Exam 1
Thurs Feb 1

One hour exam

Polymer Rheometry

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Why?

- For modeling $\rightarrow$ design and optimization. Handbook data not enough for polymers (additives and changes in manufacturing).
- For quality control, i.e., to detect variations in the supply size which in turn could result in variations in properties.

Key Requirements

- Uniform flow
- Measurement conditions (shear rate and temperature) should be “close” to processing conditions
- “Clean” relations between stress and strain rate and measurable variables (torque/speed/geometry should be available).

<table>
<tr><th>VISCOMETER TYPE</th><th>COMMON EXAMPLES</th><th>APPROX. SHEAR RATE RANGE</th><th>ADVANTAGES</th><th>DISADVANTAGES</th><th></th></tr>
<tr><td>Cone & Plate</td><td>Rheometrics</td><td>0.01-2000</td><td rowspan="5">1) Small sample size required
2) Accurate control of shear rate
3) Simple calculations
4) Effective over a wide viscosity range
5) Normal force measurements possible
6) Usually have temperature control</td><td rowspan="5">1) Need accurate gap setting
2) Problems with suspended solids
3) May be expensive
4) Operator training required
5) Flow instabilities at higher shear rates</td><td></td></tr>
<tr><td rowspan="4"></td><td>Contrives</td><td>0.1-2000</td><td></td></tr>
<tr><td>Haake</td><td>0.5-2000</td><td></td></tr>
<tr><td>Brookfield C/P</td><td>0.1-500</td><td></td></tr>
<tr><td>Ferranti-Shirley</td><td>0.1-3000</td><td></td></tr>
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VISCOMETER TYPE	COMMON EXAMPLES	APPROX. SHEAR RATE RANGE	ADVANTAGES	DISADVANTAGES
Couette (Cup & Bob)	Rheometrics	0.01-2000	1) Moderate sample size required 2) Shear rate control possible (if gap is small or corrections are made) 3) Effective over a wide viscosity range 4) Usually have temperature control 5) Can deal with suspended solids well 6) Very low shear rates	1) Calculations can be complex 2) Wide gaps cause difficulties in determination of shear rate 3) Normal force cannot be measured 4) Wall slip can occur at high viscosities 5) May be expensive 6) Operator training possible may be required
	Contrives Haake	0.001-2000 0.1-2000		
	Brookfield UL Attachment	0.1-100		
	Brookfield Small Sample	0.05-100		
	Fann (35 & 50)	2-1000		

Capillary	Cannon-Fenske	0.1-50	1) Most require moderate sample size 2) Can be very accurate 3) Inexpensive for glass types 4) High shear rates possible for extrusion type	1) Shear rate control is difficult (depends upon the viscosity) 2) Temperature control is often difficult 3) Calculations for extrusion type difficult 4) Not commonly used in industry 5) Large sample required for extrusion type
	Ubbilohde	0.1-50		
Spindle	Brookfield	~0.05-~50	1) Widely used and available 2) Simple operation 3) Wide viscosity range possible 4) Good range of rotational rates available	1) Accurate determination of shear rate is not possible 2) Effective shear rate varies with spindle changes 3) ***Not a "rheologically correct" viscometer due to points 1) and 2)***
	LVR, RVT, HAT, HBT			

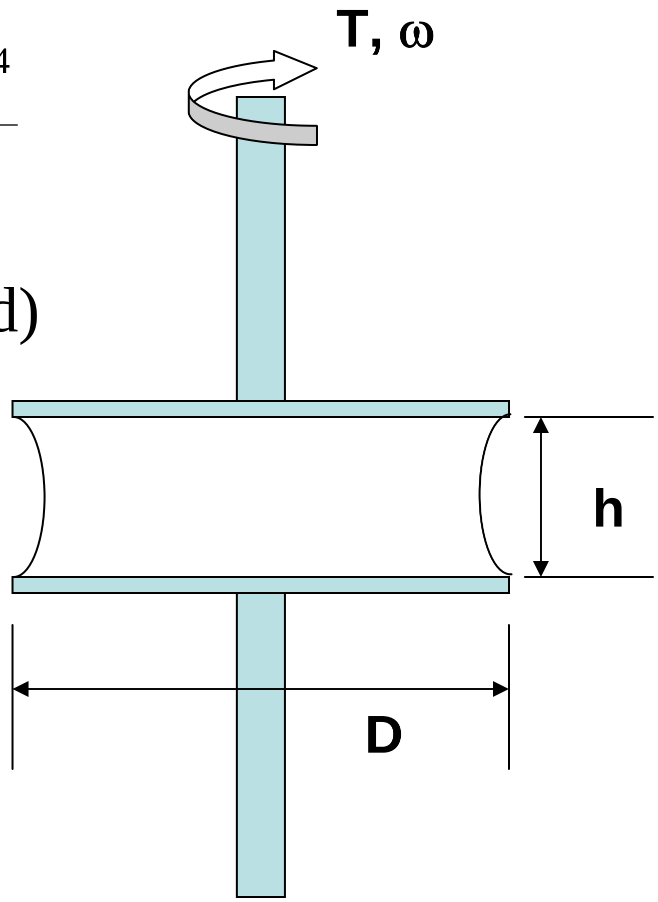
Adapted from http://www.kofg.com/tech/fluids.htm . Some of the limits of strain rates stated for various viscometers are over-optimistic …

Parallel Plate Rotational Rheometer

$$\dot{\gamma} = \frac{\omega r}{H},$$

$$T = \int_0^R \tau 2\pi r \cdot r dr = \int_0^R \eta \frac{\omega r}{H} 2\pi r \cdot r dr = \eta \frac{\pi \omega R^4}{2H}$$

$$\eta = \frac{2HT}{\pi \omega R^4} \quad \text{(assuming linear viscous fluid)}$$



- **Key problem is that shear strain rate is not constant.**
- **Can estimate normal stress using pressure transducers on surface.**

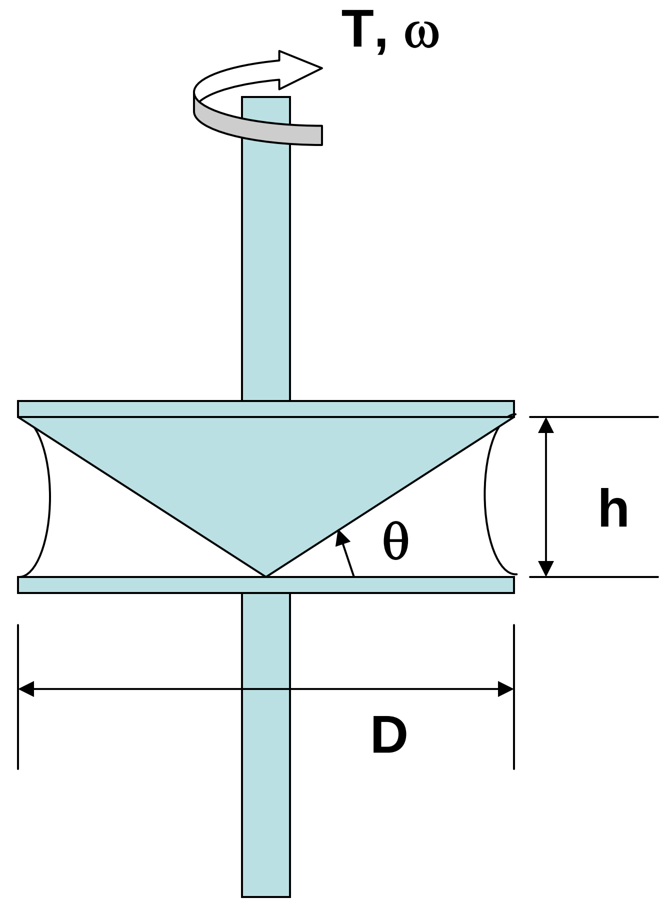
Cone and Plate

- **Near uniform strain rate if angle is small.**

$$\dot{\gamma} = \frac{\omega}{\theta}, \quad \tau = \frac{3T}{2\pi R^3}, \quad \eta = \frac{\tau}{\dot{\gamma}}$$

$$\sigma = \frac{F}{\pi R^2}, \quad \psi = \frac{\sigma}{\dot{\gamma}}$$

- **Limitation on speed due to centrifugal forces and Taylor vortices**
- **Double cone and plate and enclosed configurations are also used.**



Viscous Heating in Cone and Plate

- **HDPE data at 200°C**
  ρ=782 kg/m³ , k=0.255 W/(m°K)
  Cp=2650 J/(kg°K)
  K=4.69E3 Pa.sⁿ n=0.54

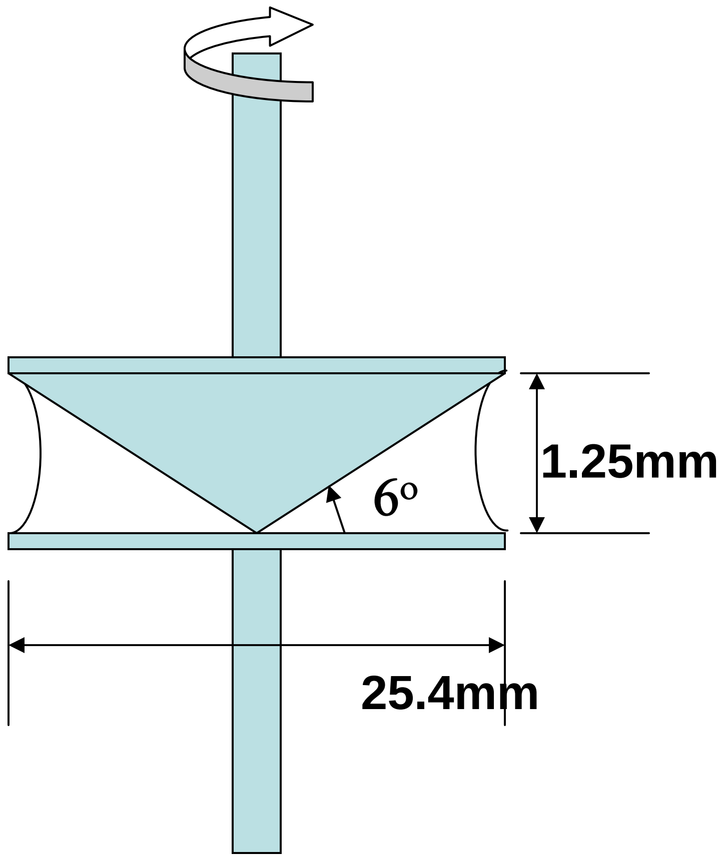
  Shearing at 100/s

  A quick and dirty calculation:

$$\tau\dot{\gamma} = \rho c\dot{\theta} \Rightarrow \dot{\theta} = \frac{\tau\dot{\gamma}}{\rho c} = \frac{K\dot{\gamma}^{n+1}}{\rho c}$$

$$= 2.72^{o} K/s \quad !!!!!....$$

This is an exaggeration (adiabatic) but it highlights the need for temperature control



Viscous Heating in flow between parallel plates

$$H = \tau \cdot \dot{\gamma} = K\dot{\gamma}^{n+1}$$

$$k\frac{d^2\theta}{dy^2} = H$$

$$\theta = \frac{K\dot{\gamma}^{n+1}}{k}\left(\frac{y}{2}\right)^2 + C_1 y + C_2$$

$$BC: \quad \theta(y=0) = \theta(y=H) = \theta_w = 200^o C$$

$$\theta = \frac{H^2 K\dot{\gamma}^{n+1}}{2k}\left(\frac{y}{H}\right)\left(1 - \frac{y}{H}\right) + \theta_w$$

$$\theta_{\max} = \frac{H^2 K\dot{\gamma}^{n+1}}{8k} + \theta_w$$

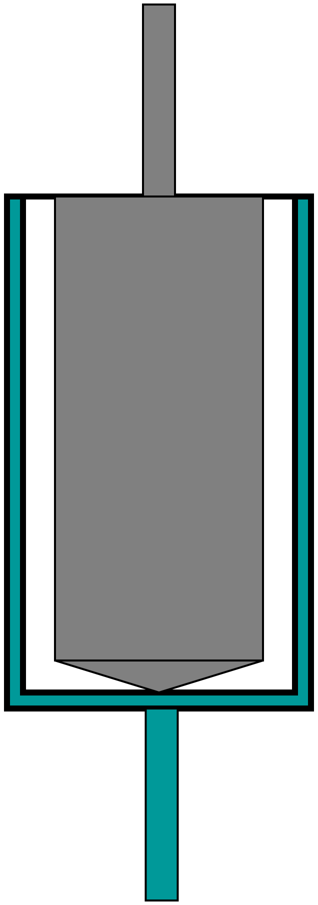
Couette (Cup and Bob)

- **If power law then**

$$\tau = \frac{T}{2\pi r_i^2 L}, \quad \dot{\gamma} \approx \frac{2\omega}{n\left(1-(r_i/r_o)^2\right)}$$

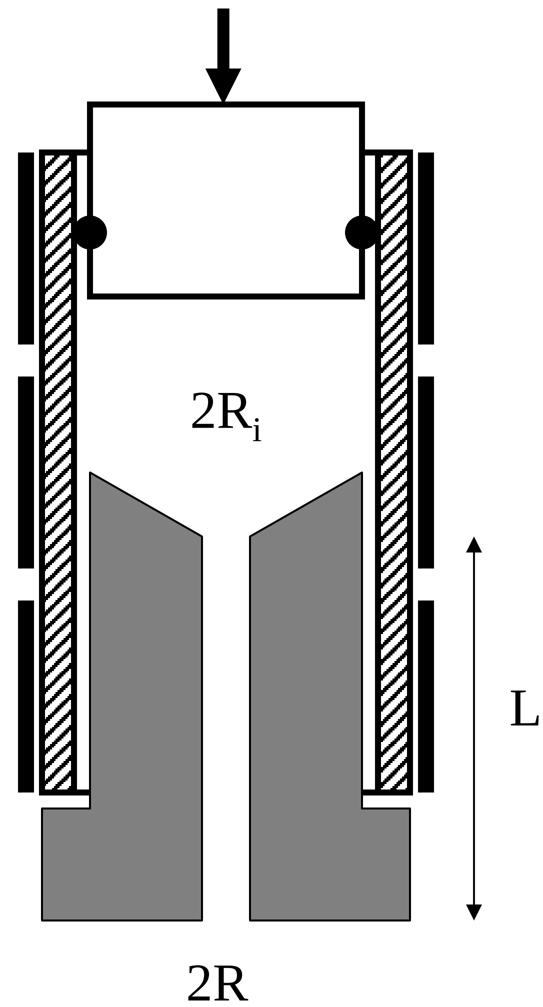
$$n = \left(\frac{\log T_1}{\log T_2}\right) / \left(\frac{\log \omega_1}{\log \omega_2}\right)$$

- **Catch-22. Flow field not known a priori.**
- **Also, large speed results in vortices**
- **End effects minimized by long length.**
- **Either fixed cup or fixed bob configurations)**



Capillary Rheometer

- **Can go to much higher strain rates than others (up to 10000/s).**
- **Different diameters can be used.**
- **Suggested length to diameter ratio is from <u>16 to >100</u>**
- **Exit correction (Bagley correction) should taken into account.**
- **Non-uniform flow field.**



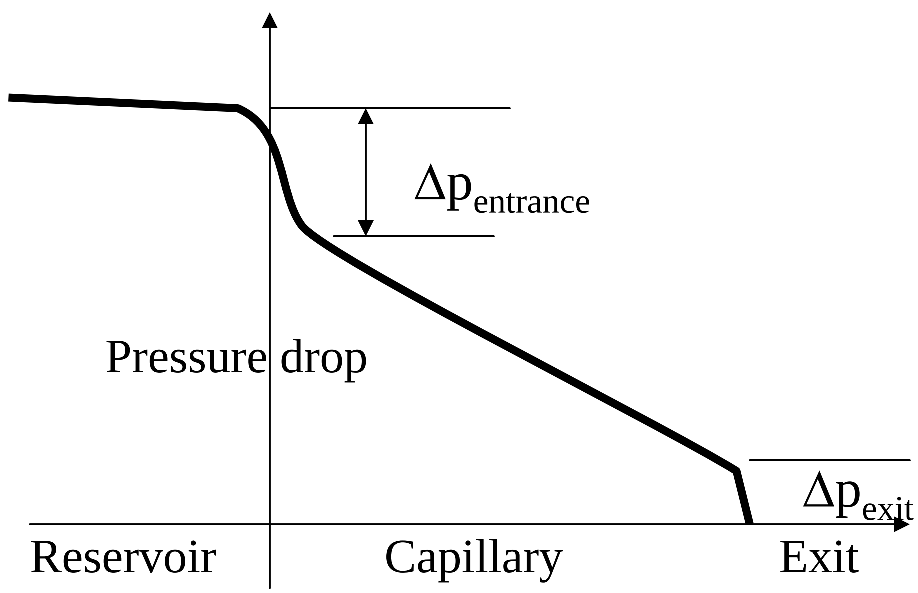
Capillary Rheometer (cont.)

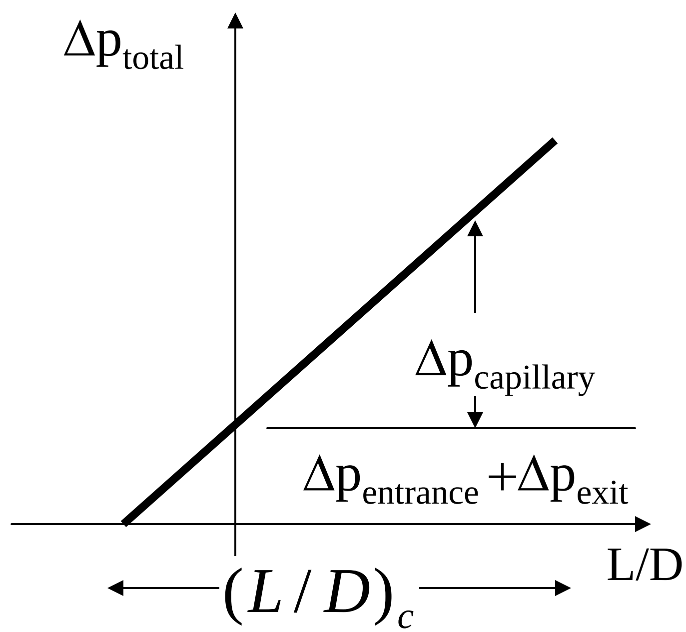
$$\tau_w = \frac{R\Delta p_{capillary}}{2L} = \frac{\Delta p_{total}}{4(L/D)_c}$$

$$\dot{\gamma}_w = \begin{cases} 4Q/(\pi R^3) & \text{linear} \\ 4Q/(\pi R^3)\left(\dfrac{3n+1}{4}\right) & \text{power law} \end{cases}$$

$$n = \left(\frac{\log \tau_{w1}}{\log \tau_{w2}}\right) / \left(\frac{\log Q_1}{\log Q_2}\right)$$

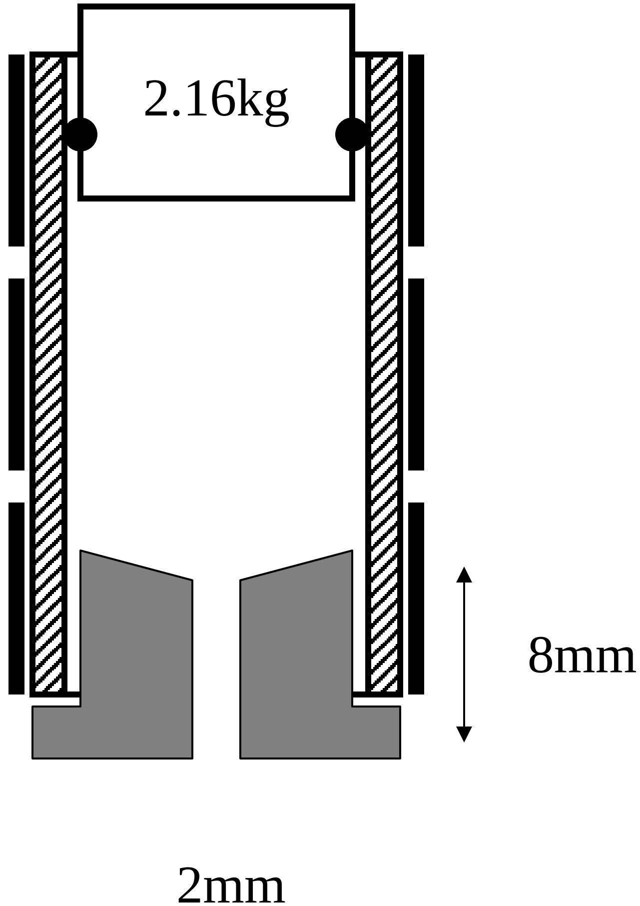
$$\Delta p_{total} = \Delta p_{capillary} + \Delta p_{entrance/exit}$$



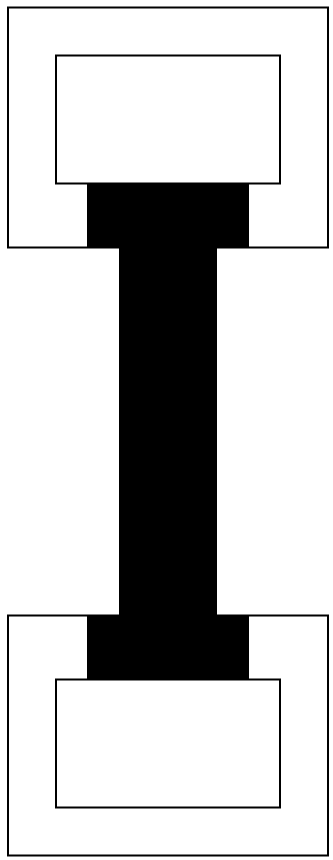


The Melt Indexer: ASTM D1238

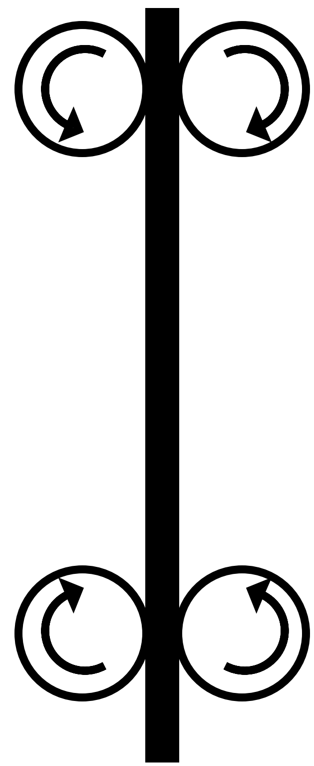
- **Introduced by DuPont engineers in the 50s.**
- **Melt Flow Index (MFI)= the weight of molten polymer pushed through for 10min**
- **IMPORTANT LIMITATIONS:**
  - **Very low (L/D=4); response dominated by entrance/exit effects**
  - **Does not offer any information on variation of viscosity with shear rate**
- ***It should only be used for comparative purposes between slightly different plastics*.**



Elongational Viscometers



Ballman method



Meissner method