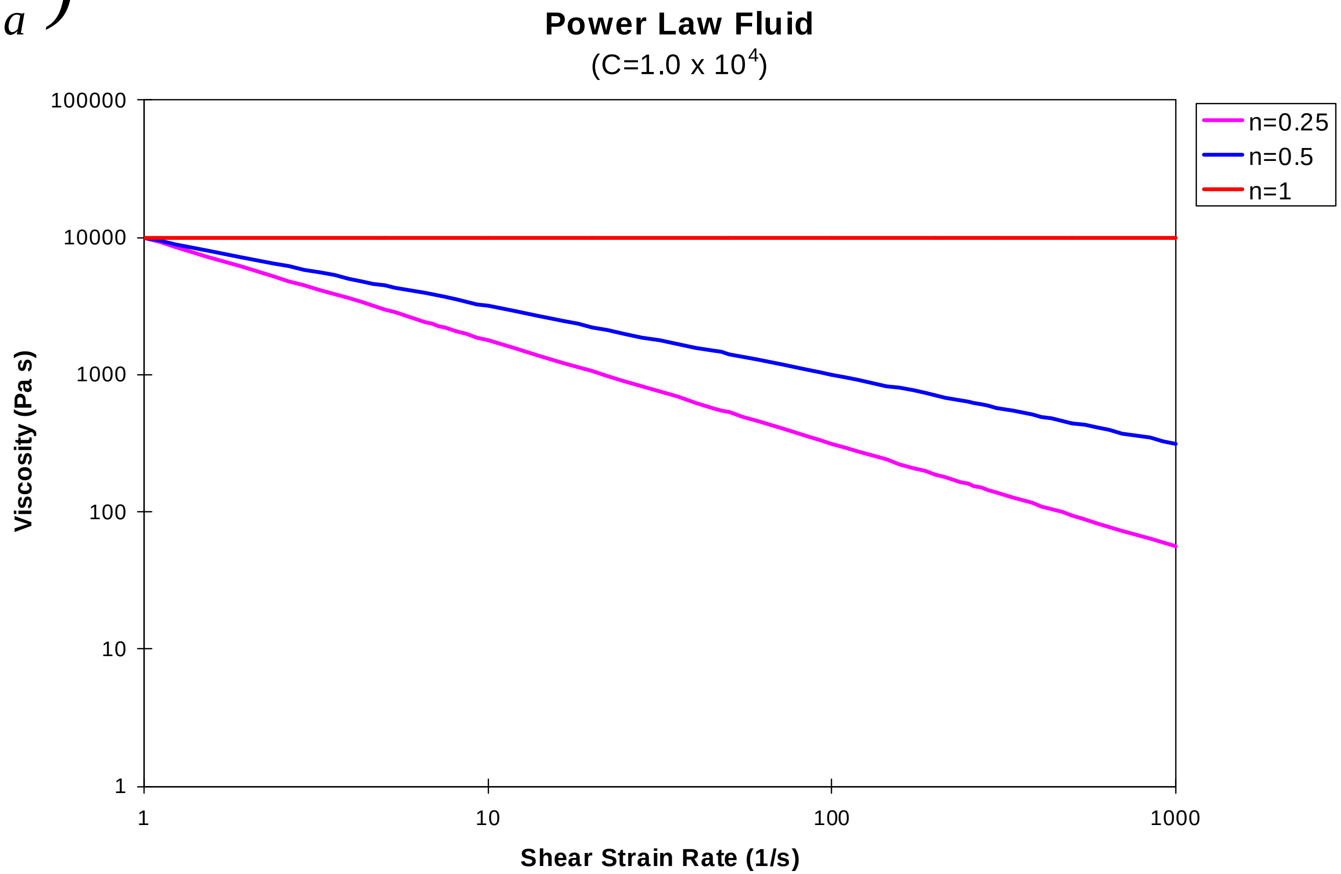
- Over a small range of shear rates, shear thinning can be represented by:

$$\tau = C(\dot{\gamma}_a)^n$$

power law index (n)

consistency (C)



2.2 Power Law Fluid Model

Worked Example - Powel law fluid model

Using Figure 4, determine appropriate power law fluid models for this particular grade of acrylic resin, including *low stress/rate* and *high stress/rate* flow properties.

Page 10

2.2 Temperature & Pressure Effects

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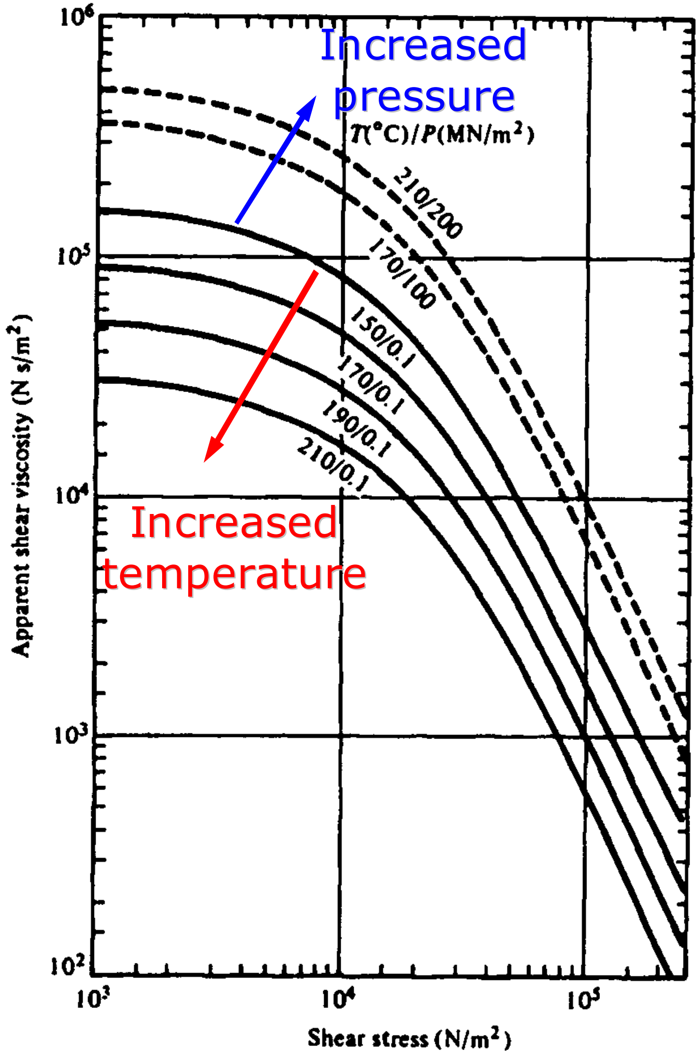
- Most polymers are processed at:

  Raised temperatures
  High pressures



Viscosity data for LDPE

Notes:

1. Injection moulding: P ~ 100-200 MPa
2. More sophisticated models available

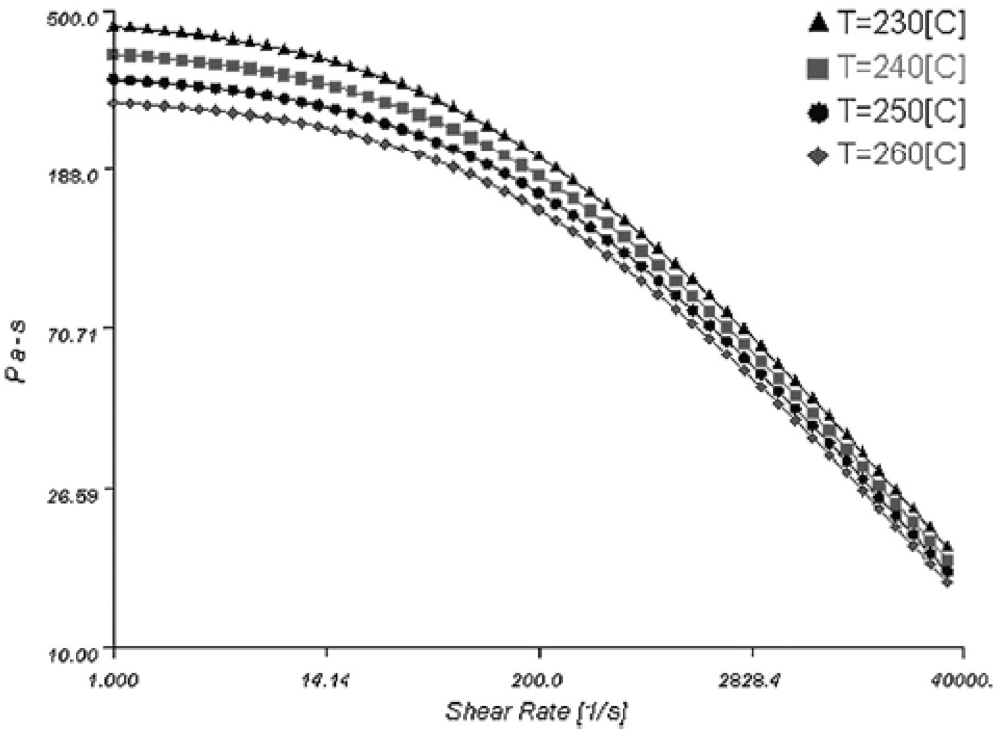
   eg.

   Arrhenius

   Carreau

2.2 Temperature & Pressure Effects

Viscosity data for Pa6 (Bayer Durethan B 30 S)



Cross-WLF model:

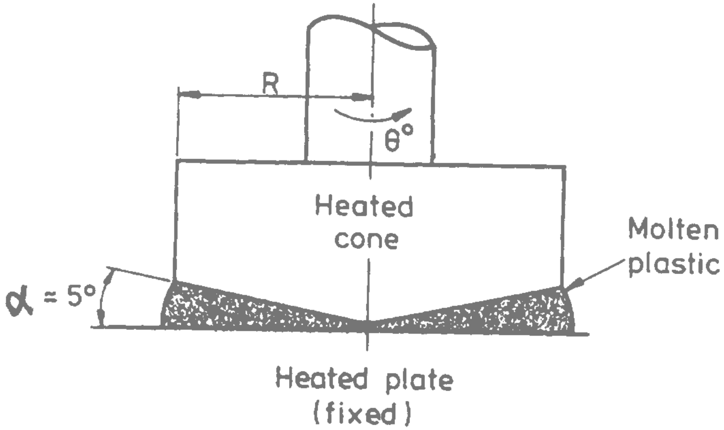
$$\eta(T, \dot{\gamma}, p) = \frac{\eta_0(T, p)}{1 + \left[\dfrac{\eta_0(T) \cdot \dot{\gamma}}{\tau^*}\right]^{(1-n)}},$$

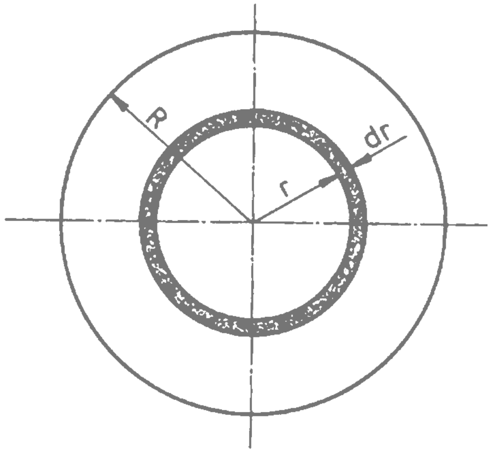
$$T > T_{\text{trans}} \rightarrow \eta_0(T, p) = B \cdot \exp\left(\frac{T_b}{T}\right) \cdot \exp(\beta \cdot p)$$

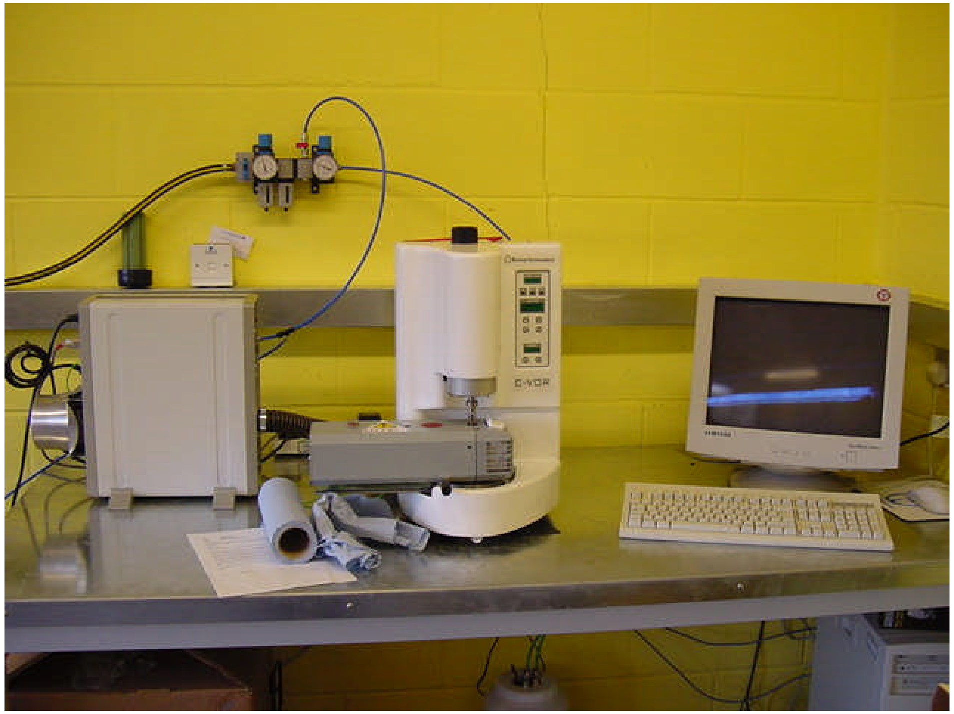
$$T < T_{\text{trans}} \rightarrow \eta_0(T, p) = \infty,$$

Influence of mold properties on the quality of injection molded parts.
J G Kovacs, T Bercsey, Periodica Polytechnica Ser. Mech. Eng. vol 49, no 2, 2005, pp 115-122.

Cone & plate rheometer

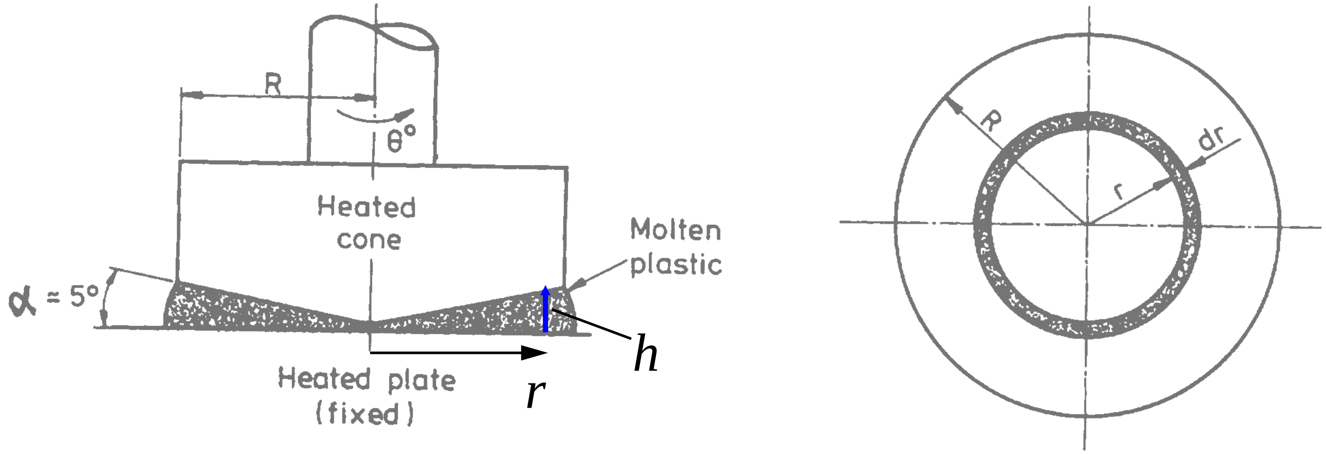






Malvern Instruments - http://www.bohlin.co.uk

3.1 Cone & Plate Rheometer



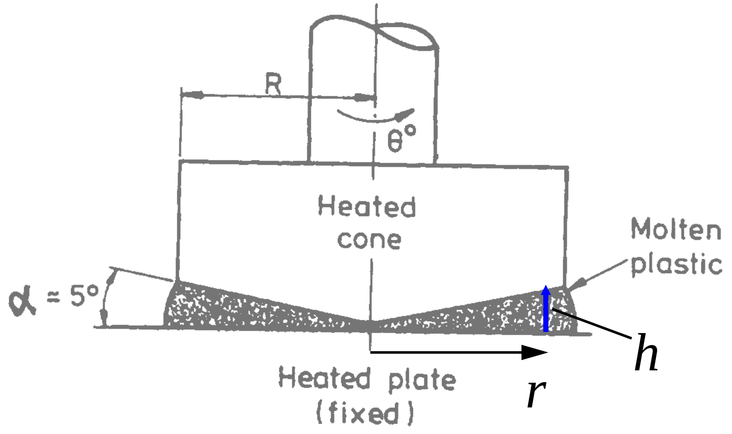
The shear stress is related to the torque:

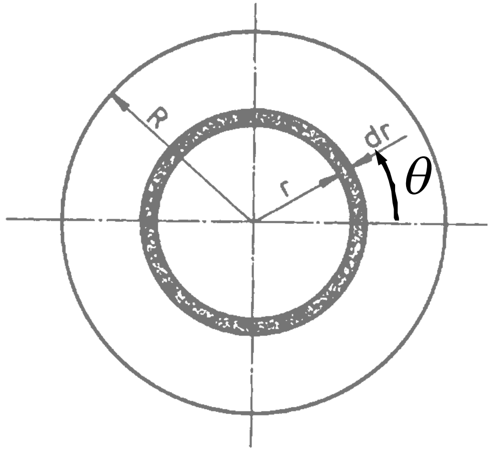
Area of annulus = $2\pi r dr$
Force = $2\pi r dr.\tau$ (where τ = shear stress)
Torque = $2\pi r^2 dr.\tau$

Total torque: $$T = \int_0^R 2\pi r^2 \tau \, dr$$

$$\Rightarrow \quad T = \tfrac{2}{3}\pi R^3 \tau \qquad \ldots (4)$$

3.1 Cone & Plate Rheometer





Shear strain: $$\gamma = \frac{r\theta}{h} = \frac{r\theta}{r\alpha} = \frac{\theta}{\alpha}$$

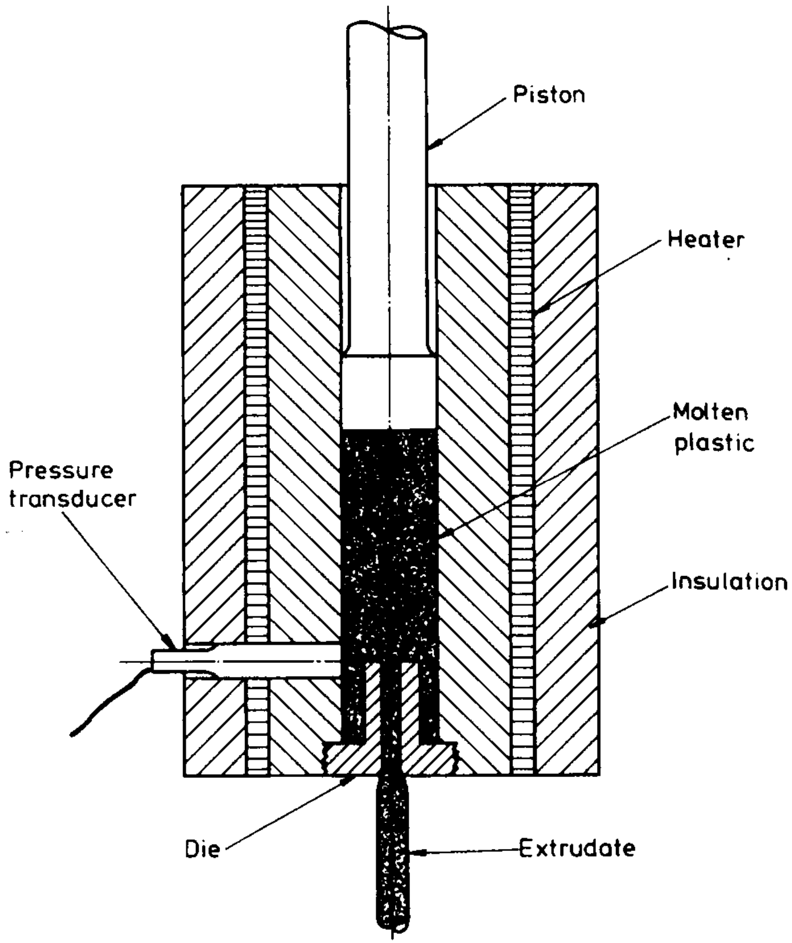
$$\Rightarrow \quad \dot{\gamma} = \frac{\dot{\theta}}{\alpha} \qquad \ldots (5)$$

Since viscosity is the ratio between shear stress and strain rate, then from Eqns. 4 and 5:

$$\eta = \frac{3T\alpha}{2\pi R^3 \dot{\theta}}$$

3.3 Pressure Flow Rheometer

Ram Extruder



- Based on Newtonian analysis, for pressure drop P:

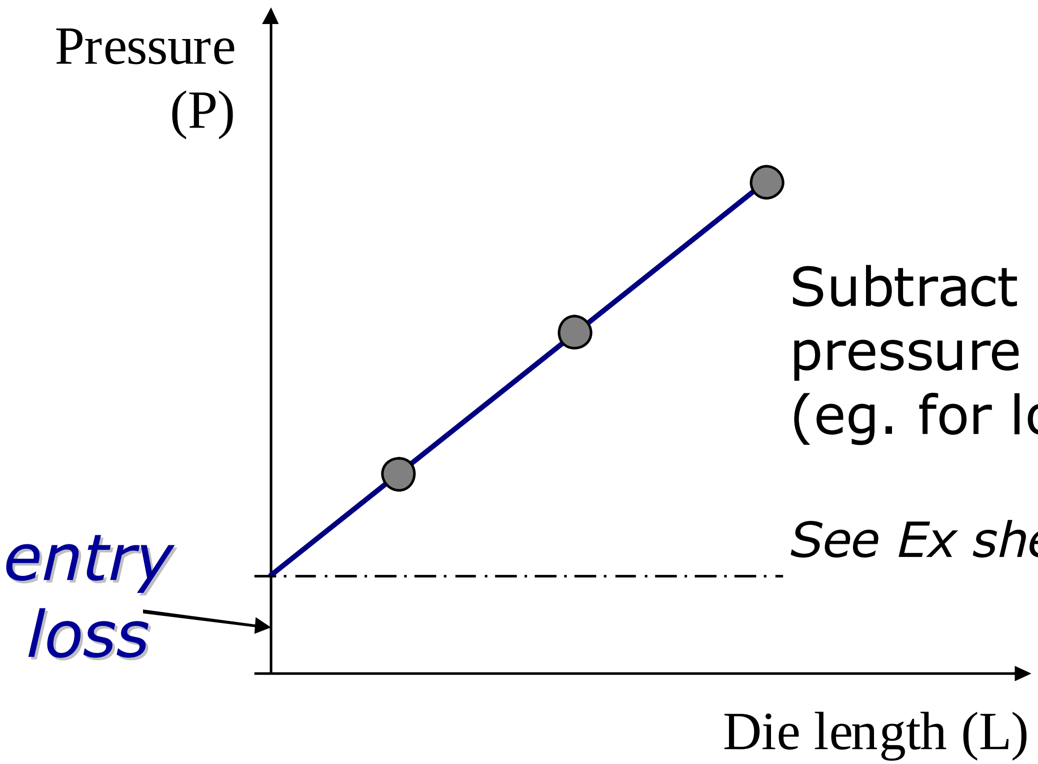
$$\eta_a = \frac{\pi P R^4}{8LQ}$$

Apparent viscosity (because of NEWTONIAN ANALYSIS)

- Must also account for pressure losses at die entry

Ram Extruder – entry Loss

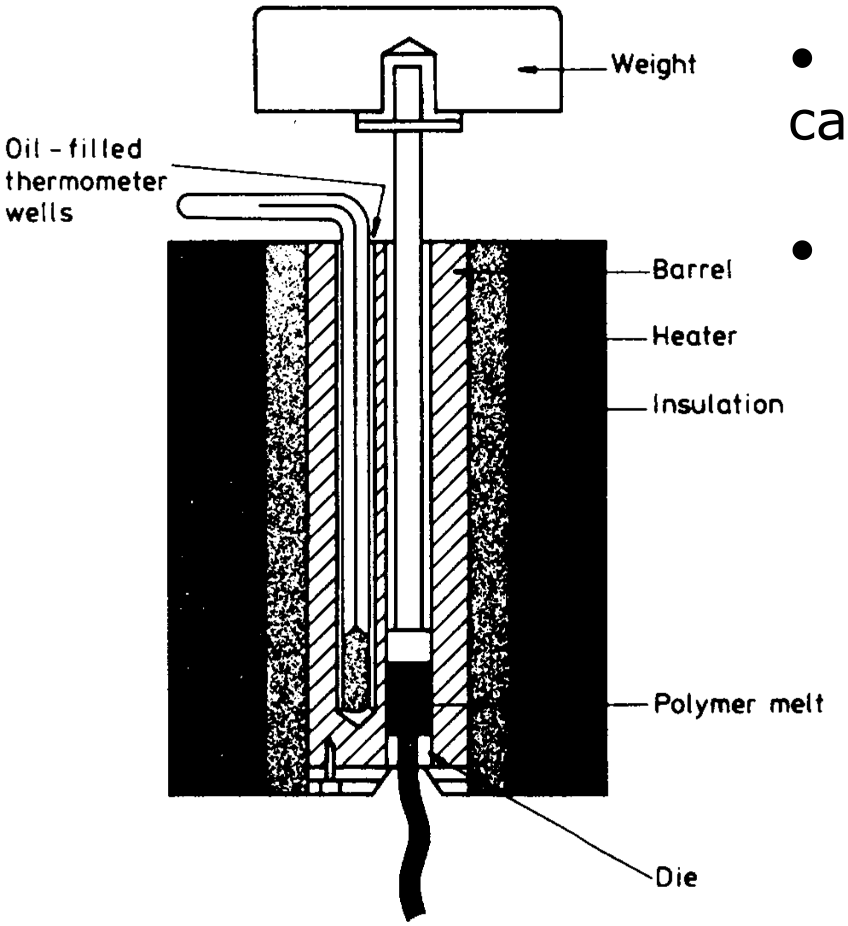
- Conduct series of tests with different die lengths
- Plot *pressure (P) vs. die length (L):*



Subtract *entry loss* from measured pressure before calculating viscosity (eg. for longest die)

See Ex sheet 3, Q2.

3.4 Melt Flow Index (MFI)



- Single point test based on capillary flow rheometer (BS 2782)

- MFI = weight of polymer extruded
  in standard time
  at standard temperature
  for standard pressure

High MFI → low viscosity
Low MFI → high viscosity

Polymer Melt Rheology

- Thermoplastic polymers are processed by melting, shaping and cooling
  - main processes are extrusion and injection moulding
- Polymer melt flow is non-Newtonian
  - power law model can be used over small range of rates/stresses
  - properties are highly dependent on temperature and pressure
- Can characterise flow properties using rheometry
  - cone & plate (low rates), pressure flow (high rates)