Rheology-Its Importance and Application in Polymer Processing

"Thinking Rheologically"

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Rheology

The Study of Deformation and Flow

Polymer Processing

The act of converting one or more polymers from one form into another more useful or desirable form.

Thinking Rheologically

Challenge everyone to use rheology in your everyday life, and at work

- Don't tap the ketchup bottle at lunch
  - Ketchup shear thickens
- Tell a someone to "Pound Sand"
  - Sand shear thickens
- Measure your materials viscosity
  - Does it shear thin, shear thicken or is it Newtonian?
- Look at your process as a rheometer or a combination of rheometers

Thinking Rheologically

All processing equipment are Rheometers if instrumented

- Extruder
  - motor current
  - Discharge pressure,
  - ΔP Melt pipe to die exit
- Caster drive/Profile puller
- Internal bubble pressure
- Orientation forces
  - Direct measure draw force
  - Motor current
- Winders
  - Tension and % elongation
  - Air layer thickness

- No Viscosity knob
- No Elasticity knob
- Seldom a shear rate knob
- Likely a strain inducing knob "draw pot"
- Need: turn the language of Rheology into language of Management, operators and trouble shooters

Engineer As Interpreter

- Language of management
  - Line speed standard
  - Reclaim level
- Language of the operators / key trouble shooters
  - Line speed
  - Screw speed
  - Barrel and die temperatures
  - Die number or manufacturer
  - Stretch ratio
- Not the Language of science
  - Not differential equations
  - Not Viscosity ratio
  - Not extension rate
  - Not shear rate
  - Not Normal force difference
  - Not power law index
  - Layer thickness ratios
- Need to convert "Rheology" into language of:
  - Operators and key trouble shooters
  - Management
- Everyone can understand Algebra

Rheological Approach

- Measure the appropriate rheological properties
  - Viscosity verses Shear rate @ temperature
  - Stretching forces at proper temperatures and rates
- Write equations of motion for the process
- Select a constitutive equation to use
- Solve the problem
  - Approximate the answer mathematically
  - Find an existing answer which is close
  - Do designed experiment to characterize system
  - From process measurements, scale up based on "model"
- Confirm the Model
  - Prediction verses experiment

Polymer Processing Engineers

- Need solutions or approximations to the Equations of Motion describing the process
  - Empirical experiments
  - Numerical Solutions
  - Exact Solutions
- The tie to the process is the Constitutive Equation for the Polymer
- A "Rheological" approach will give important insights into the process and its design & troubleshooting

- Constitutive Equation
- Ties the material behavior to the energy, momentum and mass flows in the process
- The " Constitutive Equation" is still missing
  - Complete description of the Viscoelastic behavior
- Make use of simpler models for particular applications
  - ❖ Algebra of answer gives behavior
  - Give insights into behavior
  - Permit design calculations
  - Success defines utility

Applied (Plant) Rheology

- Temperature indicators are to be doubted
- When the line is running well:
  - Read the performance of the line
    - All the pressure measurements
    - All of the motor power measurements
- When the line is running poorly:
  - Look for changes in Pressures, motor power
  - Change process conditions to move to proper level
- Characterize the performance of the equipment
  - Coextrusion System for onset of flow disturbance
  - Extruder for power consumption, output, and melt temperature levels
  - Stretching equipment for force vs. strain rate and sheet temperature

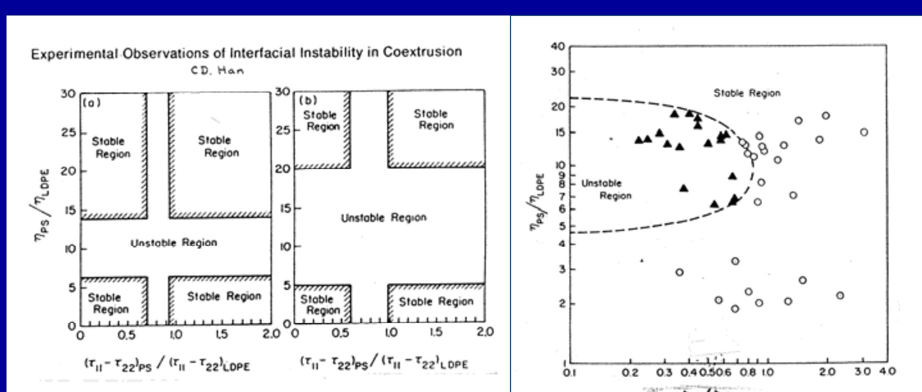
Thinking Rheologically about:

- Coextrusion Instability
- Moisture Barrier Improvement
- Die layer uniformity
- Resin change for Product design
- Solid State Orientation
  - Develop simple description
  - Measure properties of polymer in draw

Coextrusion Stability

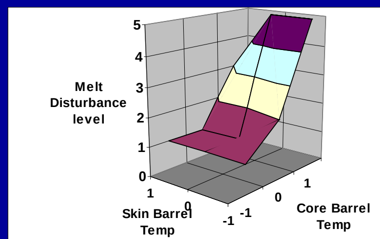
Viscosity Ratio vs. Elasticity Ratio

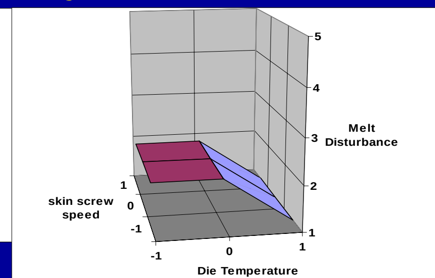
C.D. Han, "Interfacial Instability in Stratified Multiphase Flow", Chap 8, *Multiphase Flows in Polymer Processing*, Academic Press, (1981)



Characterize System Melt Disturbance

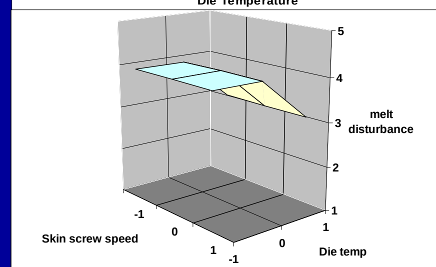
Defining Viscosity Knobs





Viscosity ➔ Temperature & Shear rate

- Melt Temperature
  - Barrel & Die temperature
  - Screw design & Output level
- Shear Rate
  - Output level (screw speed)
  - Die Land Gap dimensions



OPP WVTR Improvement

- Lower MF PP:
  - improves WVTR of OPP film
  - Increases back pressure and Orientation forces
- Send new resin to plant
  - Don't inform operators of changes expected
- Head pressure increases
  - Operators "knows" standard resin will be an operating problem at this pressure
  - Increases extrusion temperatures to "lower head pressure"
  - Creates higher MF resin from low MF resin
- WVTR of film remains the same

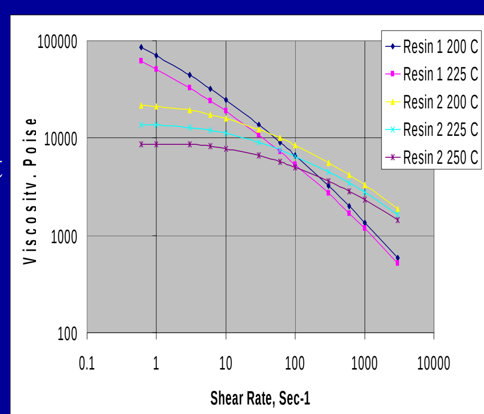
Applied Rheologists

Film Layer Distribution Problem

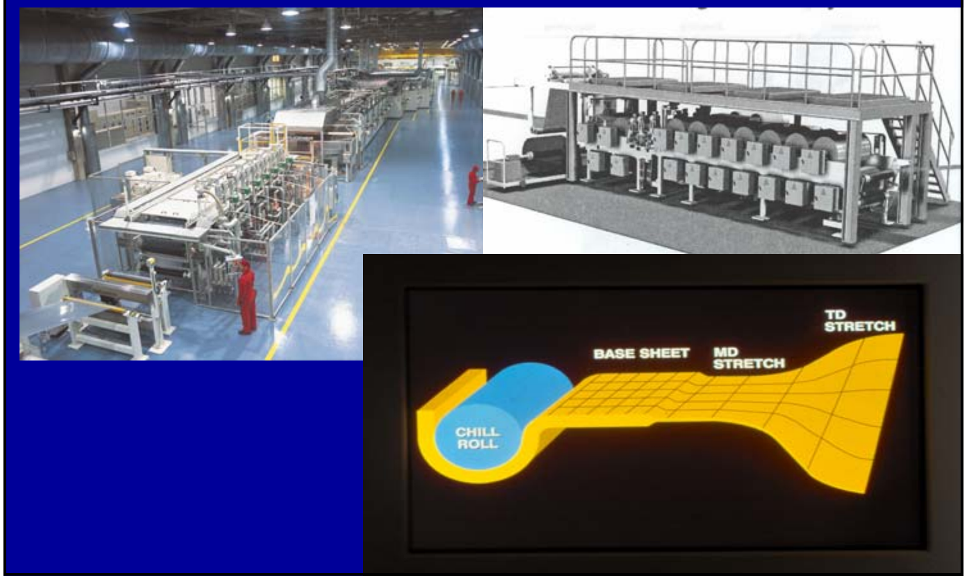
- Lower MF to Improve Product Properties
  - Teach operator to not change the resin MF!
- Viscosity of core changes layer distribution of skins
  - Change die ? Seems hard
  - Change skin resin ? Seems easy
- Change skin without regard to other extrusion systems
  - Create a flow instability on adjacent line
  - Limits line speed or reclaim utilization

Product Design Change

- Have die with good performance
- Want to replace PP copolymer film or sheet layer with LLDPE
- Layer distribution change expected and OK
- Increase line speed cause flow instability

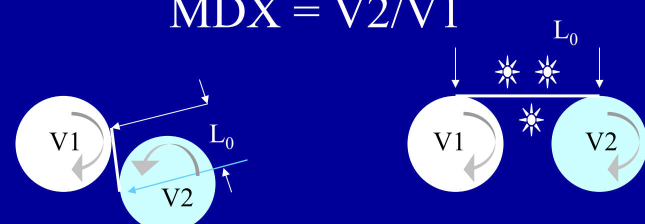


Solid State Orientation Rheology



Machine Direction Draw Point

$$MDX = V2/V1$$

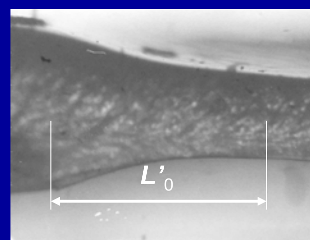


S-Wrap Draw

Roll to Roll Draw

Analysis of Draw Point

- At the draw point the polymer is deformed
  - Draw stress
    - Stress = Force / area
    - Area = $W_0 * t_0$ (for engineering stress)
    - Force = torque / roll radius
    - Torque ≈ motor power
  - Draw rate (elongation rate, $\dot{\varepsilon}$)
    - Change in speed / distance of speed change
    - $\dot{\varepsilon}$ = (V2-V1) / L_0
    - "True" L_o dependent on Neck Formation



MDO as Rheometer

- Define elongational viscosity
  - Viscosity = draw stress / elongation rate

$$\chi = \frac{\sigma}{\dot{\varepsilon}}$$

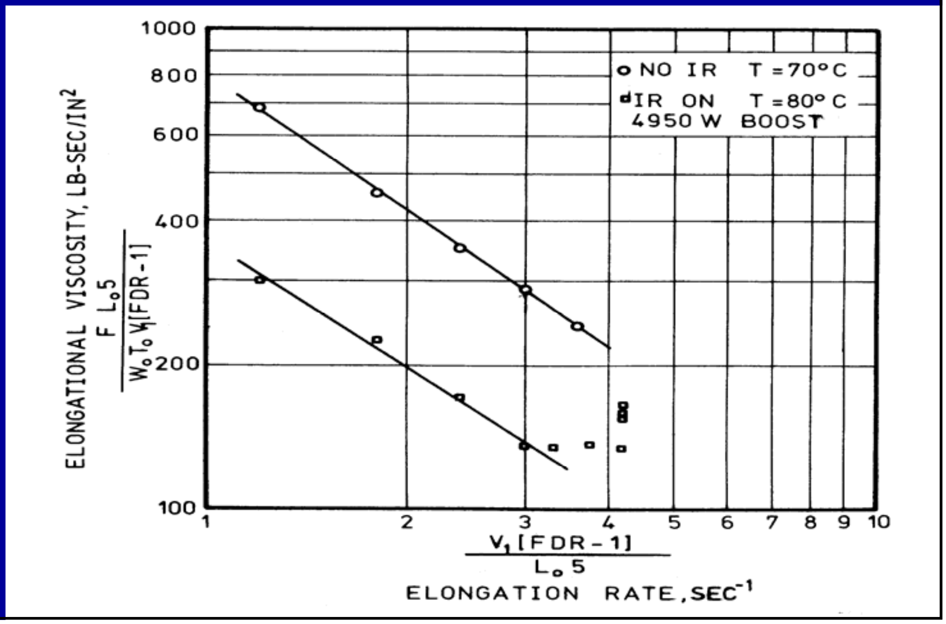
substitute in for definition of stress and elongation rate

$$\sigma = \frac{F}{A} = \frac{F}{W_0 t_0} = \frac{Torque}{R_D W_0 t_0} \propto \frac{\text{Draw Amps}}{R_D W_0 t_0}$$

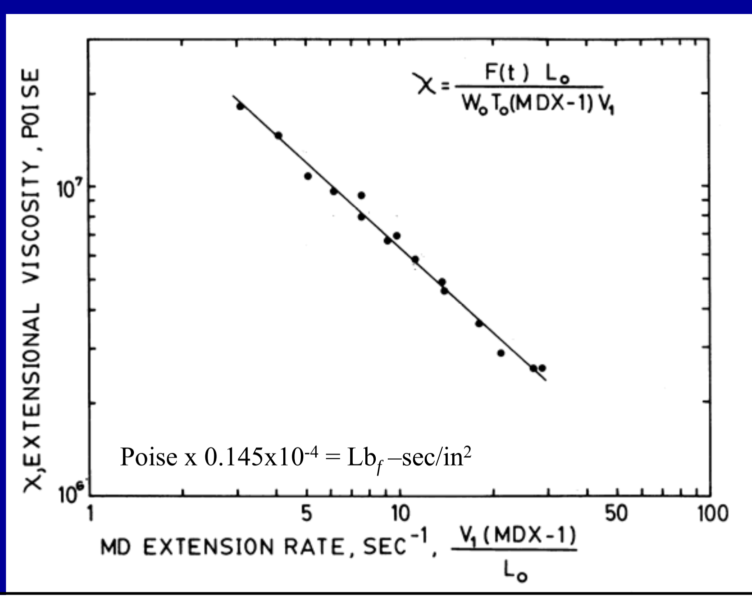
$$\dot{\varepsilon} = \frac{(V_2 - V_1)}{L_0} = \frac{V_1(MDX - 1)}{L_0}$$

$$\chi = \frac{F}{A\frac{(V_2 - V_1)}{L_0}} = \frac{FL_0}{V_1 W_0 t_0 (MDX - 1)}$$

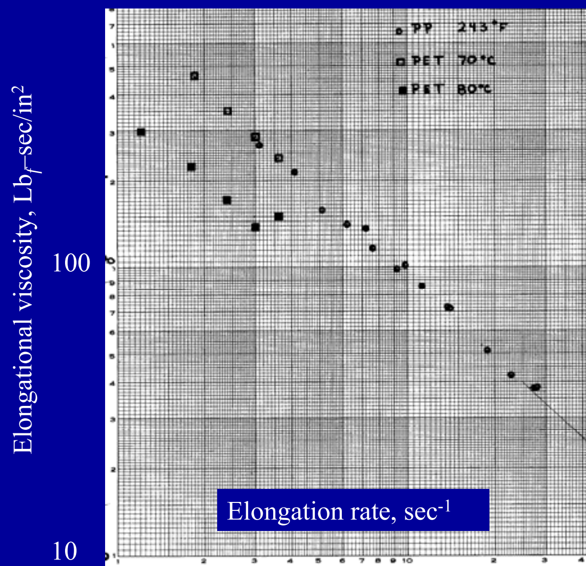
PET MD Draw Data



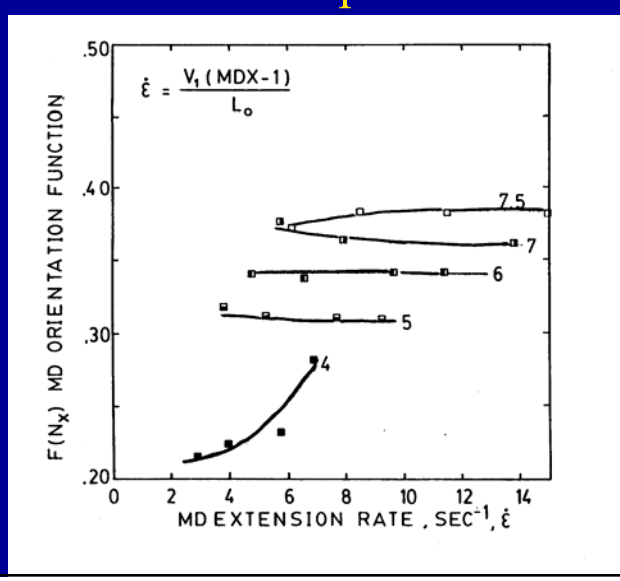
PP MD Draw Viscosity



Comparison of PP and PET Data



Impact of Necking On Orientation Development

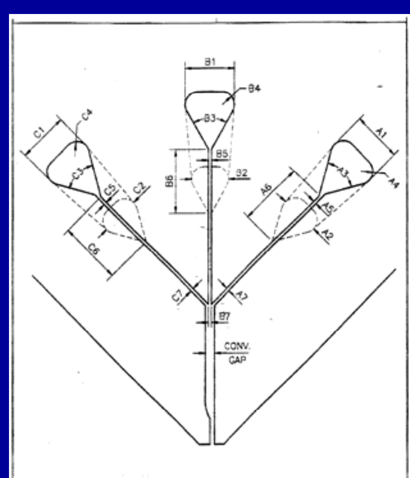


Conclusions

- Easy to Use Rheology in our everyday lives as polymer processors
- Measure Rheological properties of our materials
- Have to interpret the language of Rheology into Plant & Business language
- Model systems and Measure material response
- Interpret material behavior in Equipment

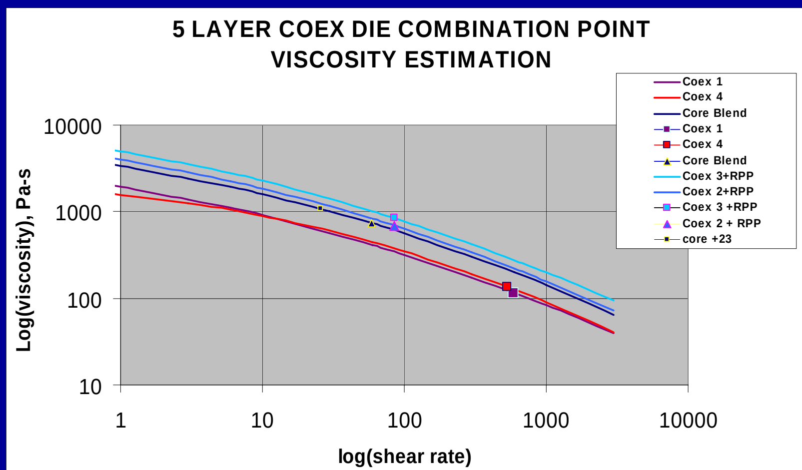
Melt Disturbance Trouble Shooting

- Die internal design
- Polymer melt rheology
- Product design, layer thickness desired
- Extrusion system performance
- Equipment set points
- Estimate relative layer viscosity at convergence



Compare Relative Layer Viscosity

Determine likelihood of Melt Disturbance



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- ***• Polymer Processing and***
- ***Troubleshooting***
- ***• Capillary Rheometer***
- ***Viscosity measurements***
- ***• Extrusion and Melt System***
- ***Design, Specification and Start-Up***
- ***• Polymer Film Design and***
- ***Manufacture***
- ***• Microscopic Film evaluation and layer***

thickness measurement

- ***• Film Surface Treatment***
- ***• Metallization of Polymer Films***
- ***• Customized In-House Training***
- ***Classes***
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- ***Property Specialist***
- ***• Literature Searches and***
- ***Technology Reviews***

- **QUALITY SERVICE**
- **Confidentiality**
- Complete confidentiality of client information with no disclosure of confidential information
- **Ethical**
- All patentable concepts developed while working for client, disclosed and assigned to client,
- **Efficiency**
- A knack for being able to “zero-in” on the problem at hand and to systematically identify solutions,
- **Team Player/Excellent Communicator**
- Able to work well with line-operators, engineering staff and management to cross-communicate technical information,
- **LIFETIME EXPERIENCE/ TOP-NOTCH KNOWLEDGE**
- Troubleshoot or focus your R & D having the advantage of a lifetime of learning and experience,
- **Continuous Improvement**
- Goal is to exceed the client’s expectations and to provide information about the most recent advancements in the field,
- **References**
- Professional references gladly provided.

PET Stretching Load
low strain rate