

Fluid Mechanics

Stress

Strain

Strain rate

Shear vs. Extension

Apparent Viscosity

Oversimplified Models:

Maxwell Model

Voigt Model

Continuity Equation

Navier-Stokes Equations

Boundary Conditions

Volumetric Flow Rate

Linear Viscoelasticity

Boltzmann Superposition

Step Strain:

Relaxation Modulus

Generalized Maxwell Model

Viscosity

Creep/Recovery:

Creep Compliance

Recoverable Compliance

Steady State Compliance

Terminal Relaxation Time

Oscillatory Shear:

Storage Modulus

Loss Modulus

Phase Angle

Loss Tangent

Time-Temperature Superposition

Molecular Structure Effects

Molecular Models:

Rouse Model (Unentangled)

Reptation Model (Entangled)

Viscosity

Recoverable Compliance

Diffusion Coefficient

Terminal Relaxation Time

Terminal Modulus

Plateau Modulus

Entanglement Molecular Weight

Glassy Modulus

Transition Zone

Apparent Viscosity

Polydispersity Effects

Branching Effects

Die Swell

Nonlinear Viscoelasticity

Stress is an Odd Function of Strain and Strain Rate

Viscosity and Normal Stress are Even Functions of Strain and Strain Rate

Lodge-Meissner Relation

Nonlinear Step Strain

Extra Relaxation at Rouse Time

Damping Function

Steady Shear

Apparent Viscosity

Power Law Model

Cross Model

Carreau Model

Cox-Merz Empiricism

First Normal Stress Coefficient

Start-Up and Cessation of Steady Shear

Nonlinear Creep and Recovery

Rheometry

Couette Devices:

- Gap Loading vs. Surface Loading
- Controlled Stress vs. Controlled Strain
- Transducer (and Instrument) Compliance
- Cone & Plate
- Parallel Plate
- Eccentric Rotating Disks
- Concentric Cylinder
- Sliding Plates

Poiseuille Devices:

- Pressure Driven vs. Rate Driven
- Capillary Rheometer
 - Wall Shear Stress
 - Wall Shear Rate
 - Bagley End Correction
 - Cogswell Orifice Short-Cut
 - Rabinowitch Correction
- Slit Rheometer
- Melt Flow Index
- Die Swell
- Extrudate Distortion

Injection Molding

Injection Molding Cycle

- Inject and pack mold

- Extrude next shot once gate solidifies

- Eject part once part solidifies

Injection Molding Economics

- Only inexpensive if we make many parts

Injection Molding Window

Poiseuille Flow in Runners and Simple Cavities

- Calculate injection pressure to fill mold

- Balance runner systems

- Calculate clamping force

- Assumptions:

 - Isothermal

 - Newtonian

Hot Runner Systems

- No runners to regrind

- More expensive

Injection Molding Defects

- and how to avoid/control them

 - Weld Lines

 - Sink Marks and Voids

 - Short Shots / Uneven Filling

 - Burn Marks

 - Sticking

 - Warping

Extrusion

Pumping vs. Mixing

Pressure Distribution

Residence Time Distribution

Twin Screw Extrusion

Dimensional Analysis

 Buckingham Π Theorem

 Intuition or Experience Helps

Mass Balance

Uses of Extruders

Injection Molding

Blow Molding

Pelletizing

 Heat Transfer

Sheet Extrusion

 Thermoforming

Fiber Spinning

Pipe Extrusion

Film Blowing

Coextrusion

 Barrier properties

Profile Extrusion

Wire Coating

Blow Molding

Blow Molding Cycle

Parison Extrusion

Parison sag

Blowing

Cooling

Ejection

Extrusion Blow Molding Economics

Less expensive than injection molding

Stretch-Blow Molding

Biaxial orientation

Ring-Neck Blow Molding

Improved thickness control

Better precision in neck of bottle

Injection-Blow Molding

Improved thickness control

Fewer surface defects

Better precision in neck of bottle

Blow Molding Defects

and how to minimize them.

Advantages of Branched Polymers

Rotational Molding

The only process we have learned about that does NOT make use of an extruder.

Rotational Molding Cycle

High-Speed Rotation to Pack Powder

Sintering

Cooling (Heat Transfer)

Removal

Rotational Molding Economics

Cheap way to make small numbers of large parts.

Thermoset Molding

Gelation:

- Divergence of Viscosity
- Growth of Modulus

Thermoset Molding Cycle

- Inject and pack mold

- Cure part

- Eject part once part solidifies

Thermoset Molding Economics

- Less capital investment than injection molding

- No way to recycle waste or final product

Compression Molding

Transfer Molding

Injection Molding

Reaction Injection Molding

- Impingement Mixing

Solvent Coating

Control of Coating Thickness

Roll Coating

Blade Coating

- Lubrication Approximation

Dip Coating

- Surface Tension

Curtain Coating

Stress and Strain

SHEAR

$$\text{Shear Stress} \quad \sigma \equiv \frac{F}{A}$$

$$\text{Shear Strain} \quad \gamma \equiv \frac{l}{h}$$

$$\text{Shear Rate} \quad \dot{\gamma} \equiv \frac{d\gamma}{dt}$$

$$\text{Hooke's Law} \quad \sigma = G\gamma$$

$$\text{Newton's Law} \quad \sigma = \eta\dot{\gamma}$$

EXTENSION

$$\text{Tensile Stress} \quad \sigma \equiv \frac{F}{A}$$

$$\text{Extensional Strain} \quad \varepsilon \equiv \frac{\Delta l}{l}$$

$$\text{Extension Rate} \quad \dot{\varepsilon} \equiv \frac{d\varepsilon}{dt}$$

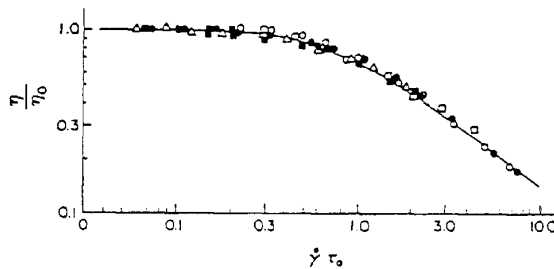
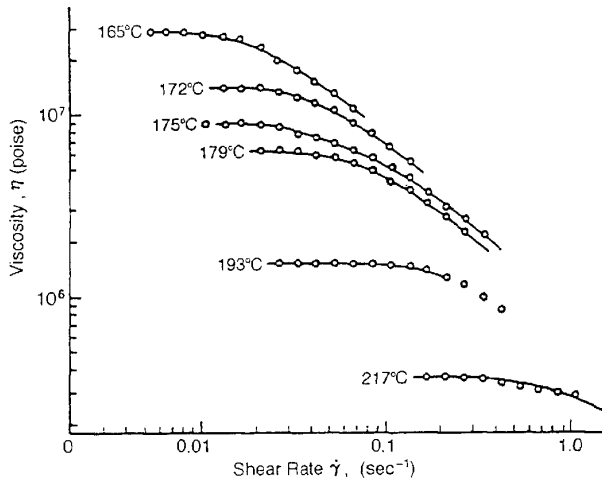
$$\text{Hooke's Law} \quad \sigma = 3G\varepsilon$$

$$\text{Newton's Law} \quad \sigma = 3\eta\dot{\varepsilon}$$

Viscoelasticity

APPARENT VISCOSITY

$$\eta \equiv \frac{\sigma}{\dot{\gamma}}$$



1. Apparent Viscosity of a Monodisperse Polystyrene.

Oversimplified Models

MAXWELL MODEL

Stress Relaxation $\sigma(t) = \sigma_0 \exp(-t/\lambda)$

$$G(t) = G_0 \exp(-t/\lambda)$$

Creep $\gamma(t) = \gamma_0(1 + t/\lambda)$

$$J(t) = J_s^0(1 + t/\lambda) = J_s^0 + t/\eta$$

Oscillatory Shear $G'(\omega) = \omega \lambda G''(\omega) = \frac{G_0(\omega \lambda)^2}{1 + (\omega \lambda)^2}$

The Maxwell Model is the simplest model of a

VISCOELASTIC LIQUID.

VOIGT MODEL

Creep $\gamma(t) = \gamma_\infty[1 - \exp(-t/\lambda)]$

$$J(t) = J_\infty[1 - \exp(-t/\lambda)]$$

The Voigt Model is the simplest model of creep for a

VISCOELASTIC SOLID.

Equations of Fluid Motion

CONTINUITY

Incompressible $\vec{\nabla} \cdot \vec{v} = 0$

Continuity is a differential equation describing conservation of mass.

NAVIER-STOKES

Slow Flows (no inertia, $Re < 1$) $\rho \frac{\partial \vec{v}}{\partial t} = -\vec{\nabla} P + \rho \vec{g} + \eta \nabla^2 \vec{v}$

The Navier-Stokes equations are force balances (per unit volume).

DO NOT MEMORIZE CONTINUITY OR N-S EQUATIONS. IF NEEDED, I WILL GIVE THEM TO YOU.

YOU DO NEED TO KNOW HOW TO USE THEM TO SOLVE FOR PRESSURE AND VELOCITY DISTRIBUTIONS.

BOUNDARY CONDITIONS

1. NO SLIP at solid surfaces
2. No infinite velocities

MAXIMUM VELOCITY

for $v_x = v_x(y)$, $\frac{\partial v_x}{\partial y} = 0$

AVERAGE VELOCITY and VOLUMETRIC FLOW RATE

$$v_{ave} = \frac{Q}{A} = \frac{1}{A} \int v_x dA$$

Linear Viscoelasticity

Stress Relaxation Modulus $G(t) \equiv \frac{\sigma(t)}{\gamma_0}$

BOLTZMANN SUPERPOSITION: Add effects of many step strains to construct ANY linear viscoelastic deformation.

Viscosity $\eta_0 = \int_0^{\infty} G(t) dt$

Creep Compliance $J(t) \equiv \frac{\gamma(t)}{\sigma}$

Steady State Compliance $J_s^0 = \lim_{t \rightarrow \infty} \left[J(t) - \frac{t}{\eta_0} \right]$

$$J_s^0 = \frac{1}{\eta_0^2} \int_0^{\infty} G(t) t dt$$

Recoverable Compliance $R(t) \equiv \frac{\gamma_r(t)}{\sigma} = J(t) - \frac{t}{\eta_0}$

$$J_s^0 = \lim_{t \rightarrow \infty} [R(t)]$$

Terminal Relaxation Time $\lambda = \eta_0 J_s^0 = \frac{\int_0^{\infty} G(t) t dt}{\int_0^{\infty} G(t) dt}$

Linear Viscoelasticity

OSCILLATORY SHEAR

apply strain $\gamma(t) = \gamma_0 \sin(\omega t)$

measure stress $\sigma(t) = \gamma_0 [G'(\omega) \sin(\omega t) + G''(\omega) \cos(\omega t)]$

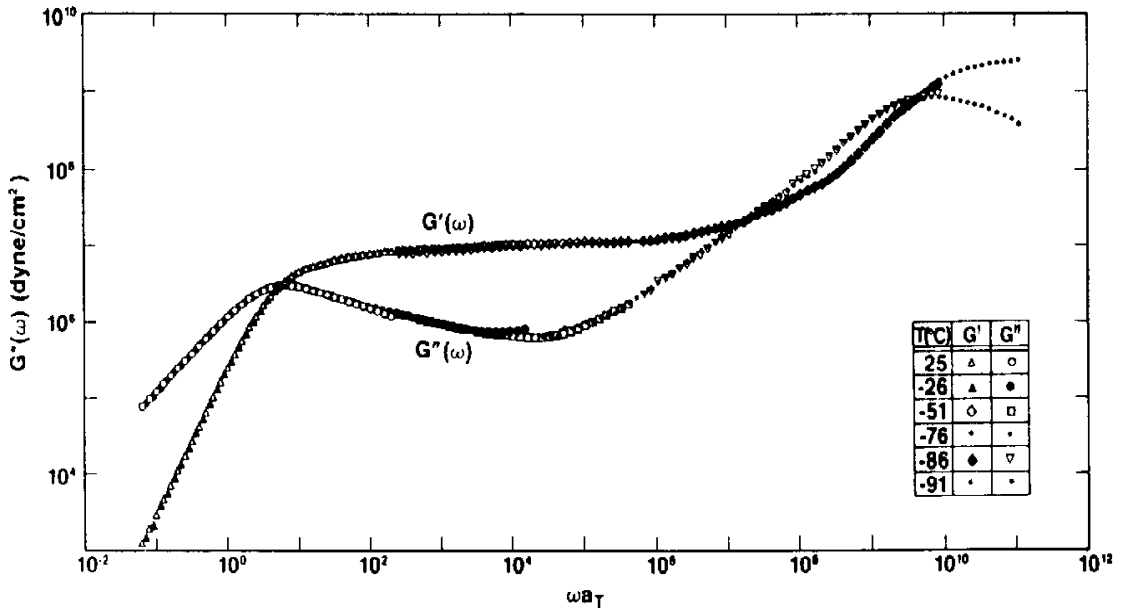
Loss Tangent $\tan(\delta) = \frac{G''}{G'}$

Viscosity $\eta_0 = \lim_{\omega \rightarrow 0} \left[\frac{G''(\omega)}{\omega} \right]$

Steady State Compliance $J_s^0 = \lim_{\omega \rightarrow 0} \left[\frac{G'(\omega)}{[G''(\omega)]^2} \right]$

Linear Viscoelasticity

OSCILLATORY SHEAR RESPONSE OF A LINEAR MONODISPERSE POLYMER



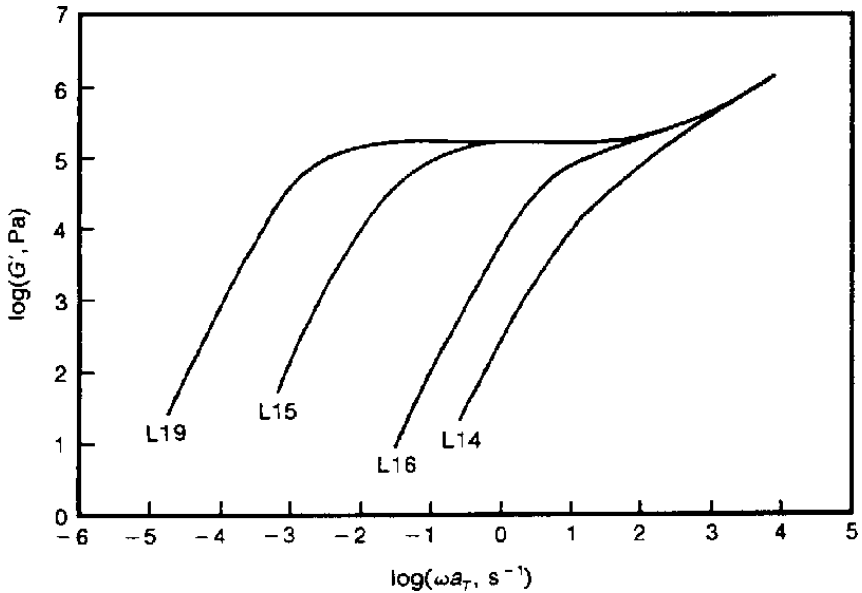
2. Storage and Loss Modulus Master Curves for Polybutadiene at Reference Temperature $T_0 = 25^\circ\text{C}$.

Linear Viscoelasticity

EFFECTS OF MOLECULAR STRUCTURE

Increase $M_w \Rightarrow$ Increase λ

Terminal response is delayed to lower frequency.

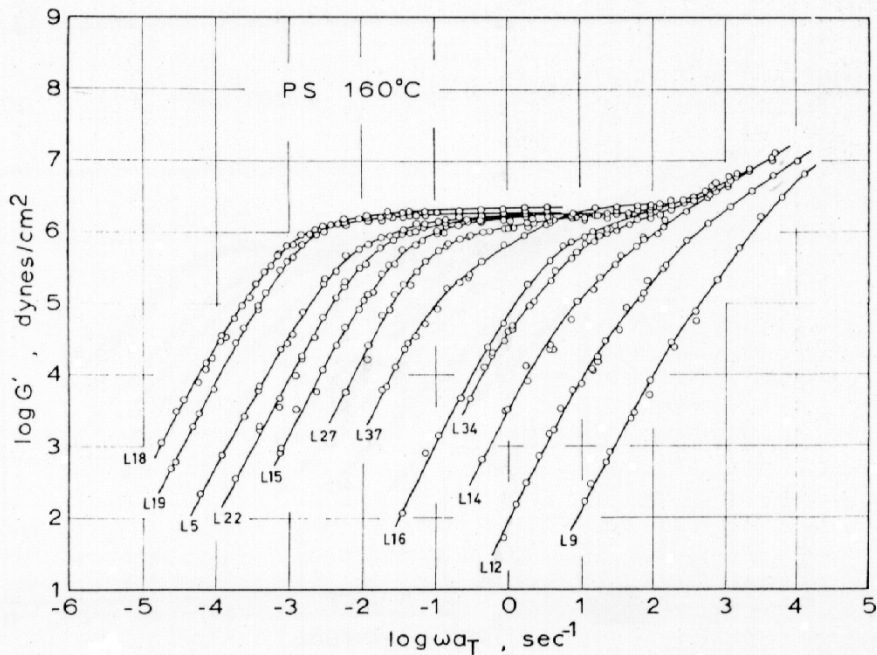


3. Storage Modulus of Four Narrow Molecular Weight Distribution Polystyrenes.

Sample	M_w
L14	28900
L16	58700
L15	215000
L19	513000

Linear Viscoelasticity

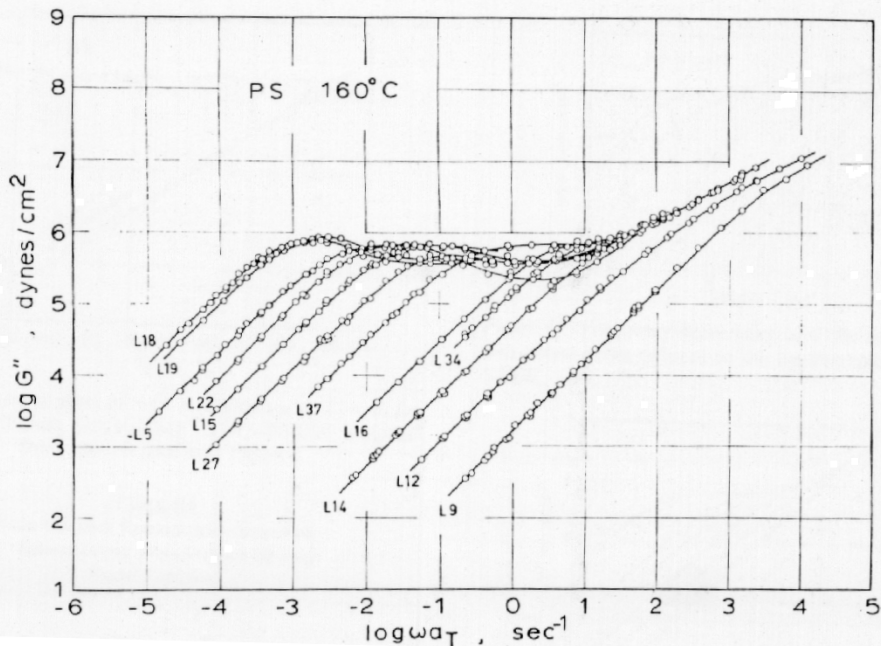
EFFECTS OF MOLECULAR STRUCTURE



4. Storage Modulus Data for Monodisperse Polystyrenes.

Linear Viscoelasticity

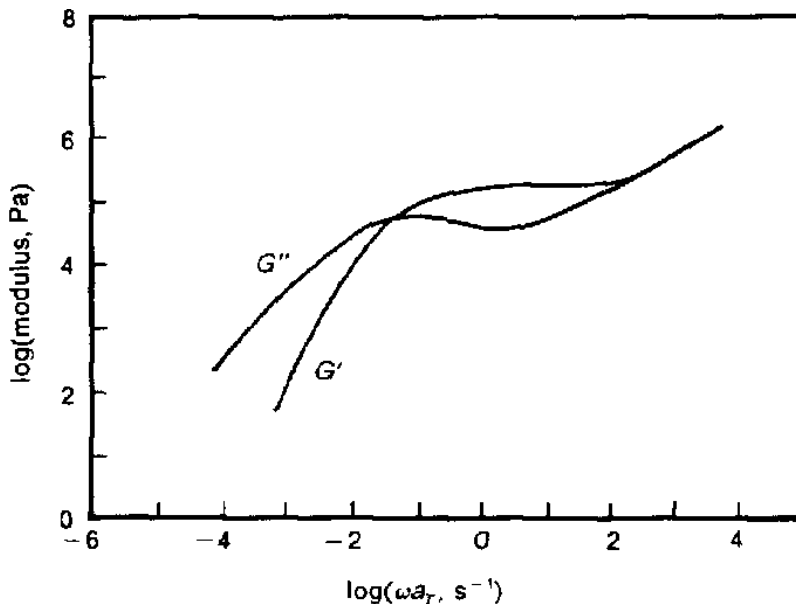
EFFECTS OF MOLECULAR STRUCTURE



5. Loss Modulus Data for Monodisperse Polystyrenes.

Linear Viscoelasticity

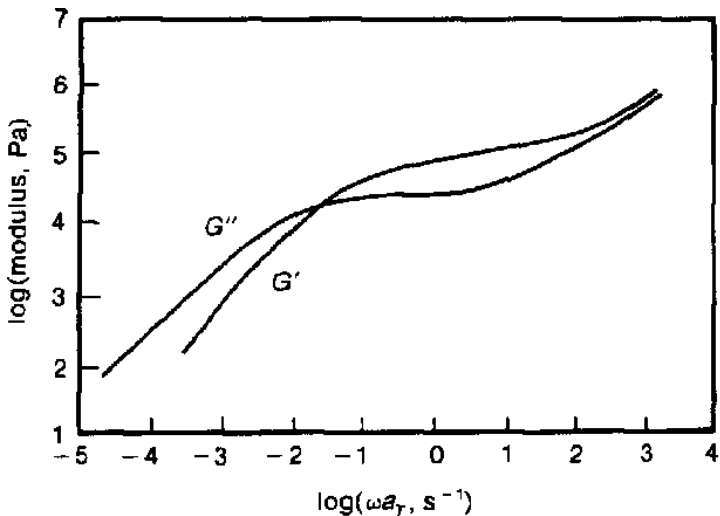
EFFECTS OF MOLECULAR STRUCTURE



6. Storage and Loss Moduli for Polystyrene $L15$ with $M_w = 215000$.

Linear Viscoelasticity

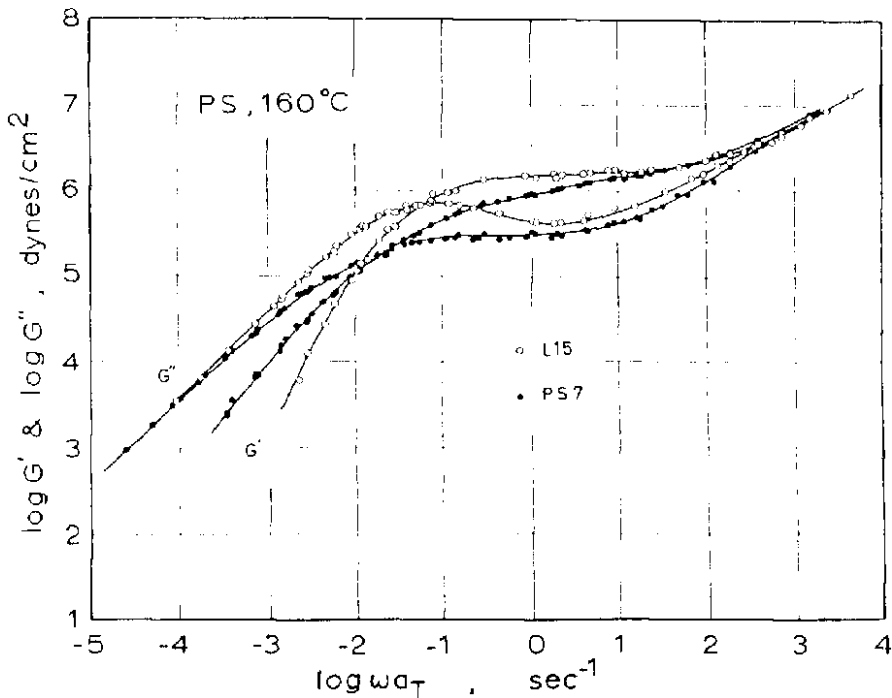
EFFECTS OF MOLECULAR STRUCTURE



7. Storage and Loss Moduli for Polystyrene with $M_w = 315000$ and $M_w/M_n = 1.8$.

Linear Viscoelasticity

EFFECTS OF MOLECULAR STRUCTURE



8. Comparison of Monodisperse (L15) and Polydisperse (PS7) Polystyrenes with the Same Viscosity.

MOLECULAR THEORIES

ROUSE MODEL:

$$D_R \sim \frac{1}{N} \quad \lambda_R \cong \frac{R^2}{D_R} \sim N^2 \quad G(\lambda_R) = \frac{\rho RT}{M} \quad \eta \cong \lambda_R G(\lambda_R) \sim N$$

$$G(t) \sim t^{1/2} \quad \text{for } \lambda_N < t < \lambda_R$$

REPTATION MODEL:

Relaxation is simple Rouse motion up to the Rouse relaxation time of an entanglement strand.

$$\lambda_e \sim N_e^2 \quad G(t) \sim t^{1/2} \quad \text{for } \lambda_N < t < \lambda_e$$

$$\text{Plateau Modulus} \quad G_N^0 = \frac{\rho RT}{M_e}$$

$$\lambda_d \cong \frac{L^2}{D_R} \sim N^3 \quad D \cong \frac{R^2}{\lambda_d} \sim \frac{1}{N^2} \quad \eta \cong \lambda_d G_N^0 \sim N^3$$

MOLECULAR THEORIES

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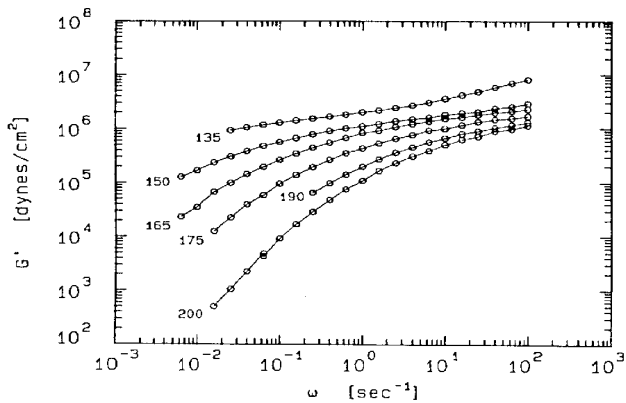
Plateau Modulus

$$G_N^0 = \frac{\rho RT}{M_e}$$

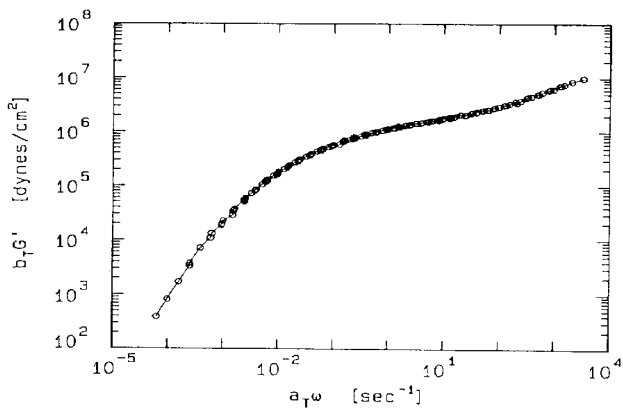
$$\lambda_d \cong \frac{L^2}{D_R} \sim N^3 \quad D \cong \frac{R^2}{\lambda_d} \sim \frac{1}{N^2} \quad \eta \cong \lambda_d G_N^0 \sim N^3$$

Linear Viscoelasticity

TIME-TEMPERATURE SUPERPOSITION



(A)



(B)

Figure 1: (A) Isothermal Storage Modulus $G'(\omega)$ of a Polystyrene at Six Temperatures. (B) Storage Modulus Master Curve at Reference Temperature $T_0 = 150$ °C.

Linear Viscoelasticity

OSCILLATORY SHEAR RESPONSE OF A LINEAR MONODISPERSE POLYMER

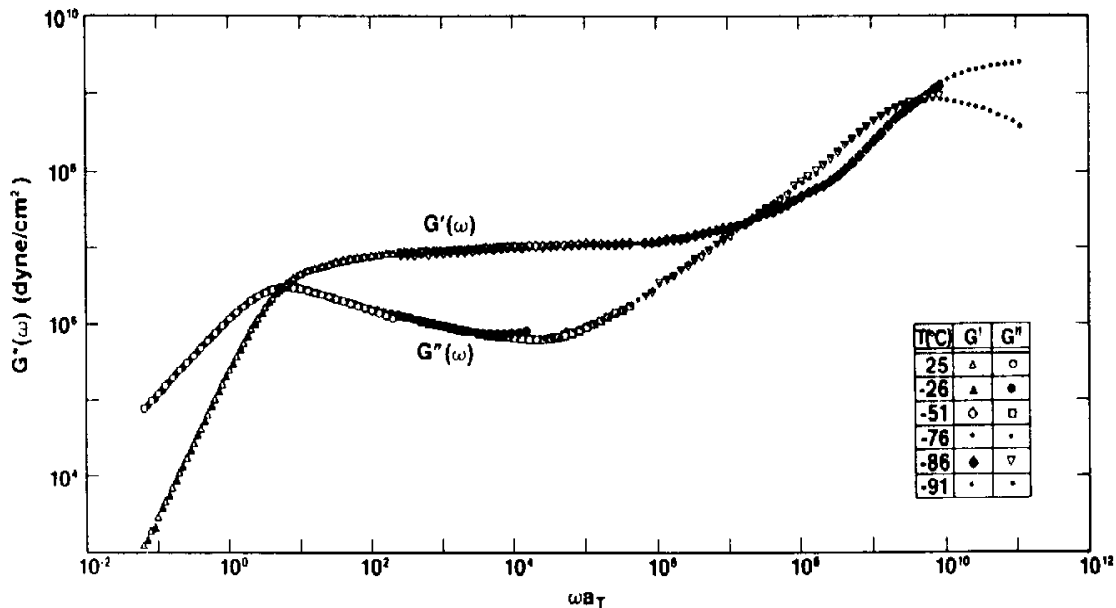


Figure 2: Storage and Loss Modulus Master Curves for Polybutadiene at Reference Temperature $T_0 = 25$ °C.

Experimentally, $G' \sim G'' \sim \omega^u$ with $0.5 < u < 0.8$ in the transition zone.

Experimentally, $\eta_0 \sim M_w^{3.4}$ instead of the reptation prediction of $\eta_0 \sim M_w^3$

Otherwise the molecular theory works fine.

Nonlinear Stresses

Shear Stress is an odd function of shear strain and shear rate.

$$\sigma(\gamma) = G\gamma + A_1\gamma^3 + \dots$$

$$\sigma(\dot{\gamma}) = \eta_0\dot{\gamma} + A_2\dot{\gamma}^3 + \dots$$

Apparent viscosity is thus an even function of shear rate.

$$\eta(\dot{\gamma}) \equiv \frac{\sigma(\dot{\gamma})}{\dot{\gamma}} = \eta_0 + A_2\dot{\gamma}^2 + \dots$$

The first normal stress difference is an even function of shear strain and shear rate.

$$N_1(\gamma) = G\gamma^2 + B_1\gamma^4 + \dots$$

The first term comes from the Lodge-Meissner Relation

$$\frac{N_1}{\sigma} = \gamma$$

$$N_1(\dot{\gamma}) = \Psi_1^0\dot{\gamma}^2 + B_2\dot{\gamma}^4 + \dots$$

First Normal Stress Coefficient is thus an even function of shear rate.

$$\Psi_1 \equiv \frac{N_1(\dot{\gamma})}{\dot{\gamma}^2} = \Psi_1^0 + B_2\dot{\gamma}^2 + \dots$$

Nonlinear Step Strain SHORT-TIME RELAXATION PROCESSES

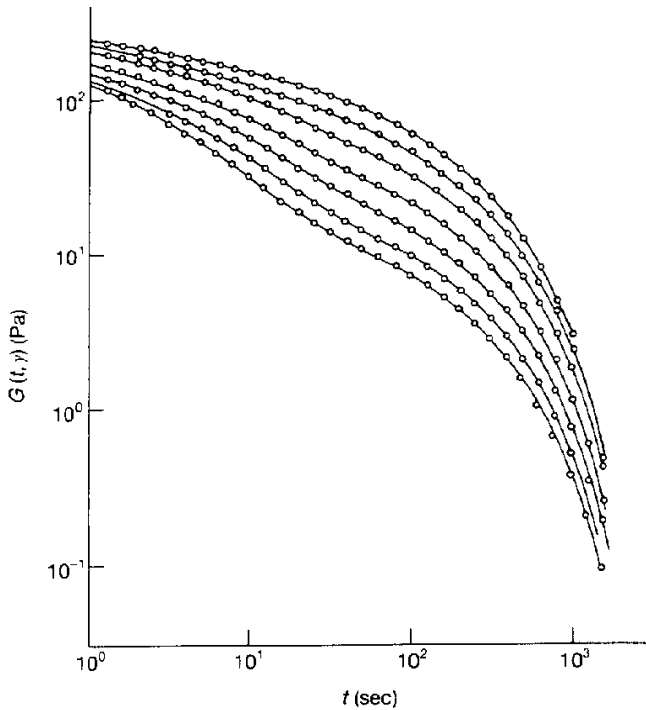


Figure 3: Nonlinear Relaxation Modulus $G(t)$ for a 6% Polystyrene Solution at 30 °C.

SEPARABILITY AT LONG TIMES

$$G(t, \gamma) = h(\gamma)G(t, 0)$$

$$N_1(t, \gamma) = \gamma^2 h(\gamma)G(t, 0)$$

$$h(\gamma) \leq 1$$

Steady Shear

Apparent Viscosity $\eta \equiv \frac{\sigma}{\dot{\gamma}}$

First Normal Stress Coefficient $\Psi_1 \equiv \frac{N_1}{\dot{\gamma}^2}$

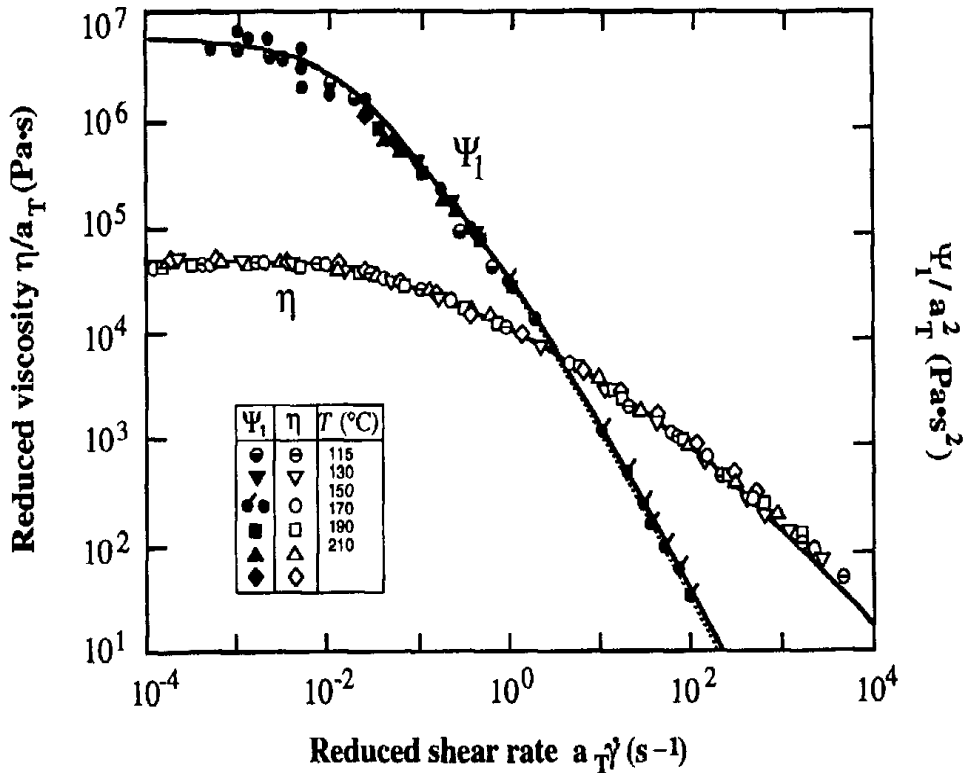


Figure 4: Shear Rate Dependence of Viscosity and First Normal Stress Coefficient for Low Density Polyethylene.

Steady Shear APPARENT VISCOSITY MODELS

Power Law Model $\eta = \eta_0 |\lambda \dot{\gamma}|^{n-1}$

Cross Model $\eta = \eta_0 [1 + |\lambda \dot{\gamma}|^{1-n}]^{-1}$

Carreau Model $\eta = \eta_0 [1 + (\lambda \dot{\gamma})^2]^{(n-1)/2}$

MOLECULAR WEIGHT DEPENDENCES

$$\eta_0 = K M_w^{3.4}$$

$$\lambda = \frac{\eta_0}{G_N^0} \sim M_w^{3.4}$$

$$\Psi_{1,0} = 2\eta_0^2 J_s^0 \sim M_w^{6.8}$$

THE COX-MERZ EMPIRICISM

$$\eta(\dot{\gamma}) = |\eta^*(\omega)| \quad (\omega = \dot{\gamma})$$

Nonlinear Viscoelasticity START-UP OF STEADY SHEAR

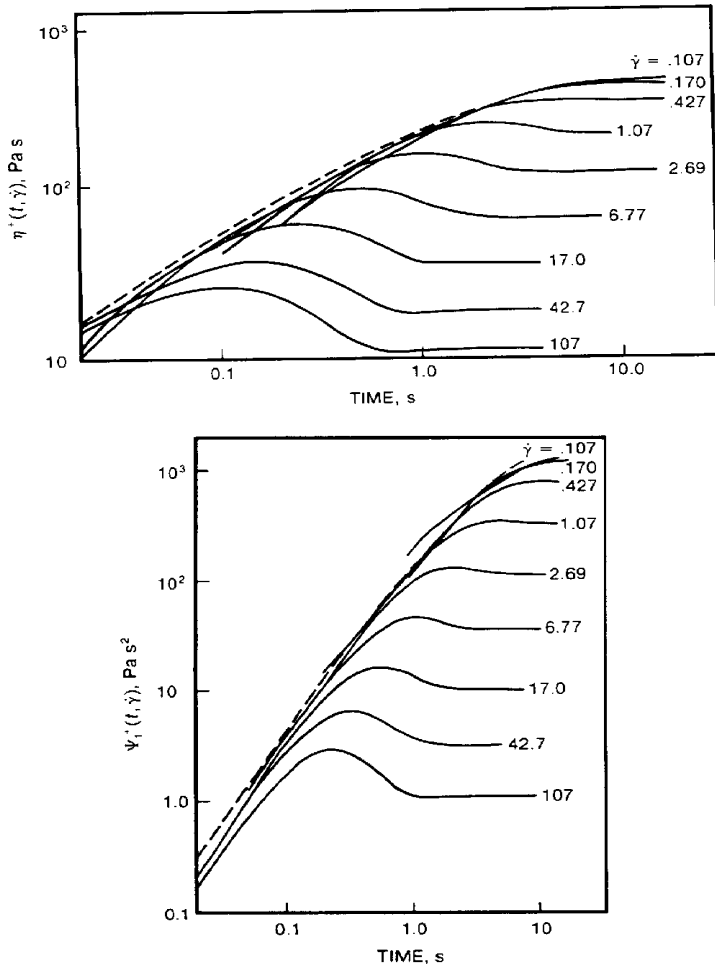


Figure 5: Shear Stress Growth and Normal Stress Growth Coefficients for the Start-Up of Steady Shear of a Polystyrene Solution.

Start-up of nonlinear steady shear shows maxima in shear and normal stress growth functions, indicating extra short-time relaxation processes induced by the large shear rate.

Nonlinear Viscoelasticity CESSATION OF STEADY SHEAR

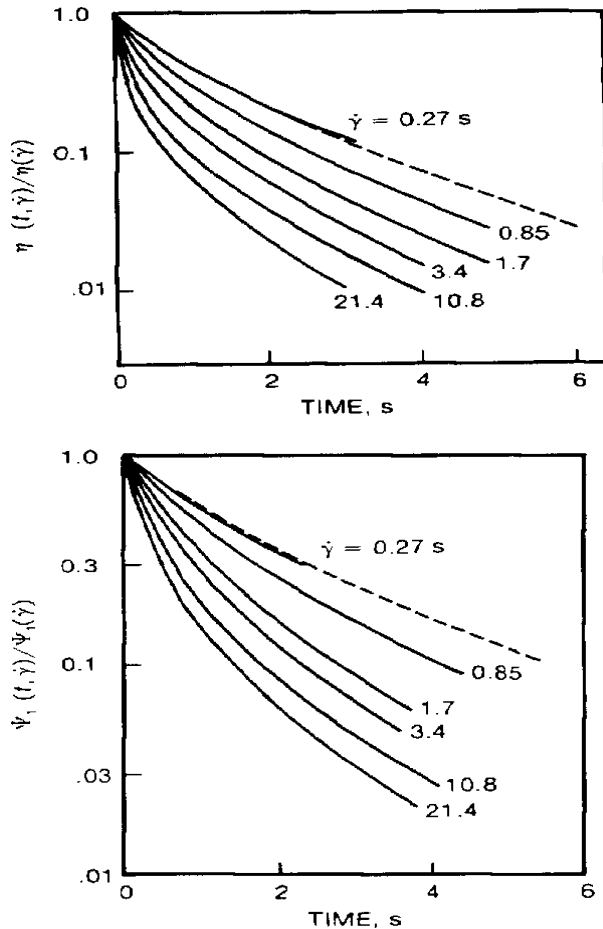


Figure 6: Shear Stress Decay and Normal Stress Decay Coefficients for Cessation of Steady Shear Flow of a Polyisobutylene Solution.

Shear and normal stresses both decay FASTER at larger shear rates, consistent with long relaxation modes being replaced by shorter-time relaxation processes that are activated in steady shear.

Nonlinear Viscoelasticity

NONLINEAR CREEP

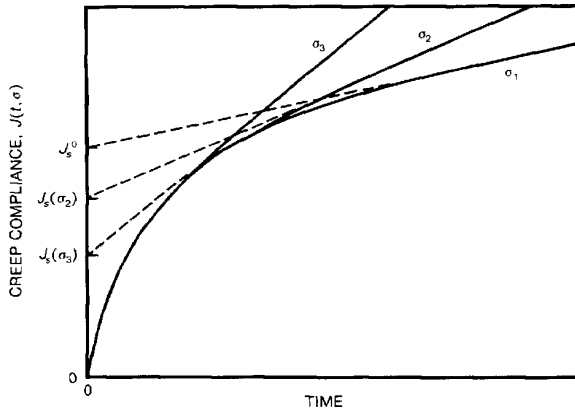


Figure 7: Creep Compliance at a Linear Viscoelastic Stress σ_1 and two Nonlinear Stresses with $\sigma_3 > \sigma_2 > \sigma_1$.

As stress increases, the viscosity drops and the recoverable strain drops, consistent with large stresses inducing additional dissipation mechanisms.

NONLINEAR RECOVERY

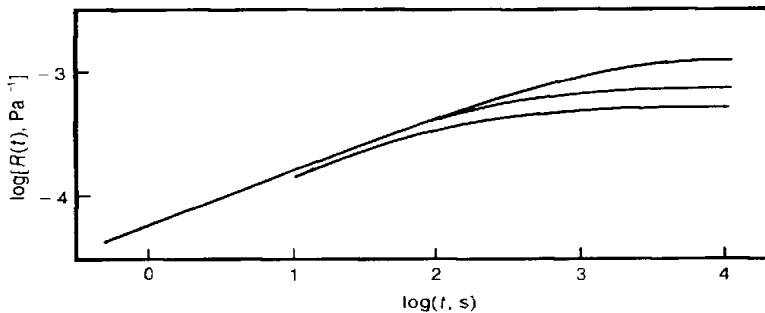


Figure 8: Recoverable Compliance after Creep at Three Stress Levels (Increasing Creep Stress from Top to Bottom).

Nonlinear Viscoelasticity

RECOIL DURING START-UP OF SHEAR

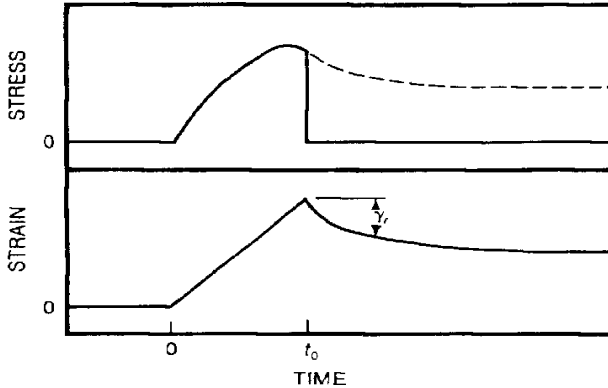


Figure 9: Recoil Part-Way Through Start-Up.

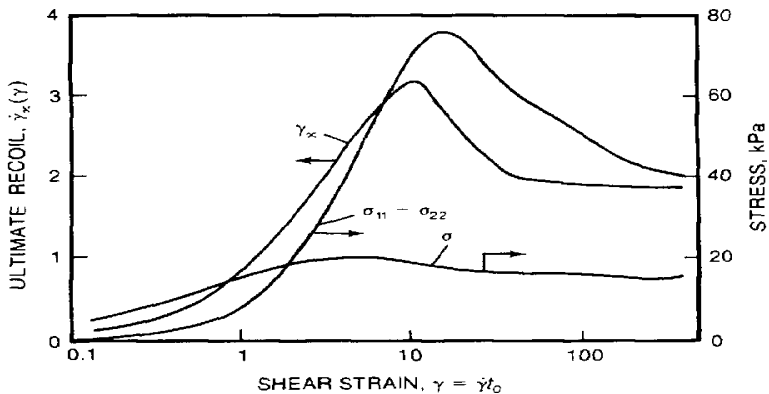


Figure 10: Ultimate Recoil During Start-Up Compared with the Shear and Normal Stress Growth Functions for LDPE.

Recoil during start-up of nonlinear steady shear shows a strong maximum because there is a short-time relaxation process activated by the strong shear.

Rheometry

ROTATIONAL AND SLIDING SURFACE RHEOMETERS

GAP LOADING vs. SURFACE LOADING

Compare rheometer gap h to shear wavelength $\lambda_s = \frac{2\pi}{\omega\sqrt{\rho/G_d} \cos(\delta/2)}$

$$\text{Gap Loading Limit:} \quad \frac{h}{\lambda_s} \ll 1$$

$$\text{Surface Loading Limit:} \quad \frac{h}{\lambda_s} \gg 1$$

For liquids of high viscosity, the shear wavelength is large and thus we are always in the gap loading limit for polymer melts and concentrated solutions.

TWO CLASSES OF GAP LOADING INSTRUMENTS:

1. Impose Strain and Measure Stress
2. Impose Stress and Measure Strain

INSTRUMENT AND TRANSDUCER COMPLIANCES

$$G'_a = \frac{\eta \left(\frac{c\eta}{K} + \lambda \right) \omega^2}{\left(\frac{c\eta}{K} + \lambda \right)^2 \omega^2 + 1}$$

$$G''_a = \frac{\eta\omega}{\left(\frac{c\eta}{K} + \lambda \right)^2 \omega^2 + 1}$$

For a known instrument/transducer compliance, one may calculate the true moduli of the material from the apparent values.

$$G' + iG'' = \frac{G'_a + iG''_a}{1 - \frac{G'_a}{k} - \frac{iG''_a}{k}}$$

Rheometry

ROTATIONAL AND SLIDING SURFACE RHEOMETERS

GEOMETRIES OF GAP LOADING INSTRUMENTS:

1. Cone and Plate

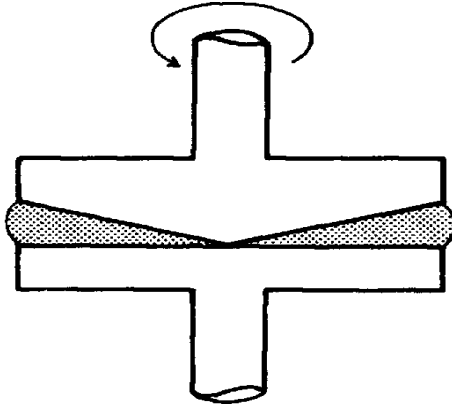


Figure 11: The Cone and Plate Rheometer.

2. Parallel Disks

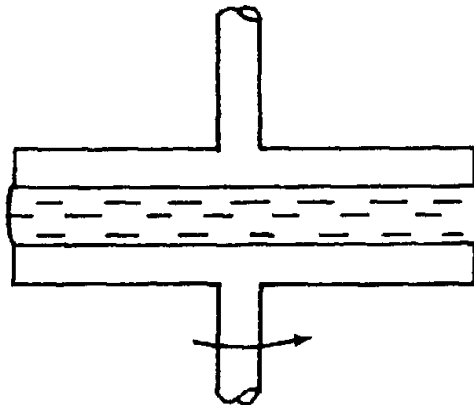


Figure 12: The Parallel Disk Rheometer.

Rheometry

CAPILLARY RHEOMETER

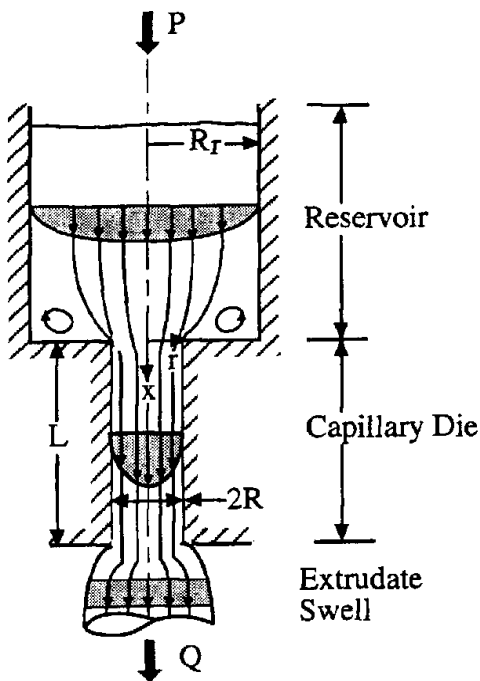


Figure 1: The Capillary Rheometer.

Wall Shear Stress

$$\sigma_w = \frac{R}{2} \left(-\frac{dP}{dz} \right)$$

Apparent Wall Shear Rate

$$\dot{\gamma}_A = \frac{4Q}{\pi R^3}$$

Rheometry

CAPILLARY RHEOMETER

END CORRECTIONS

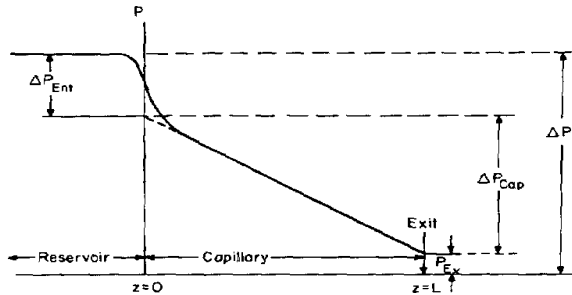


Figure 2: Pressure Distribution in Both the Reservoir and the Capillary.

Bagley correction finds dP/dz in capillary by measuring the end effects through experiments using dies of different length.

$$\sigma_w = \frac{P_d}{2(L/R + e)}$$

End Correction $e \equiv \frac{\Delta P_{ends}}{2\sigma_w}$

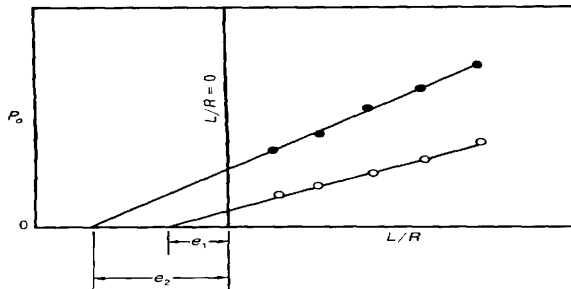


Figure 3: Bagley End Correction for Capillary Flow.

Rheometry

CAPILLARY RHEOMETER

Alternatively, we can use the Cogswell Orifice Short-Cut

$$\sigma_w = \frac{(P_d^L - P_d^0)R}{2L}$$

RABINOWITCH CORRECTION

Finally, we plot $\log \dot{\gamma}_A$ vs. $\log \sigma_w$ to perform the Rabinowitch correction which calculates the true shear rate at the wall for a general (non-Newtonian) liquid.

$$\dot{\gamma}_w = \left(\frac{3+b}{4} \right) \dot{\gamma}_A$$

$$b \equiv \frac{d(\log \dot{\gamma}_A)}{d(\log \sigma_w)}$$

QUESTION: What happens if the slope of $\log \dot{\gamma}_A$ vs. $\log \sigma_w$ is unity for all shear rates? What does this special case correspond to?

$$b \equiv \frac{d(\log \dot{\gamma}_A)}{d(\log \sigma_w)} = 1$$

$$\dot{\gamma}_w = \left(\frac{3+b}{4} \right) \dot{\gamma}_A = \dot{\gamma}_A$$

This case corresponds to a Newtonian liquid, with $\sigma_w = \eta \dot{\gamma}_w$.

QUESTION: What happens with a shear thinning polymer melt?

$$b \equiv \frac{d(\log \dot{\gamma}_A)}{d(\log \sigma_w)} > 1$$

$$\dot{\gamma}_w = \left(\frac{3+b}{4} \right) \dot{\gamma}_A > \dot{\gamma}_A$$

Rheometry

SLIT RHEOMETER

The true pressure drop in the slit is measured directly using flush-mounted pressure transducers.

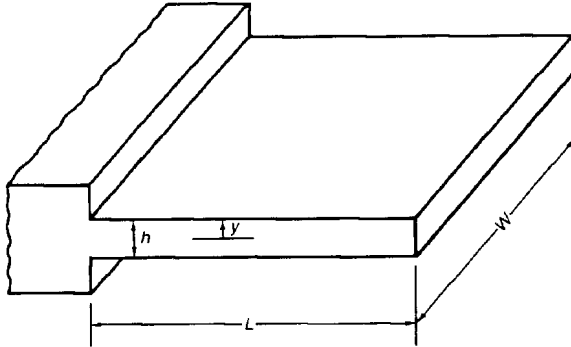


Figure 4: The Slit Rheometer. $L > W \gg h$.

$$\text{Wall Shear Stress} \quad \sigma_w = \frac{-\Delta P h}{L} \frac{1}{2}$$

$$\text{Wall Shear Rate} \quad \dot{\gamma}_w = \left(\frac{6Q}{h^2 w} \right) \left(\frac{2 + \beta}{3} \right)$$

$$\beta = \frac{d [\log(6Q/h^2 w)]}{d [\log(\sigma_w)]}$$

$$\text{Apparent Viscosity} \quad \eta = \frac{\sigma_w}{\dot{\gamma}_w} = \frac{-\Delta P}{L} \frac{h^3 w}{4Q(2 + \beta)}$$

Rheometry

SLIT AND CAPILLARY RHEOMETERS

DIE SWELL

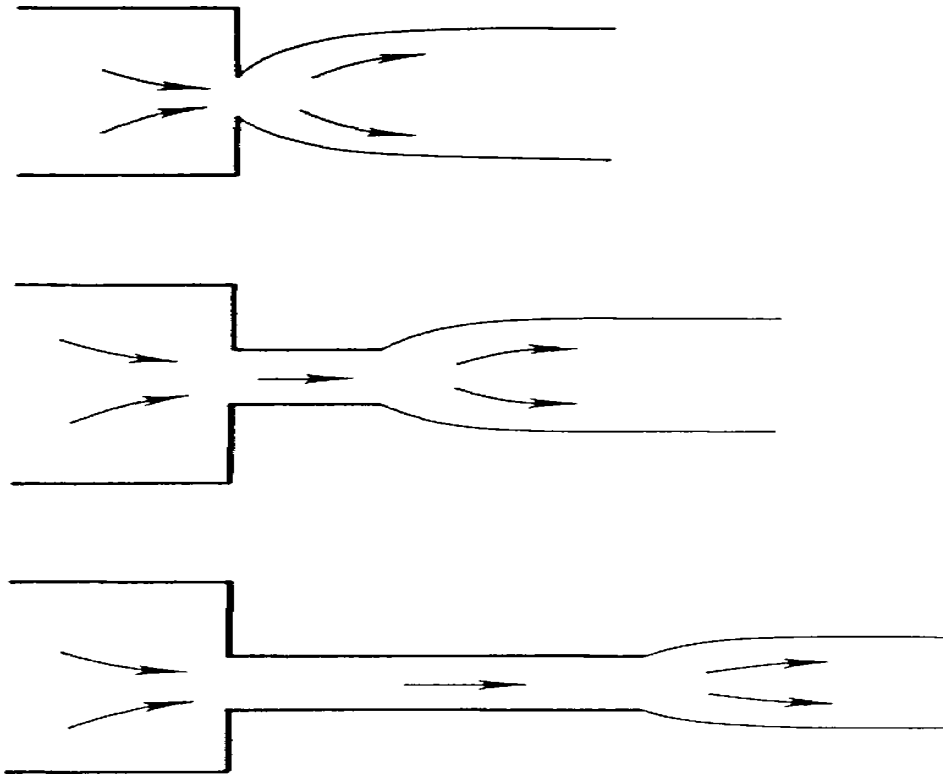


Figure 5: Extrudate Swell after Exiting the Die Diminishes as the Die is Made Longer because the Memory of the Flow Contraction at the Entrance is Reduced.

With a specific polymer and die, die swell increases with increasing shear stress.

Die swell increases as the die is shortened.

Die swell increases as the molecular weight increases.

Die swell increases as the molecular weight distribution is broadened, as it is particularly sensitive to the high molecular weight tail of the distribution.

Rheometry

SLIT AND CAPILLARY RHEOMETERS

EXTRUDATE DISTORTION

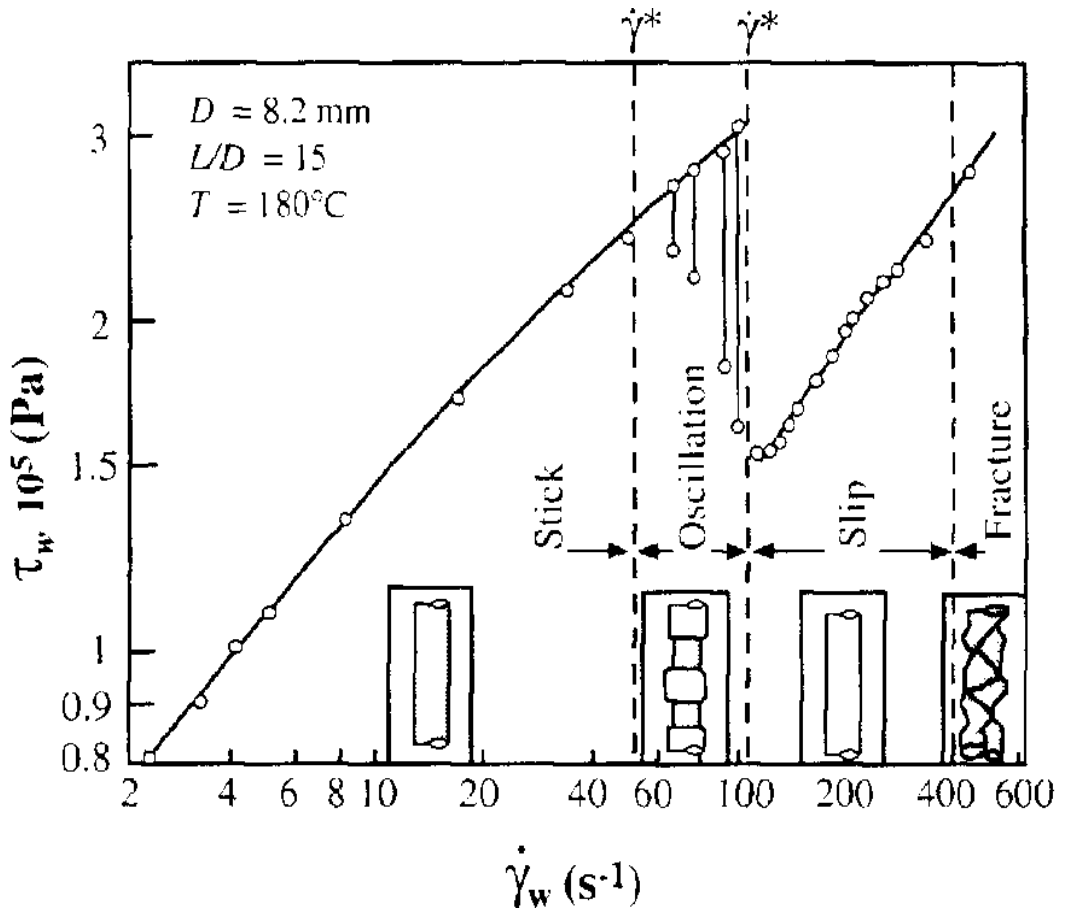


Figure 6: Wall Shear Stress vs. Wall Shear Rate for HDPE Showing Flow Instabilities and Wall Slip.

Flow instabilities occur in all rheometers at sufficiently high stress levels.

In cone and plate and parallel disk rotational Couette rheometers, the shear stress required for the onset of flow instabilities is considerably lower than for the Poiseuille flow rheometers.

Molecular Structure Effects

POLYDISPERSITY

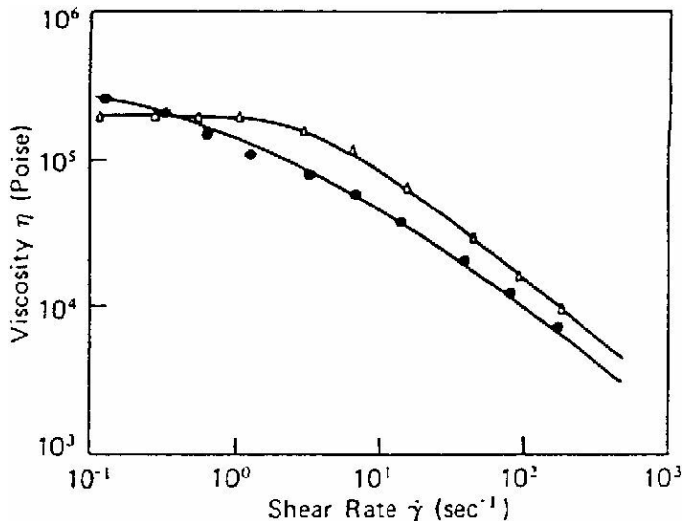


Figure 21: Apparent Viscosity in Steady Shear for Polystyrene. Filled symbols have $M_w = 260000$ with $M_w/M_n = 2.4$. Open symbols have $M_w = 160000$ with $M_w/M_n < 1.1$.

Zero shear viscosity is simply a function of weight-average molecular weight.

$$\eta_0 = \begin{cases} K_1 M_w & \text{for } M_w < M_c \text{ (unentangled)} \\ K_2 M_w^{3.4} & \text{for } M_w > M_c \text{ (entangled)} \end{cases}$$

Steady state compliance, and other measures of elasticity (such as first normal stress difference and die swell) are strong functions of polydispersity.

$$J_s^0 \sim \left(\frac{M_z}{M_w} \right)^a \quad \text{with } 2 < a < 3.7$$

Molecular Structure Effects

BRANCHING

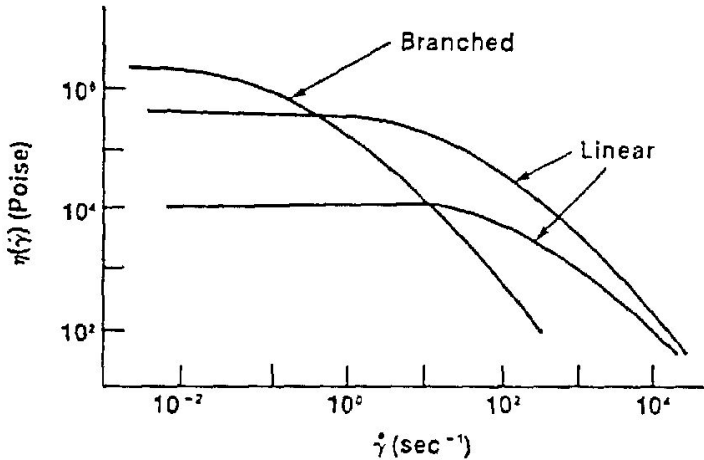


Figure 22: Apparent Viscosity of Randomly Branched Polymers Compared to Linear Polymers.

Monodisperse entangled branched polymers have a stronger dependence of viscosity on molecular weight than linear polymers.

$$\eta_0 \sim \exp\left(\frac{\nu M_b}{M_e}\right)$$

Monodisperse entangled branched polymers have steady state compliance increasing with molecular weight.

$$J_s^0 = \frac{0.6M_b}{cRT}$$

M_b is the molecular weight of the star arm.

Randomly branched polymers have effects of **both** branching and polydispersity.

Injection Molding

Injection Molding Cycle

- Inject and pack mold

- Extrude next shot once gate solidifies

- Eject part once part solidifies

Injection Molding Economics

- Only inexpensive if we make many parts

Injection Molding Window

Poiseuille Flow in Runners and Simple Cavities

- Calculate injection pressure to fill mold

- Balance runner systems

- Calculate clamping force

- Assumptions:

 - Isothermal

 - Newtonian

Hot Runner Systems

- No runners to regrind

- More expensive

Injection Molding Defects

- and how to avoid/control them

 - Weld Lines

 - Sink Marks and Voids

 - Short Shots / Uneven Filling

 - Burn Marks

 - Sticking

 - Warping

Extrusion

Extruder Characteristic:

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

Die Characteristic:

$$Q = \frac{K}{\mu} \Delta P$$

together, they determine the Operating Point

Pumping vs. Mixing:

Compression Ratio and Flow Restrictions

Pressure Distribution

Residence Time Distribution

Twin Screw Extrusion

Dimensional Analysis

Buckingham PI Theorem

Intuition or Experience Helps

Mass Balance

Uses of Extruders

Injection Molding

Blow Molding

Pelletizing

Heat Transfer

Sheet Extrusion

Thermoforming

Fiber Spinning

Pipe Extrusion

Film Blowing

Coextrusion

Barrier properties

Profile Extrusion

Wire Coating

Blow Molding

Blow Molding Cycle

Parison Extrusion

Parison sag

Blowing

Cooling

Ejection

Extrusion Blow Molding Economics

Less expensive than injection molding

Stretch-Blow Molding

Biaxial orientation

Ring-Neck Blow Molding

Improved thickness control

Better precision in neck of bottle

Injection-Blow Molding

Improved thickness control

Fewer surface defects

Better precision in neck of bottle

Blow Molding Defects

and how to minimize them.

Advantages of Branched Polymers

Rotational Molding

The only process we have learned about that does NOT make use of an extruder.

Rotational Molding Cycle

High-Speed Rotation to Pack Powder

Sintering

Cooling (Heat Transfer)

Removal

Rotational Molding Economics

Cheap way to make small numbers of large parts.

Thermoset Molding

Gelation:

- Divergence of Viscosity

- Growth of Modulus

Thermoset Molding Cycle

- Inject and pack mold

- Cure part

- Eject part once part solidifies

Thermoset Molding Economics

- Less capital investment than injection molding

- No way to recycle waste or final product

Compression Molding

Transfer Molding

Injection Molding

Reaction Injection Molding

- Impingement Mixing