Simulation, Rheology and Efficiency of Polymer Enhanced Solutions

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Background

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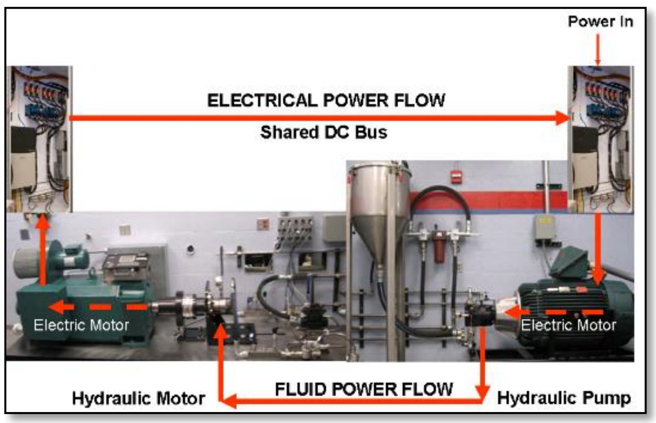
- Higher efficiency hydraulic fluids typically contain polymeric additives (viscosity index improvers or VIIs) that thicken oil at high temperatures
- Polymer additives are susceptible to permanent and temporary viscosity loss due to shear
- Polymer additives that resist shear are required to assure that the viscosity of the fluid stays in grade
- However, still not fully understood are:
  - The relationship between shear stability and hydraulic efficiency
  - The mechanisms of thickening for different polymers and the effect of shear on that behavior

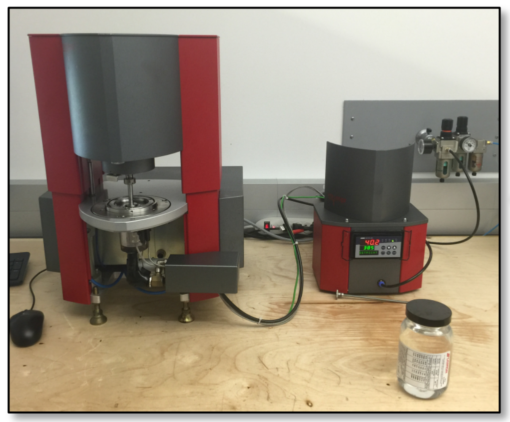
Research Strategy

Project Goal: Bridge the gap between fundamental behavior of polymer enhanced fluids and the performance of complex fluid power systems

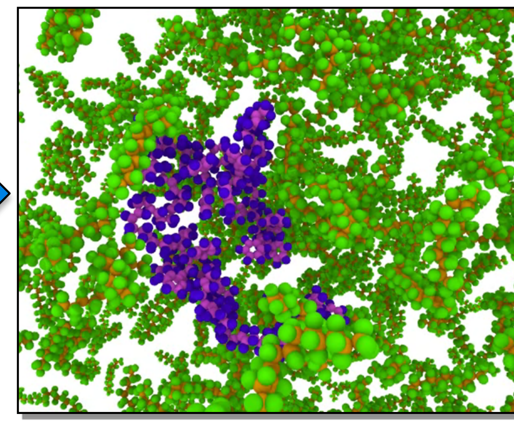
Hydraulic Efficiency



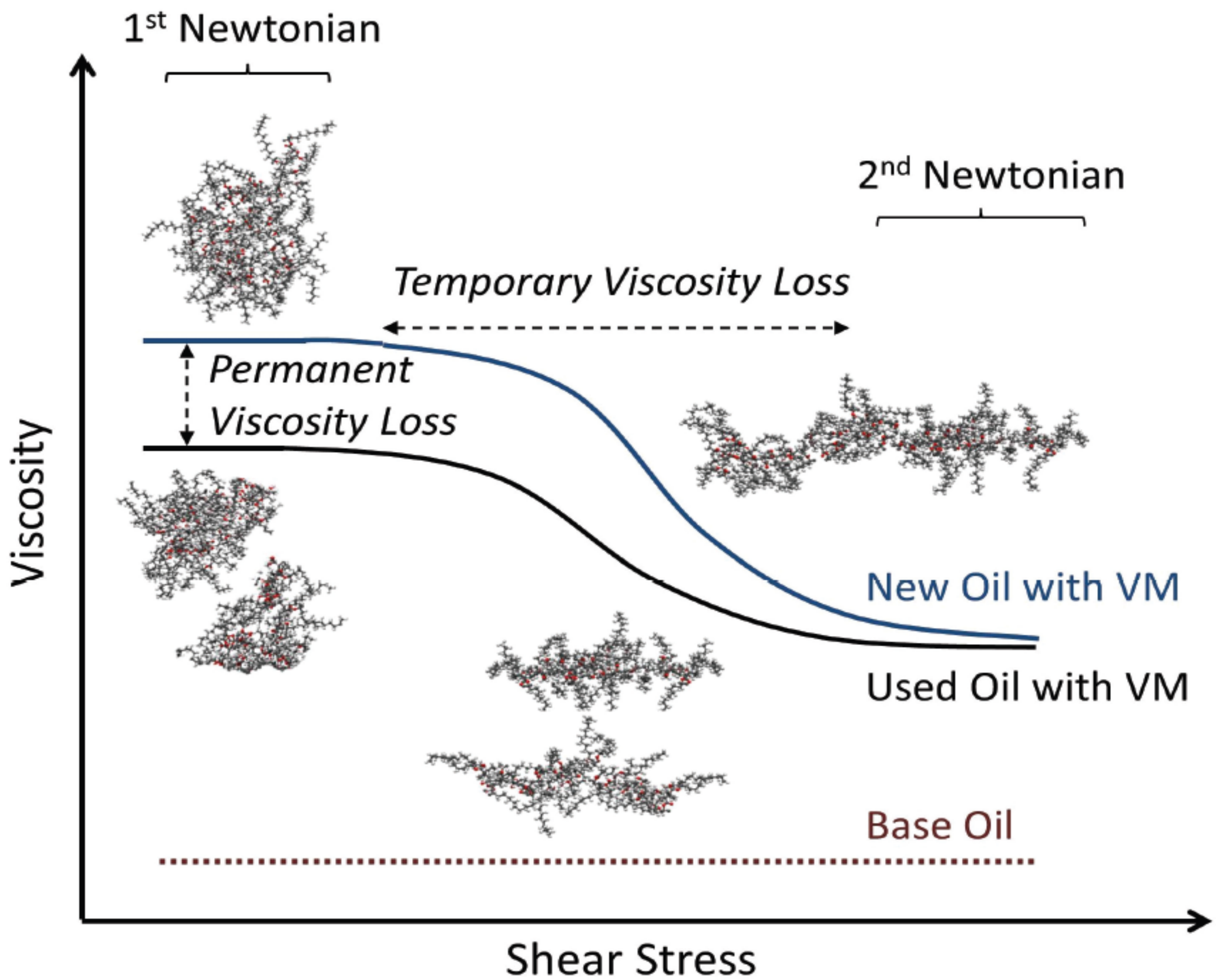
Solution Rheology



Molecular Properties



Shear Stability



Correlating Viscosity to Efficiency

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Viscosity:

- Low shear before test
- Low shear after test
- High shear before test
- High shear after test
- After Sonic Shear
- After KRL

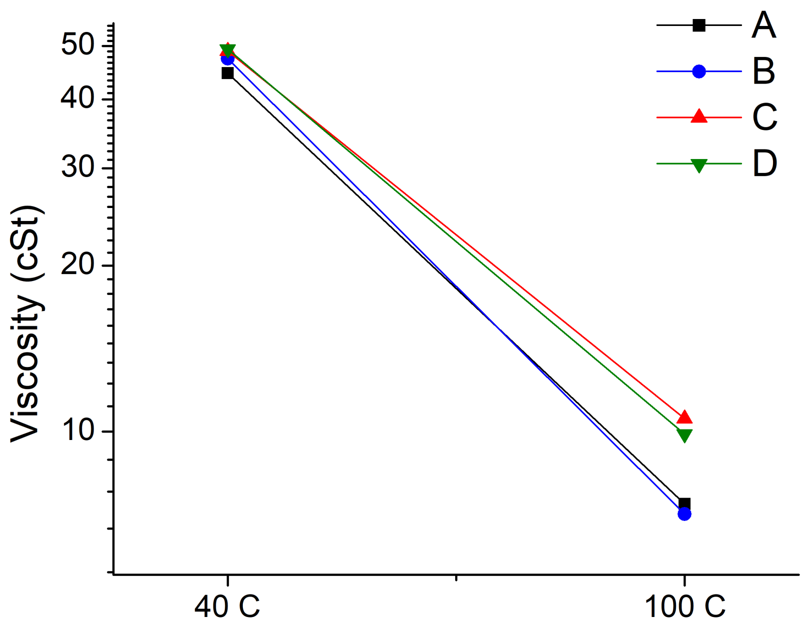
? →

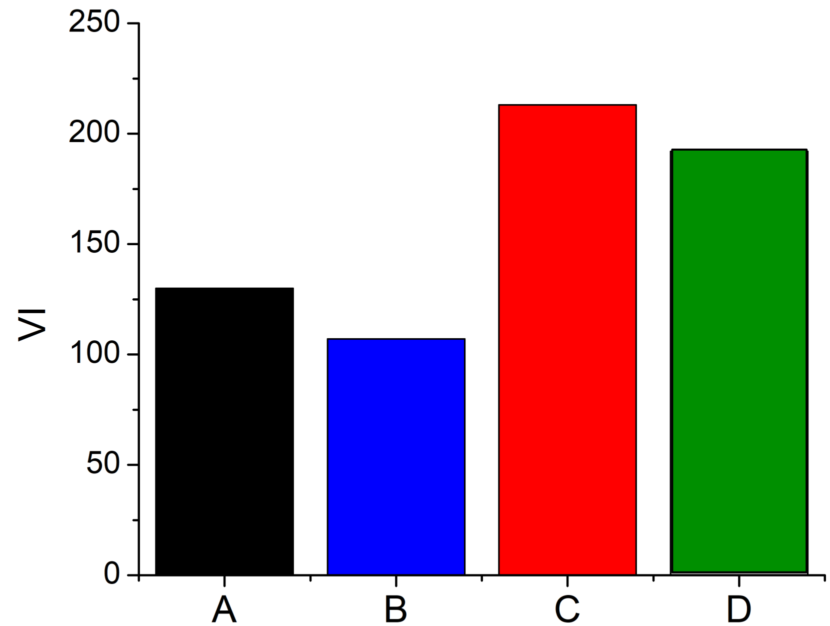
Efficiency:

- Flow loss
- Motor torque loss
- Pump inlet torque

Viscosity Index

- Measurements performed with two straight grade fluids (**A** and **B**) and two fluids with PAMA VII (**C** and **D**)
- Addition of the VII reduces flow loss





Measurements

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- Permanent Viscosity Loss
  - Sonic shear stability test
  - KRL test
  - Low shear viscosity of samples taken during dynamometer testing
- Temporary Viscosity Loss
  - Viscosity of samples prior to testing measured at a range of temperatures and shear rates
- Hydraulic Efficiency
  - Flow loss
  - Motor torque
  - Input power

Permanent Viscosity Loss

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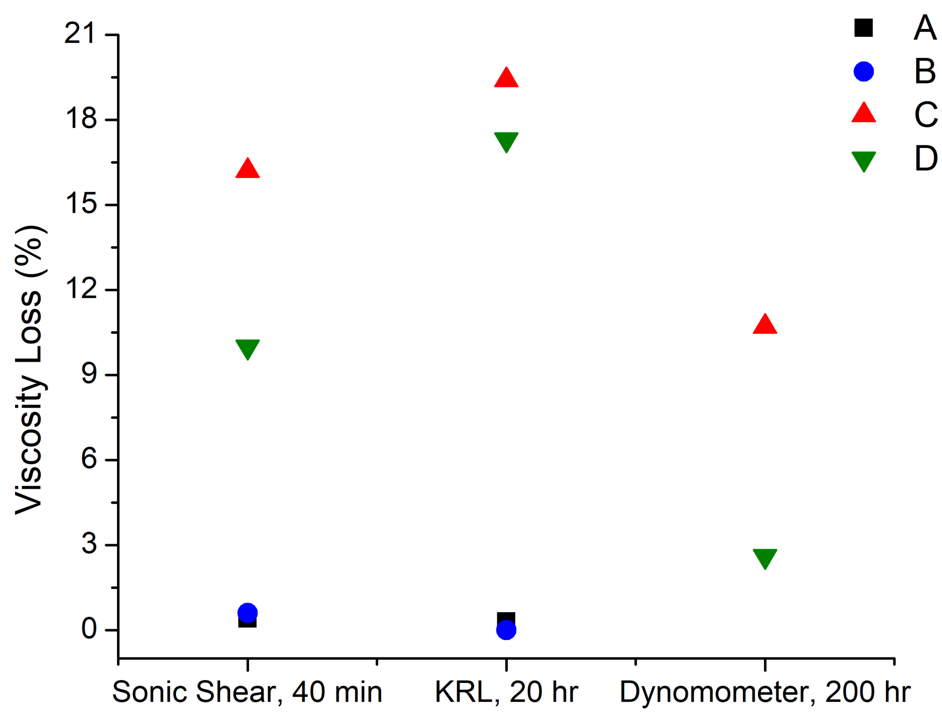
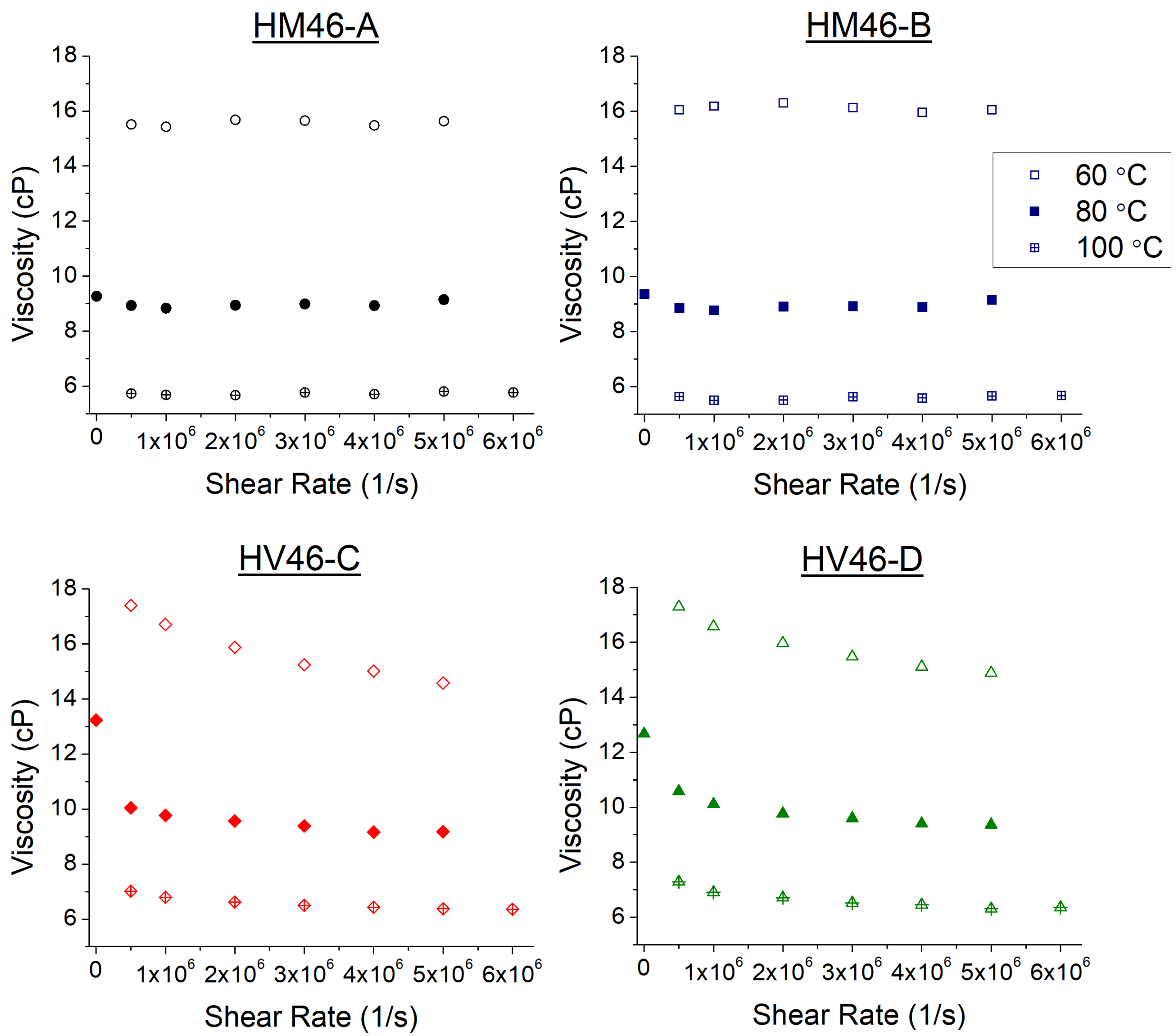
- Fluids with VII have significant viscosity loss, but the more shear stable polymer (**D**) performs better



Temporary Viscosity Loss



Dynamometer

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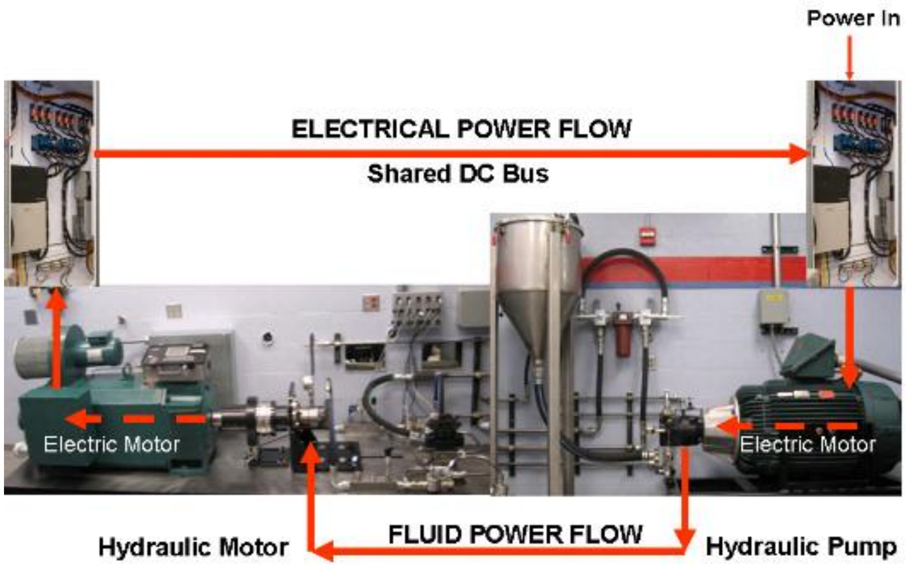

Danfoss Series 45 Pump
Modified ISO 4409
Axial piston pump
Variable displacement
50ºC and 80ºC inlet temp

Danfoss Series 90 Motor
Modified ISO 4392-1
Axial piston motor
1000 to 4000 psi
1 to 1400 RPM

- Studied change in system flow losses over time
- Flow losses = internal leakage that is lost kinetic energy that doesn't produce work
- Flow losses = pump and motor case drains + pressure compensator + valves
- 35 Data sets
- 328 combinations of pressure, speed and temperature for each data set
- 11,480 measurements

Circuit Schematic

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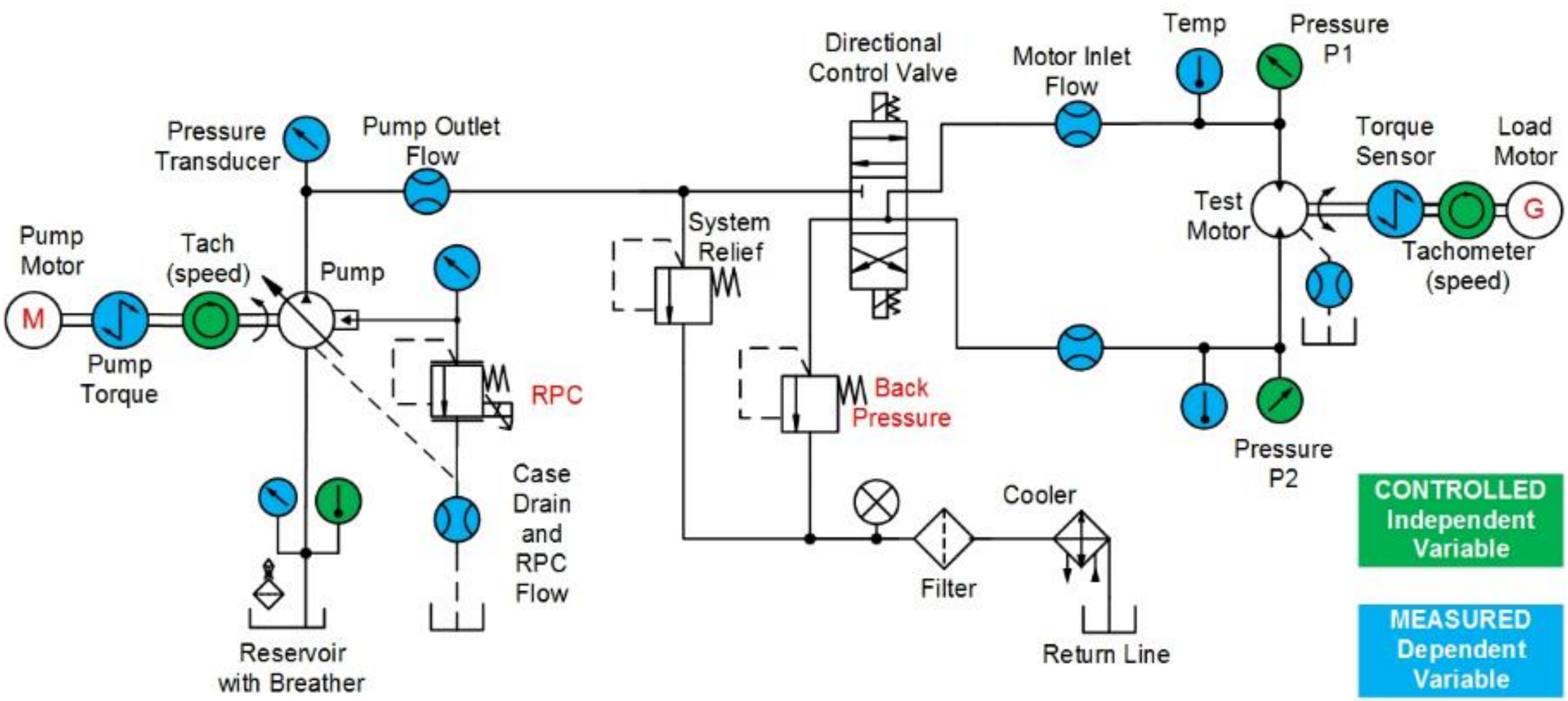
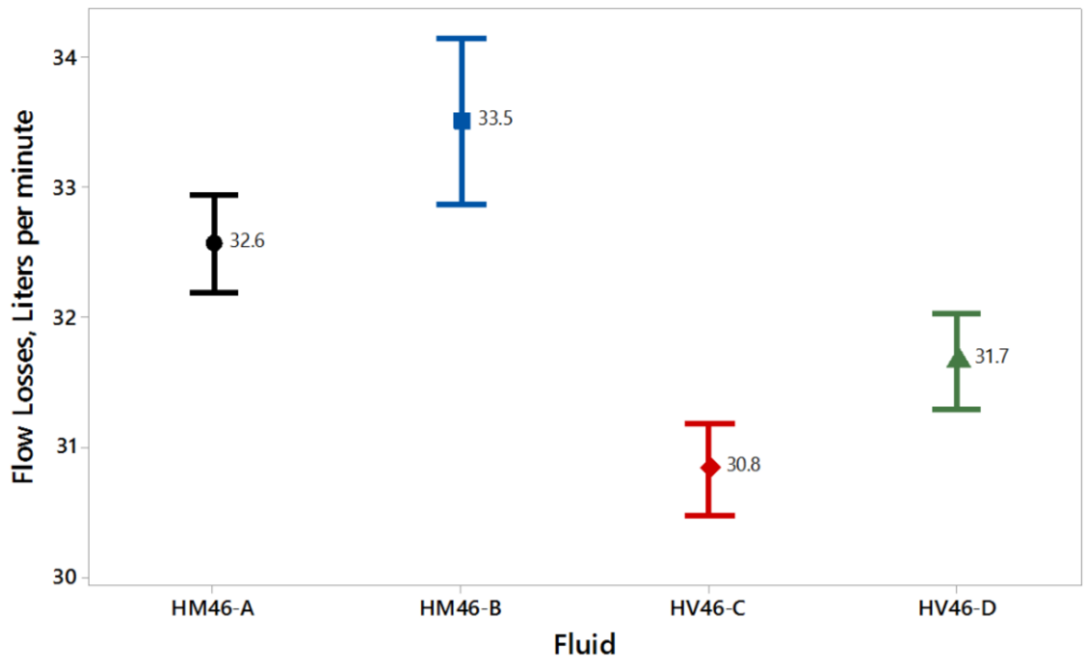


Flow Loss

- Measurements performed with two straight grade fluids (**A** and **B**) and two fluids with PAMA VII (**C** and **D**)
- Addition of the VII reduces flow loss



Results include rows where Temp=80°C and P > 15 MPa

Model

The performance of hydraulic pumps and motors is affected by friction, viscous drag, fluid compressibility and pressure driven flow losses

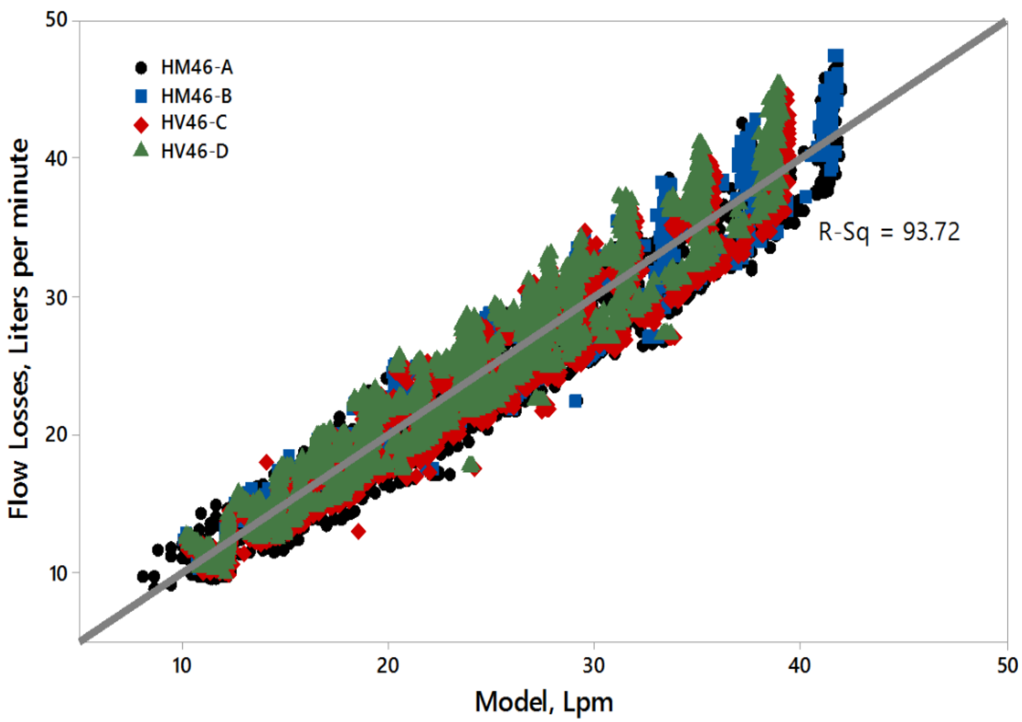
$$Q_l = C_o + C_\mu \frac{\Delta P}{\mu} + C_\rho \sqrt{\frac{\Delta P}{\rho}} + C_K \frac{\omega \Delta P}{K}$$

Laminar Flow Loss   Turbulent Flow Loss   Compressibility Loss

Flow loss data was fit to this equation with viscosities measured different ways

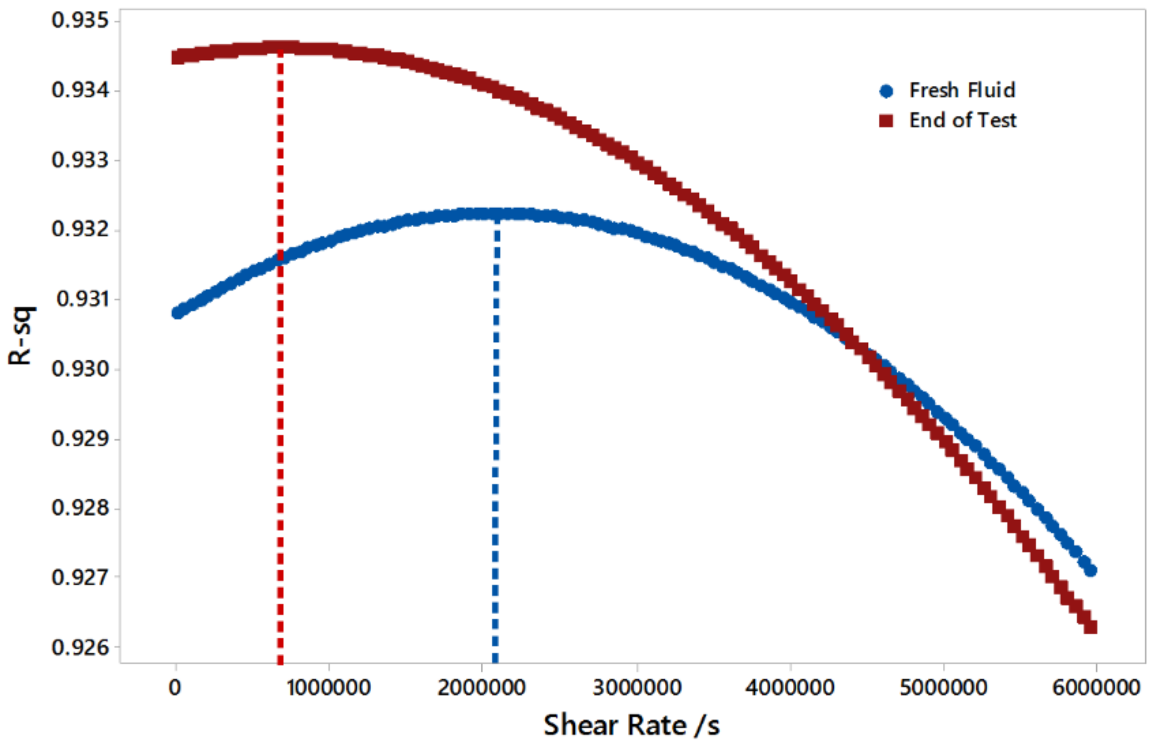
Model Fit

- Example of data fit with viscosity from the Sonic Shear test
- Repeated with other measures of viscosity and goodness of fit quantified for each



Shear Rate?

- Flow losses of used fluids correlate better with viscosity measured at higher shear rates, i.e. subject to temporary viscosity loss



Motor Torque Losses

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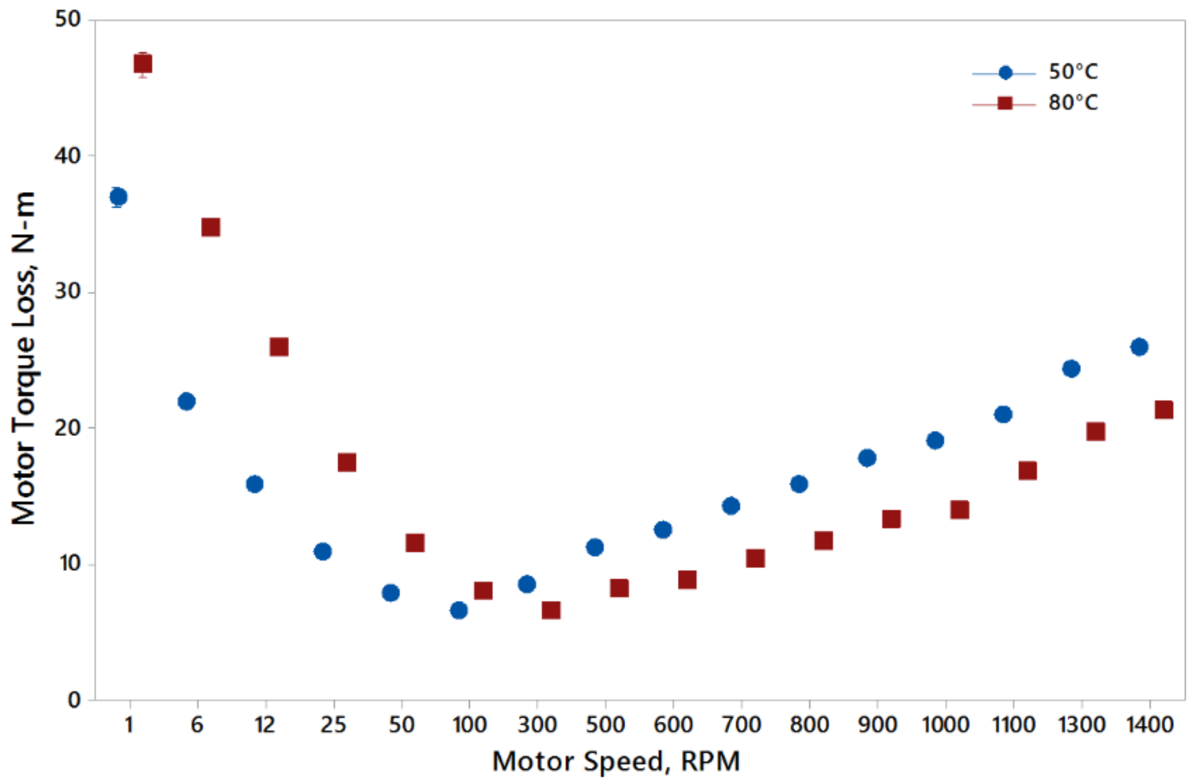
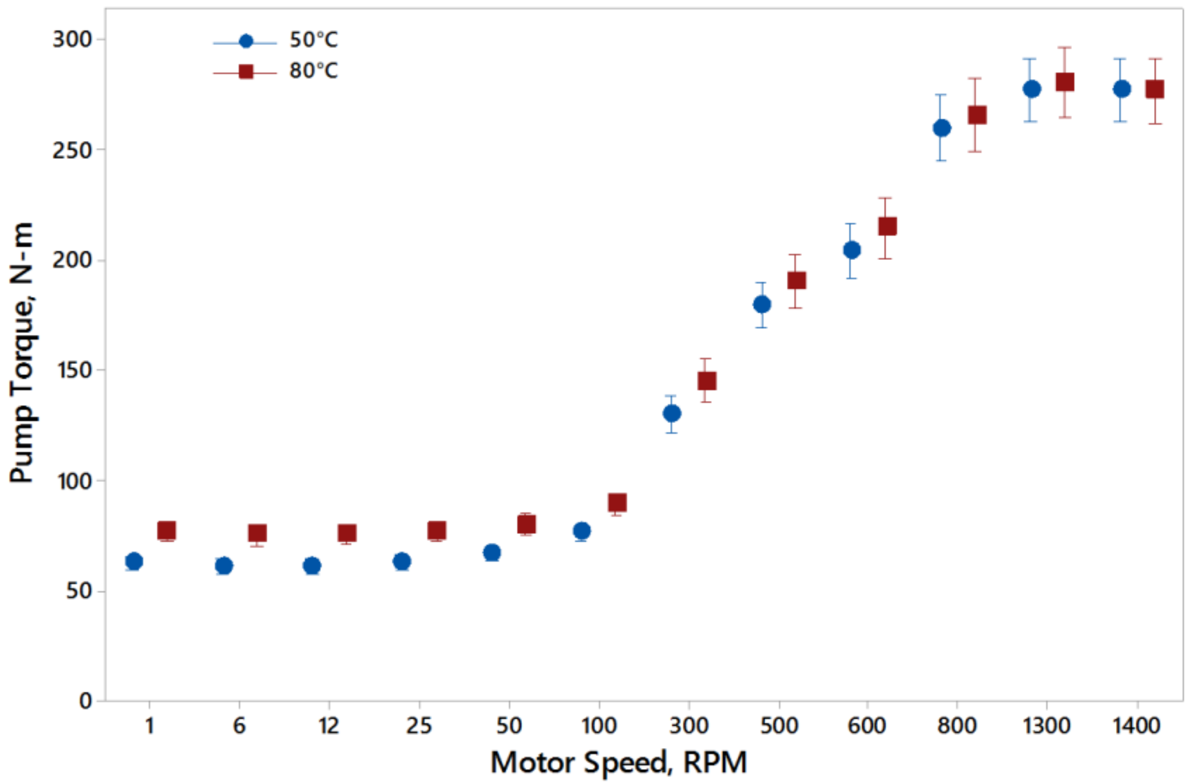
- Torque losses in the motor are not proportional to viscosity, but rather exhibit speed-dependent behavior



Pump Inlet Torque

- Contrary to convention, an increase in viscosity at lower temperature reduces torque due to lower leakage flow



Summary of Power and Losses

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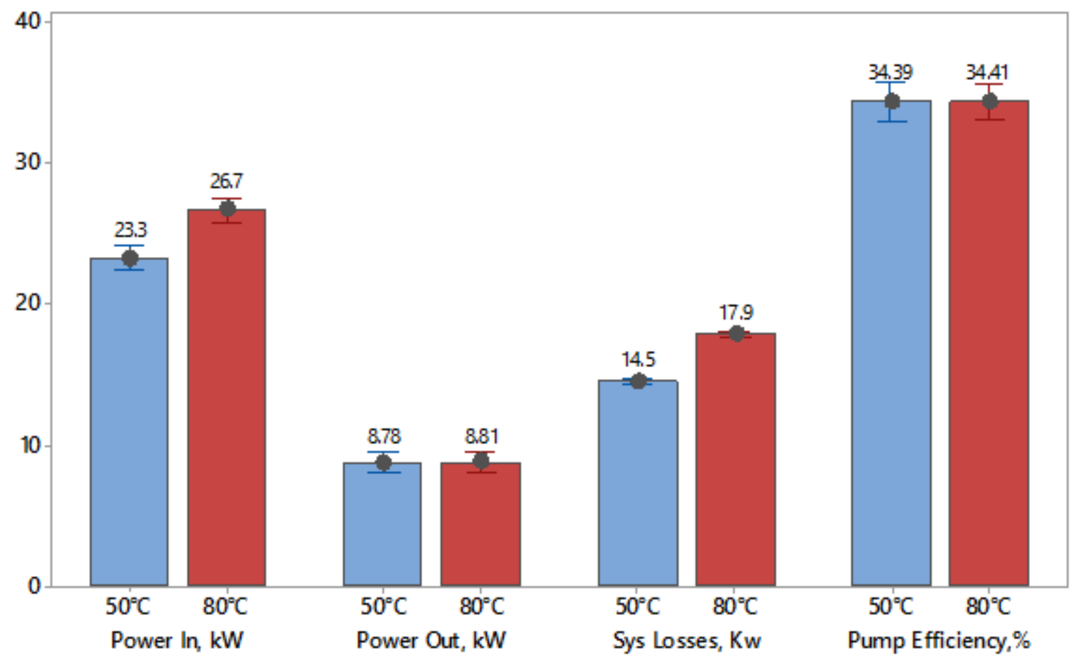
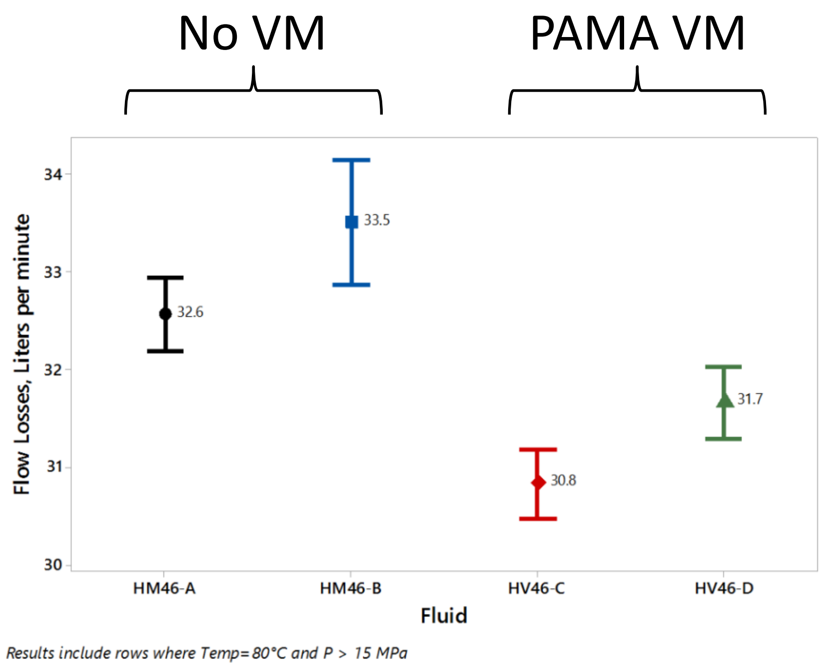
- Pump efficiency exhibits negligible change with input power
- This illustrates why "losses" tend to be a better indicator of the effects of fluid on system performance than efficiency



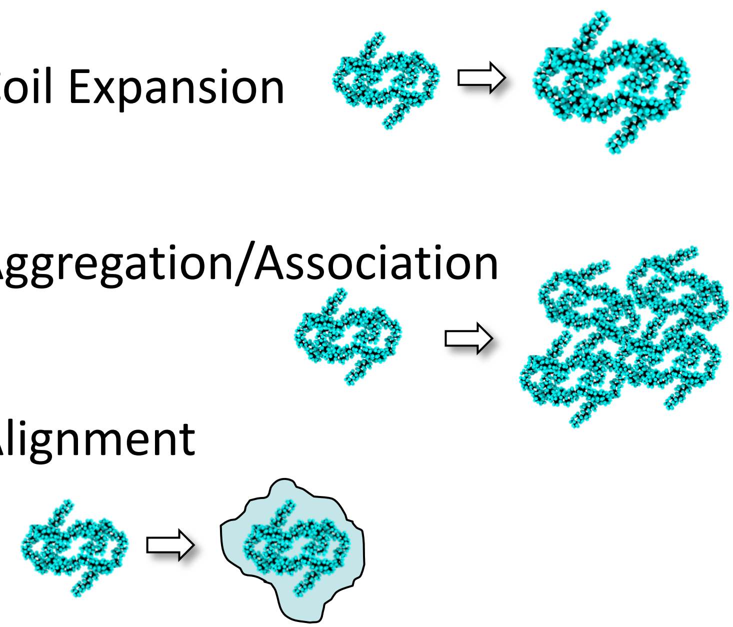
Results include rows where pressure > 200 Bar.

Simulation Contribution

- Experimental results clearly show the important role of viscosity modifiers in hydraulic efficiency
- How do viscosity modifiers perform this function and can they be further optimized to improve performance?



- Coil Expansion
- Aggregation/Association
- Alignment



Simulation Tool-Set

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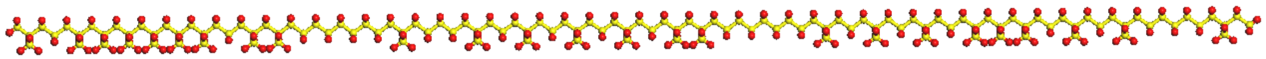
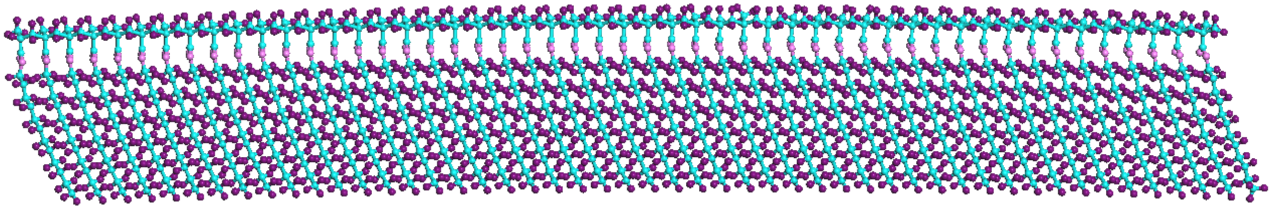
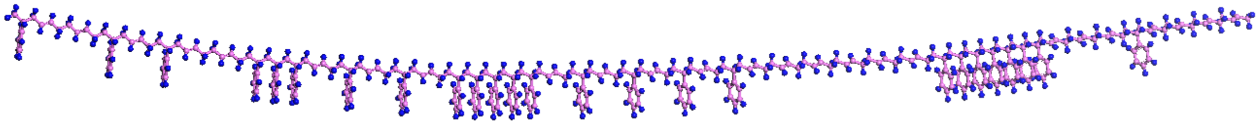
Random Ethylene - Propylene Copolymer (OCP)



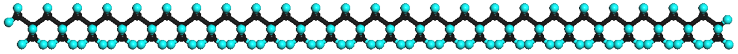
Polydodecyl Methacrylate (PMA)



Styrene-Butadiene (SB)

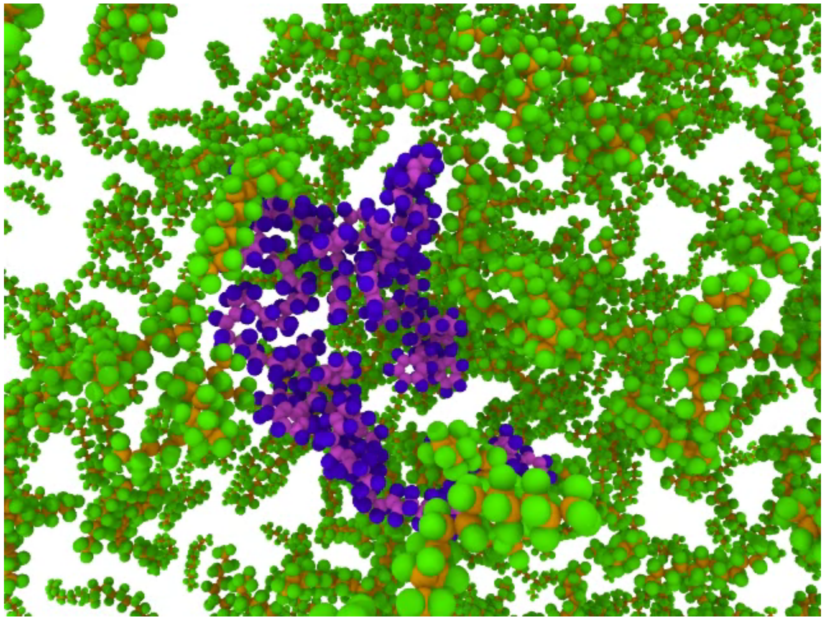


Polyisobutylene (PIB)

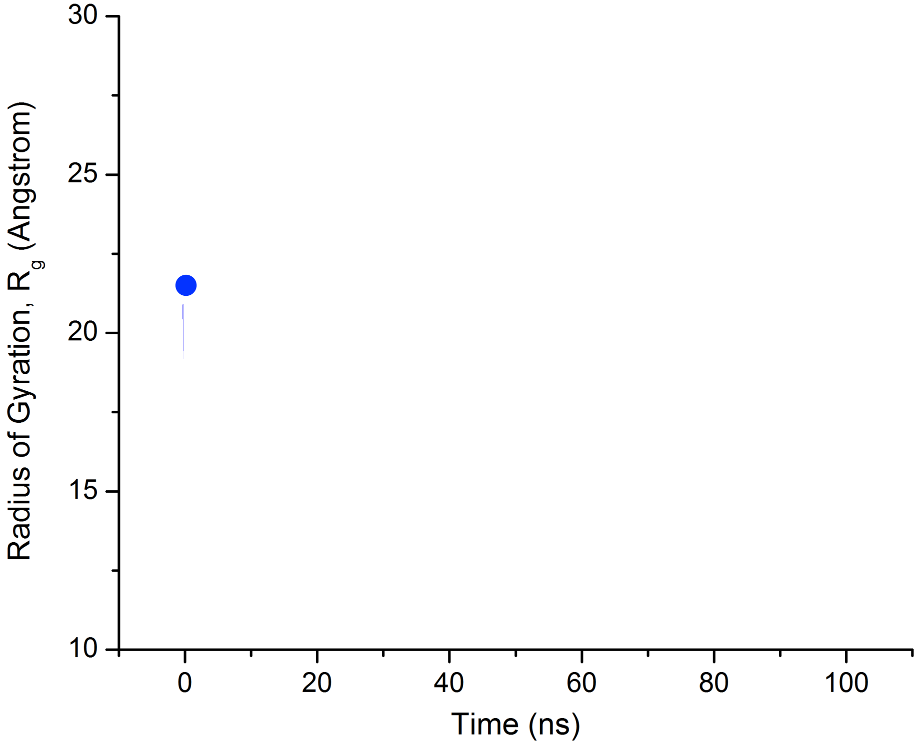


Testing the Expansion Mechanism

Model polymer in base fluid molecules and simulate dynamics



Calculate the radius of gyration from atom positions



Testing the Expansion Mechanism

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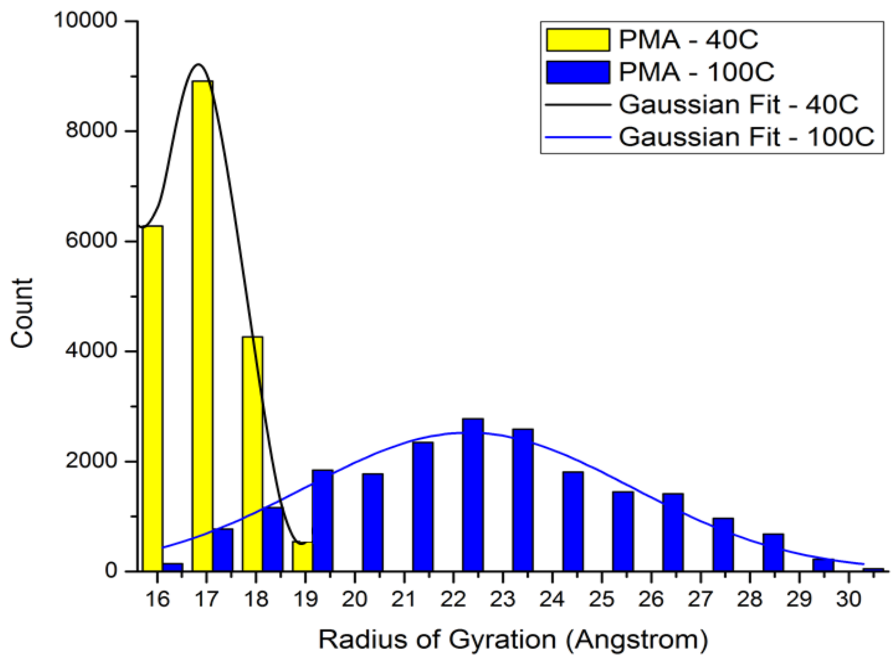
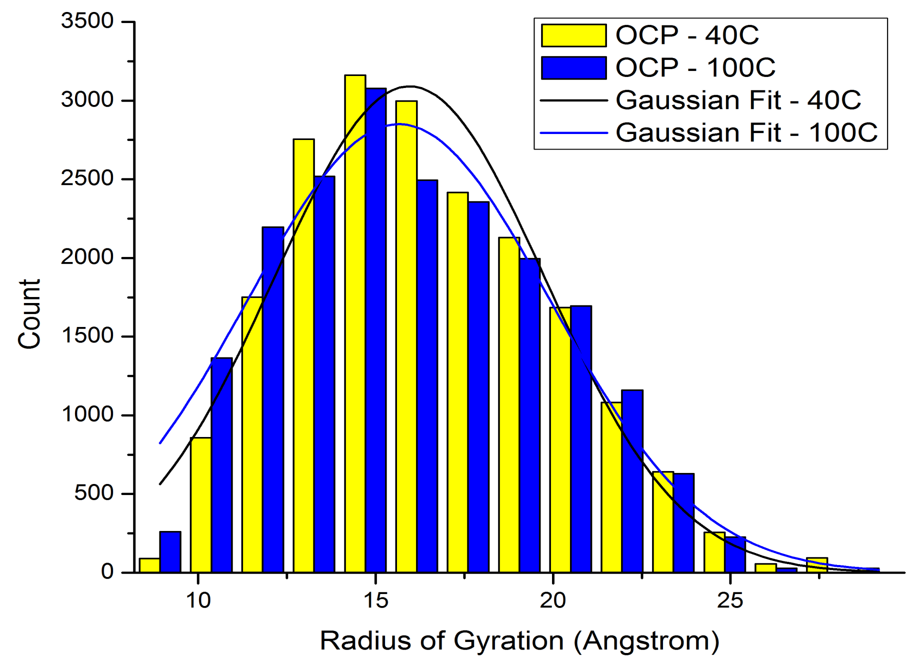
Characterize the distribution of coil sizes during the simulation at 40C and 100C

PAMA



OCP



Testing the Expansion Mechanism

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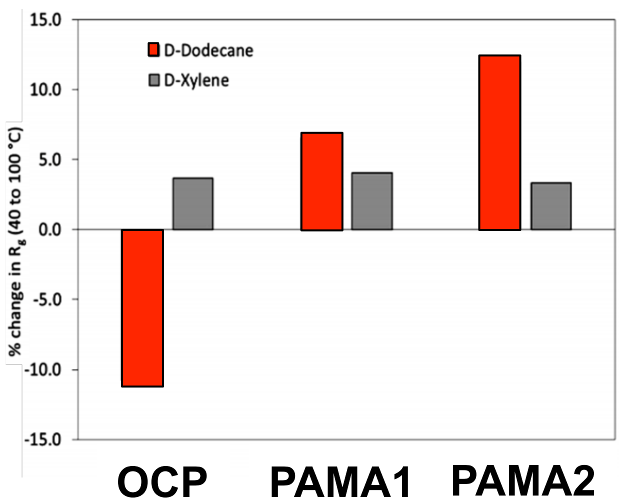
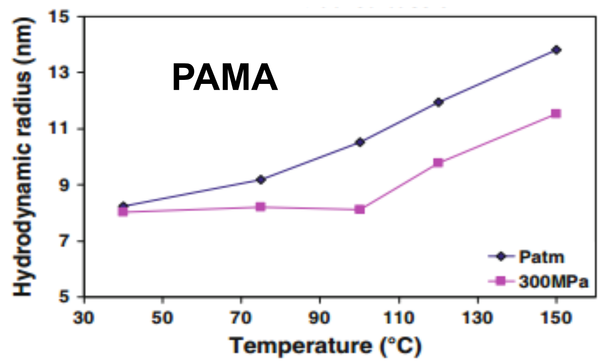
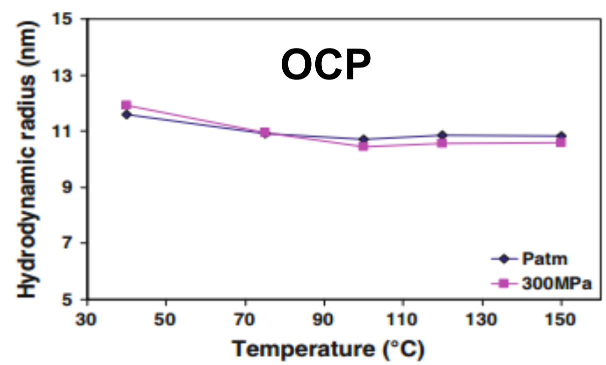
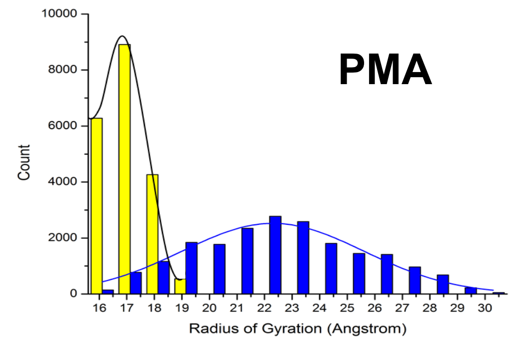
Experiments using direct and indirect coil size measurements and simulations show PAMA expands with temperature but OCP does not

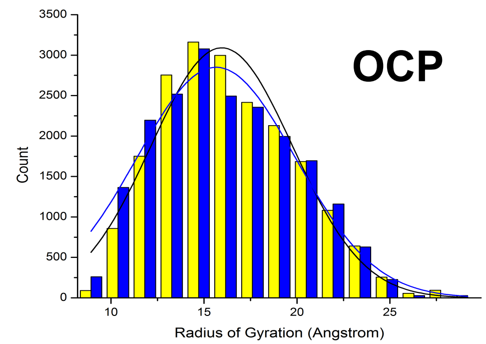


M.J. Covitch, K.J. Trickett, Adv. Chem. Eng. Sci., (5), 134-151 (2015)









C. Mary et al., Tribol. Lett., (52) 3, 357-369 (2013)

Publications

- P Michael, M Cheekolu, P Panwar, M Devlin, R Davidson, D Johnson, A Martini, Temporary and Permanent Viscosity Loss Correlated to Hydraulic System Performance, *Tribology Transactions*, In Press
- M Len, US Ramasamy, S Lichter, Martini A, (2018) Thickening Mechanisms of Polyisobutylene in Polyalphaolefin, *Tribology Letters*, 66, 5
- US Ramasamy, M Len, A Martini, (2017) Correlating Molecular Structure to the Behavior of Linear Styrene–Butadiene Viscosity Modifiers, *Tribology Letters*, 65, 147
- A Martini, US Ramasamy, M Len, Review of Viscosity Modifier Lubricant Additives, *Tribology Letters*, In Press (Invited Review)

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Thank you for your kind attention!