Polymer-Enhanced Fluid Effects on Mechanical Efficiency of Hydraulic Pumps

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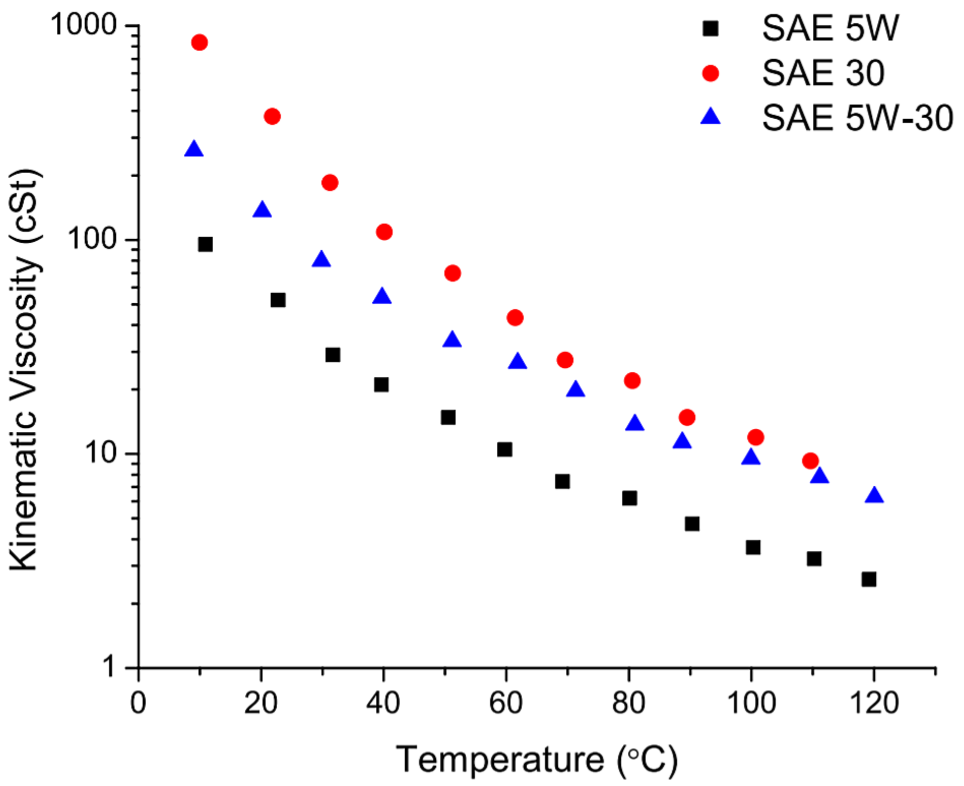
Viscosity Modifiers

- Viscosity modifiers (VMs) or viscosity index improvers (VIIs) are used in many hydraulic fluid formulations
- VM polymers thicken the fluid at high temperatures
- These additives help minimize the variation of viscosity during operation



Data replotted in Martini et al., *Tribol Lett* (2018) 66:58 from Ver Strate & Struglinski, In Schulz & Glass (eds.), *ACS,* Washington (1991)

Shear Thinning

- VMs may experience high shear stress, causing temporary and permanent viscosity loss
- Our previous study showed that volumetric efficiency is more correlated to temporary viscosity loss [1]
- Project goal: understand how VMs and shear thinning of VM-containing fluids affect mechanical efficiency

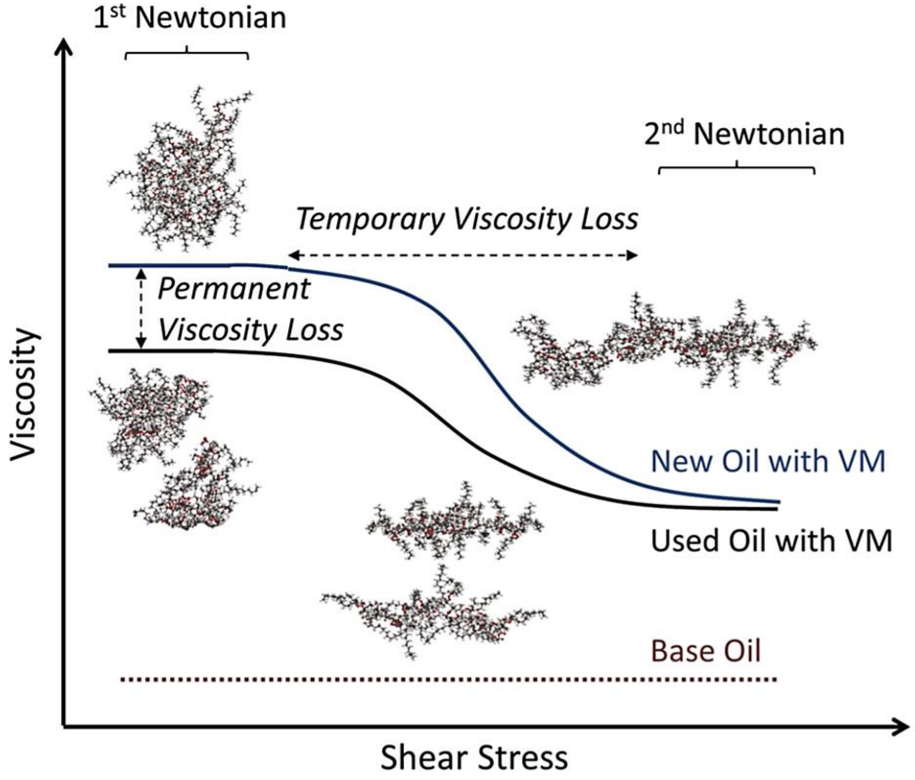
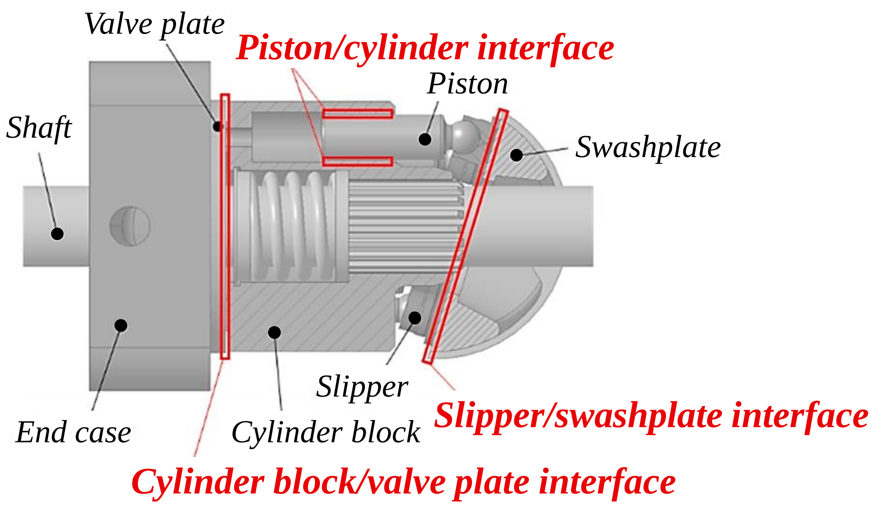


Figure from Reference [2]

[1] Michael et al. Tribol Trans (2018) 61:901
[2] Martini et al., Tribol Lett (2018) 66:58

Axial Piston Pump: Critical Shear Rates

The major lubricating gaps in an axial piston pump exist between the interfaces indicated in red:



Modified from Shang & Ivantysynova, *Energies* **2018**, *11*(11), 3210

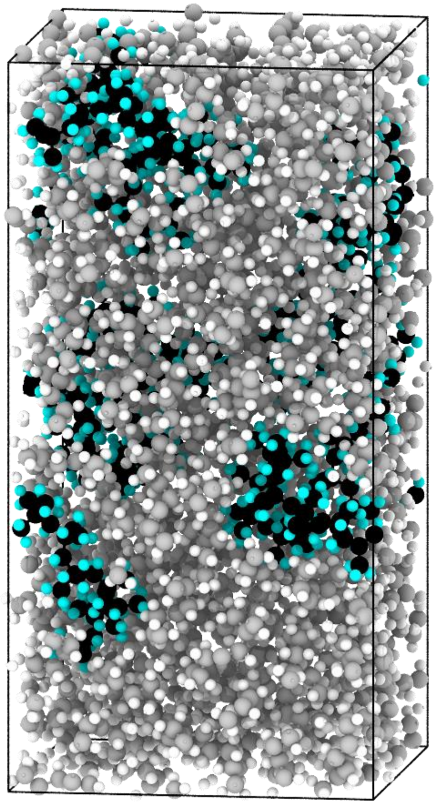
Significant viscous friction occurs at the following shear rates:

	Shear Rate Range [1/s]
Piston/cylinder	8.85×10^4—5.19×10^5
Slipper/swashplate	8.42×10^4—1.10×10^6
Cylinder block/valve plate	1.00×10^6—8.58×10^6

Therefore, the approximate critical shear rate range in an axial piston pump is 10^4—10^7 1/s

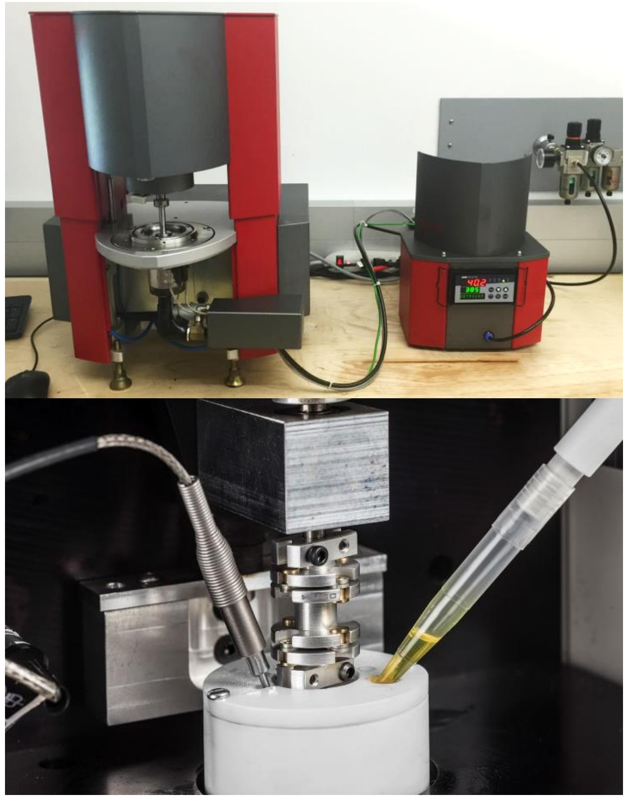
Our Approach

Molecular Simulations



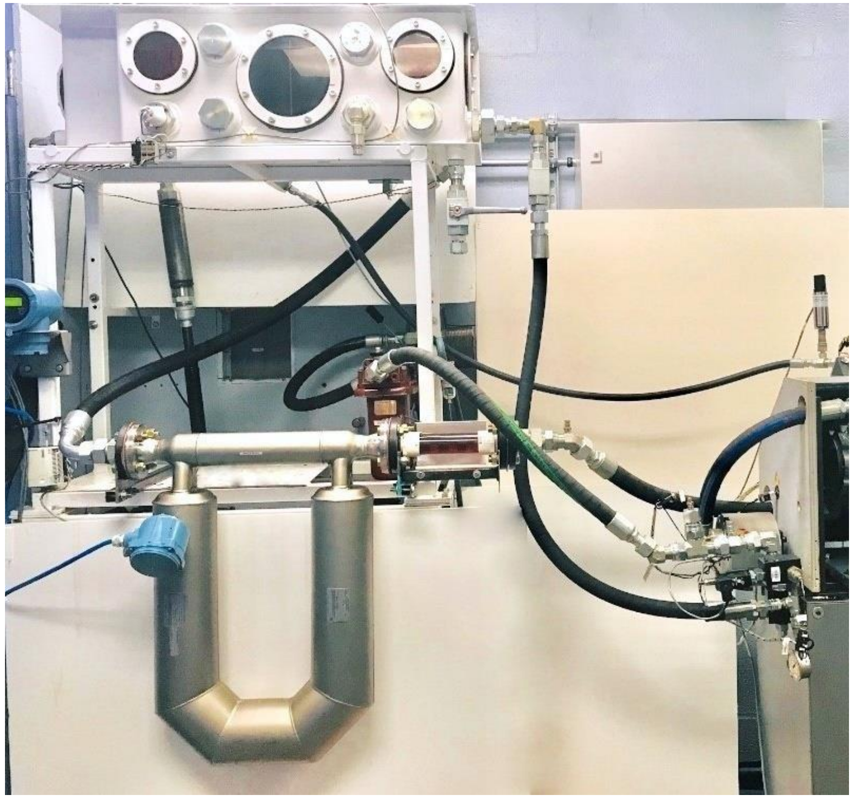
Molecular dynamics (MD) simulations performed in LAMMPS; Image rendered using OVITO

Viscosity Measurements



(Top) Cannon StressTech HR Oscillating Rheometer; (Bottom) PCS Ultra Shear Viscometer

Pump Performance Tests



Dynamometer showing Coriolis flow meter before the pump inlet which enables measurement of the fluid density

Test Fluids

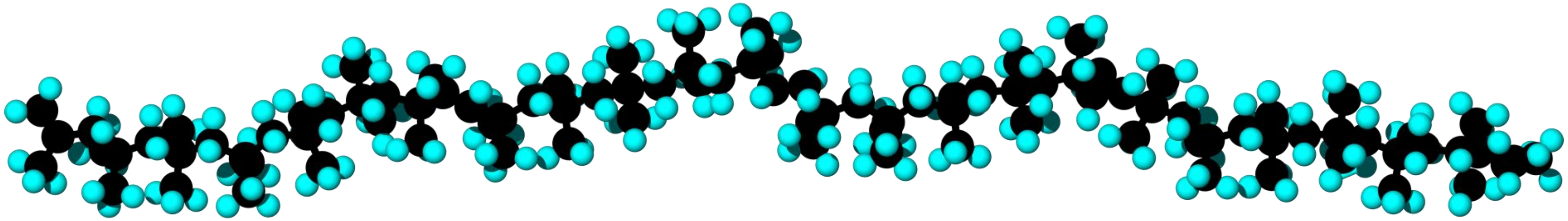
- 3 hydraulic fluid formations were created to have the same viscosities but different concentrations of VMs
- All fluids were formulated with poly(isobutylene) (PIB) and/or poly(alphaolefin) (PAO)
- These formulations enable the effect of base oil viscosity reduction to be isolated

	HV46-1	HV46-2	HV46-3
Viscosity @ 40°C [cSt]	48.92	46.75	46.74
Viscosity @ 100°C [cSt]	8.89	8.08	7.86
Viscosity Index	164	146	138
Vis loss @ 40°C, D5621	0.84%	0.62%	0.36%
PAO 2 [wt.%]	61.5%		
PAO 4 [wt.%]		81.0%	
PAO 8 [wt.%]			100%
PIB [wt.%]	38.5%	19.0%	

* All formulated with the same commercial anti-wear additive package

PIB and PAO Molecular Structures

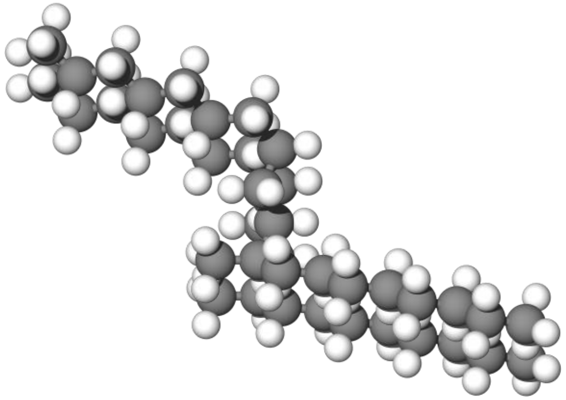
Polyisobutylene (1300 g/mol)

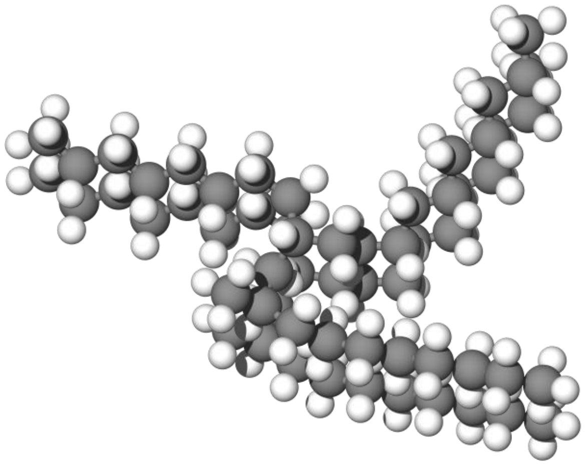


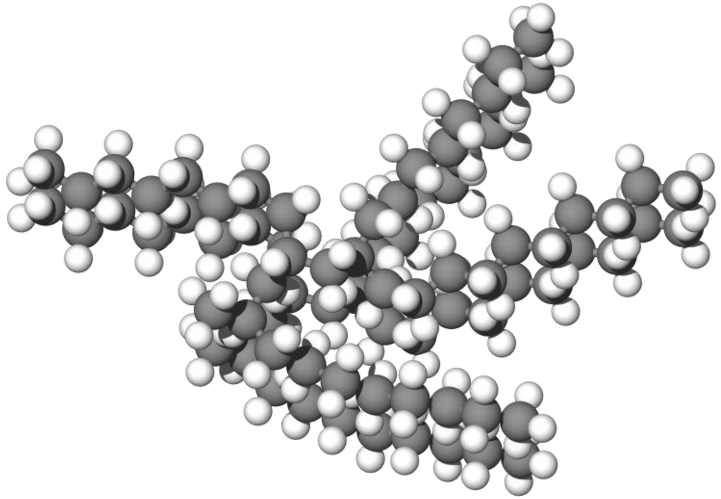
Dimer (C_{20}) of 1-Decene

Trimer (C_{30}) of 1-Decene

Tetramer (C_{40}) of 1-Decene

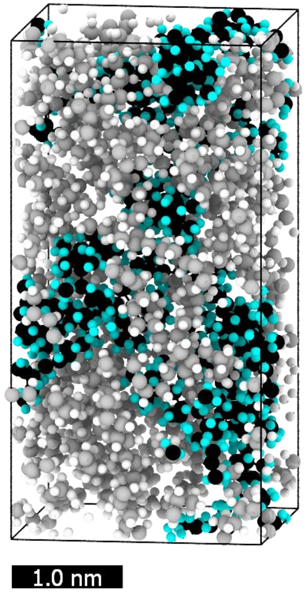






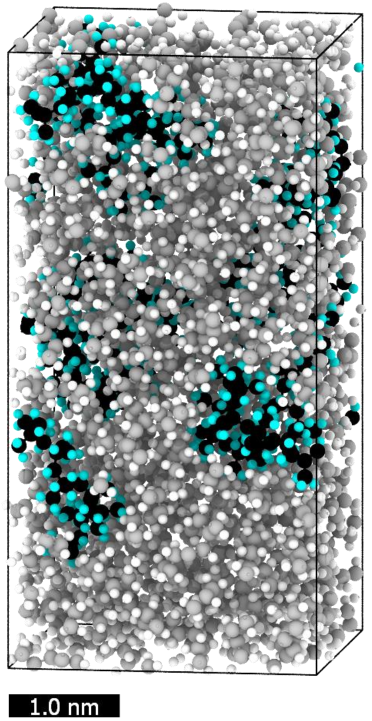
MD Simulation Setup

38.4% PIB
61.6% PAO2



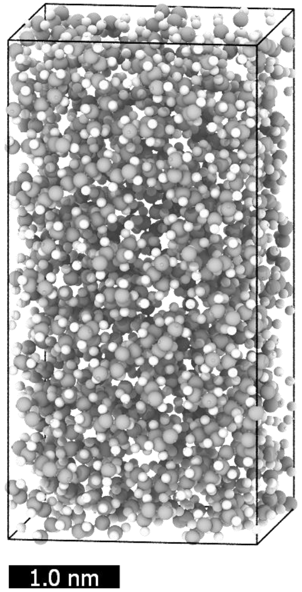
HV46-1

20.4% PIB
79.6% PAO4

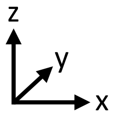


HV46-2

100% PAO8



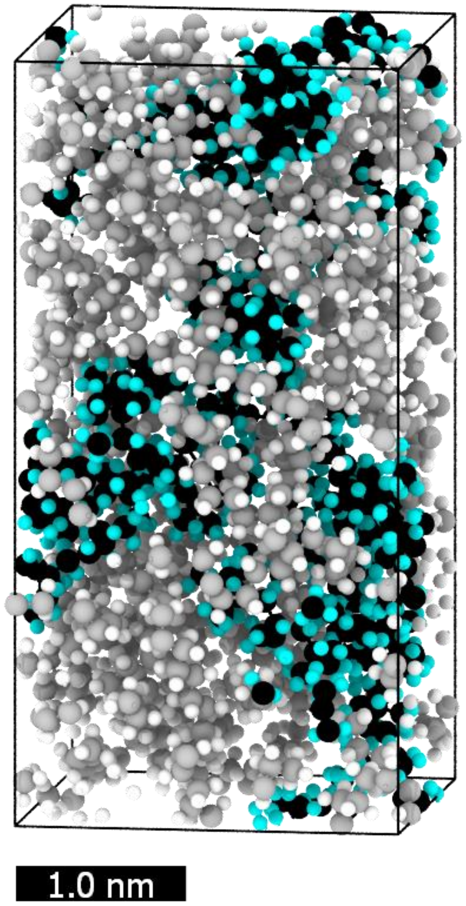
HV46-3



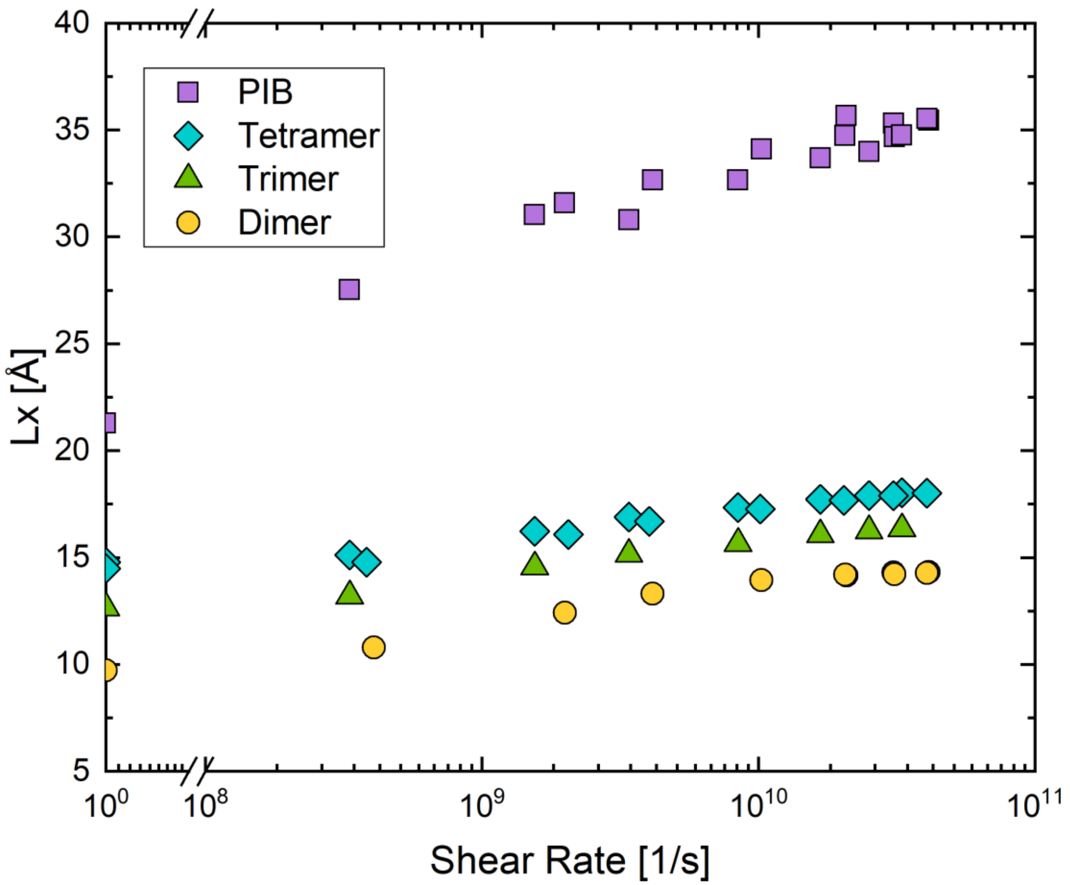
MD Simulation Validation

- To validate our MD simulations, we tested our viscosity prediction for HV46-1 at 100°C
- The average viscosity value and standard deviation were calculated from four independent simulations
- Reasonable predictions suggest that the simulations can be used to calculate viscosity trends where experimental data is not available

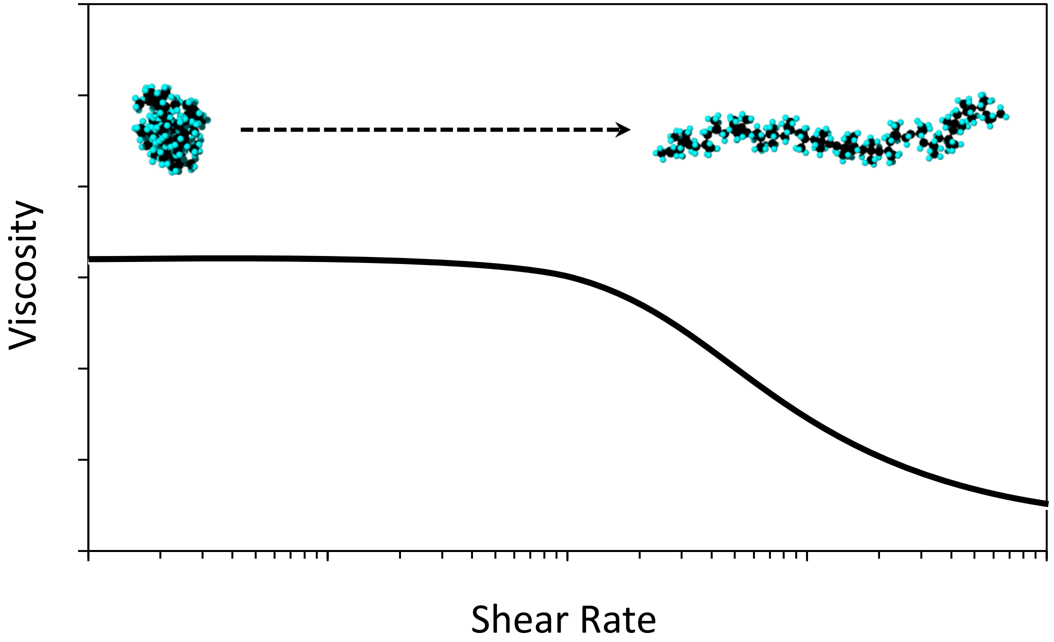
	Expected [cSt]	Simulation Prediction [cSt]	Error [cSt]
Viscosity	8.89	8.40 ± 3.31	0.49



Shear Thinning in MD Simulations

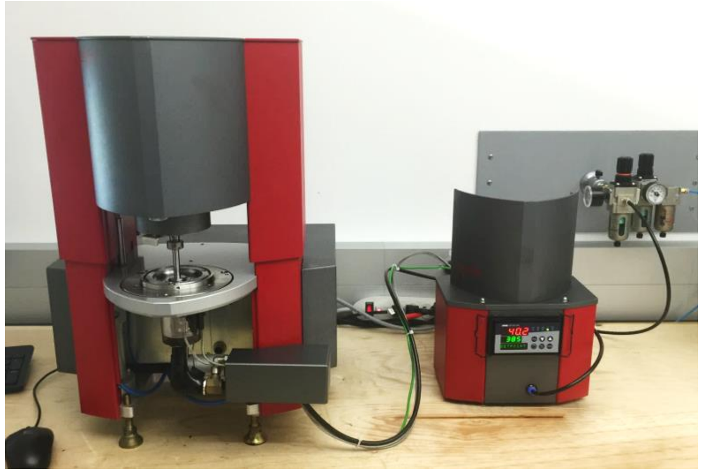


- Viscosity decreases due to shear-induced alignment of the polymers, causing temporary viscosity loss

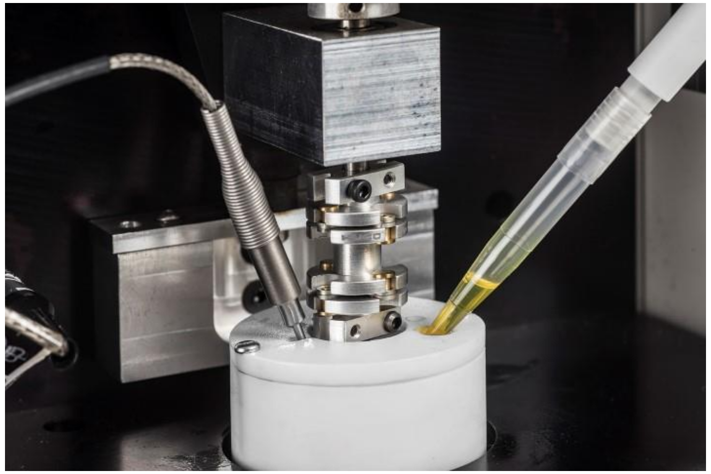


Shear Rate Range for Each Method

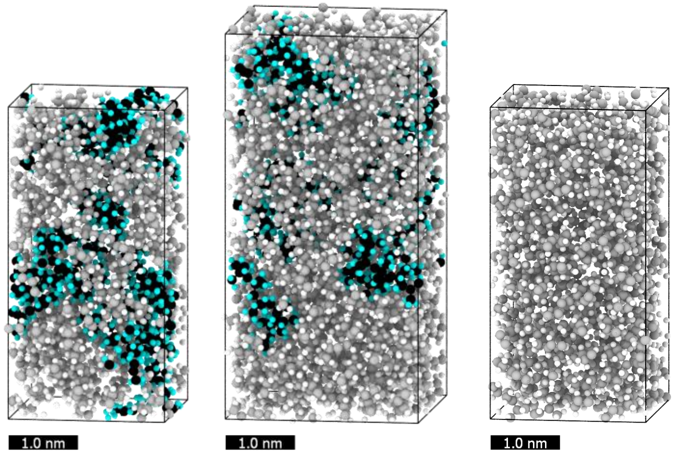
UC Merced Rheometer



Ultra Shear Viscometer



Molecular Dynamics Simulations



Low Shear:

1—1×10^{3} 1/s

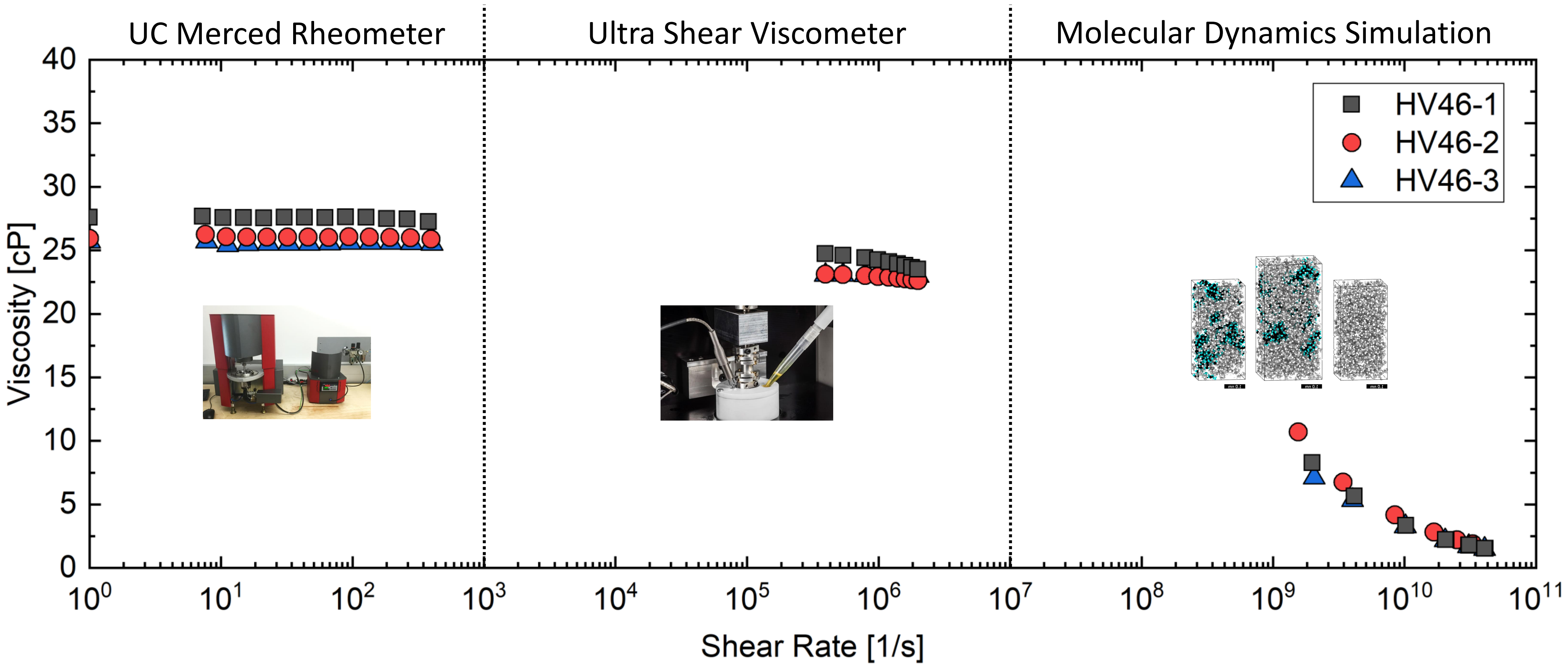
High Shear:

1×10^{5}—2×10^{6} 1/s

Ultra High Shear:

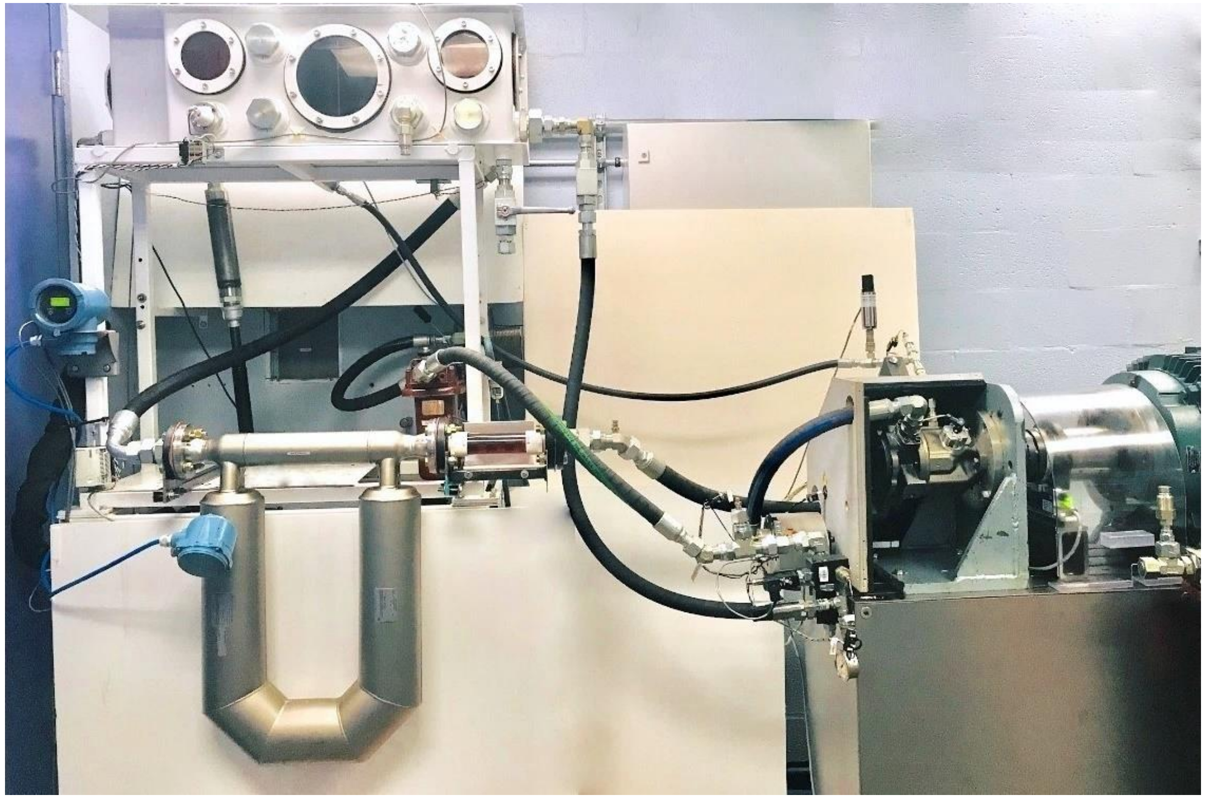
1×10^{9}—1×10^{11} 1/s

Viscosity vs Shear Rate Results at 50°C



Dynamometer

- Pump performance testing was conducted for all fluids in a dynamometer per the ISO 4409 standard
- The dynamometer consists of:
  - 46cc variable displacement axial piston pump
  - Electronic swashplate control



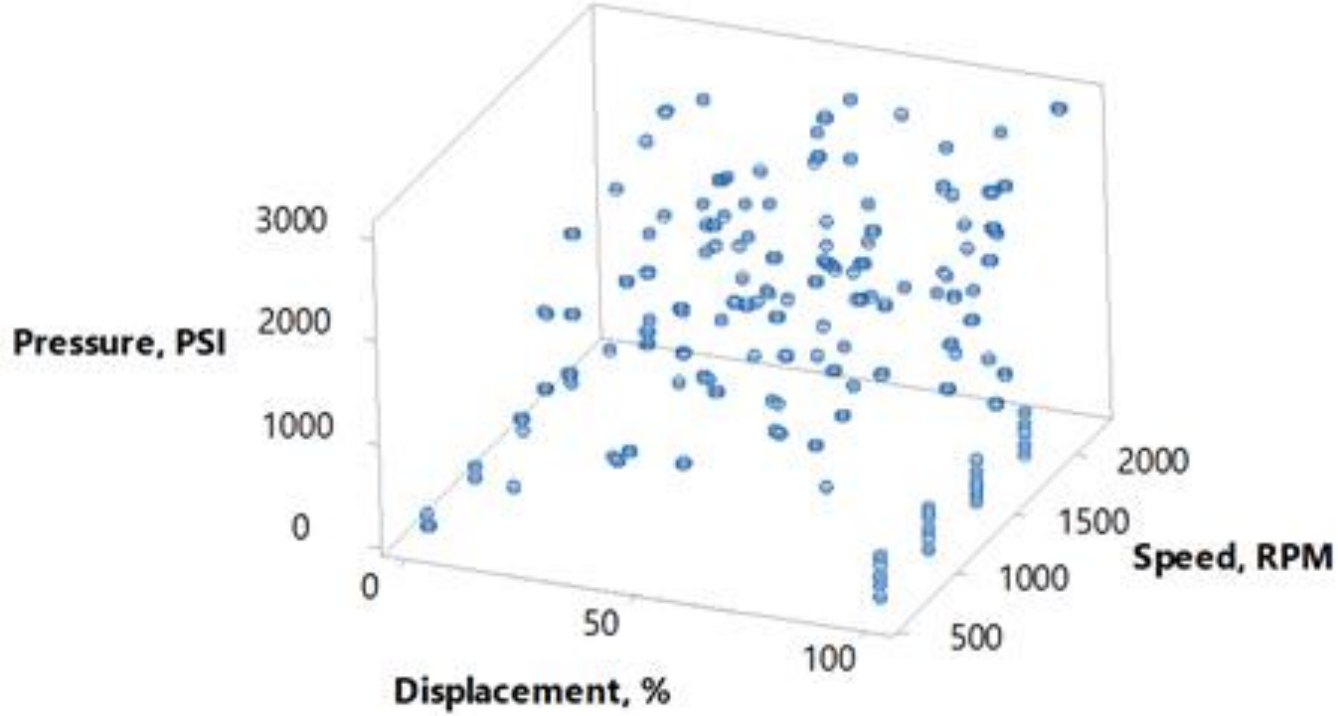
Dynamometer showing Coriolis flow meter before the pump inlet which enables measurement of the fluid density

Test Conditions

- Test points via Latin Hypercube method
- Pump testing parameters are shown in the table below:

Pump Testing Parameters	
Speed	600−2200 rpm
Displacement	0−100%
System Pressure	7−207 bar
Nominal Fluid Temperature	50°C

Test Points

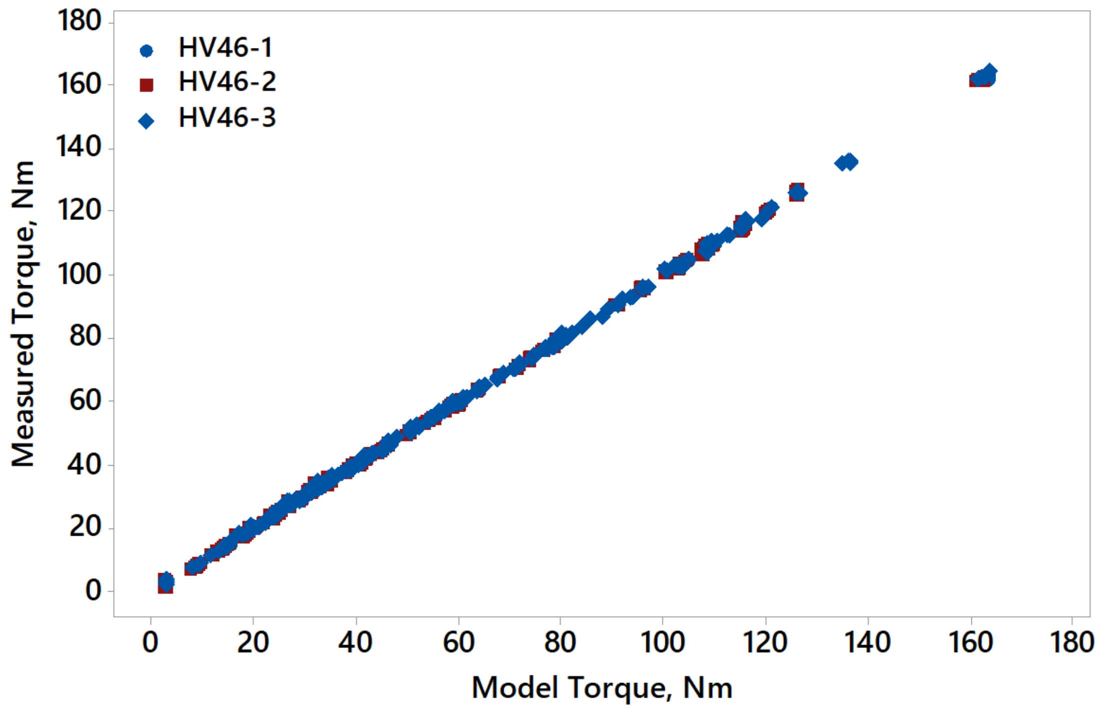


Dynamometer Results - Torque

Best subsets regression identified three model terms for pump input torque:

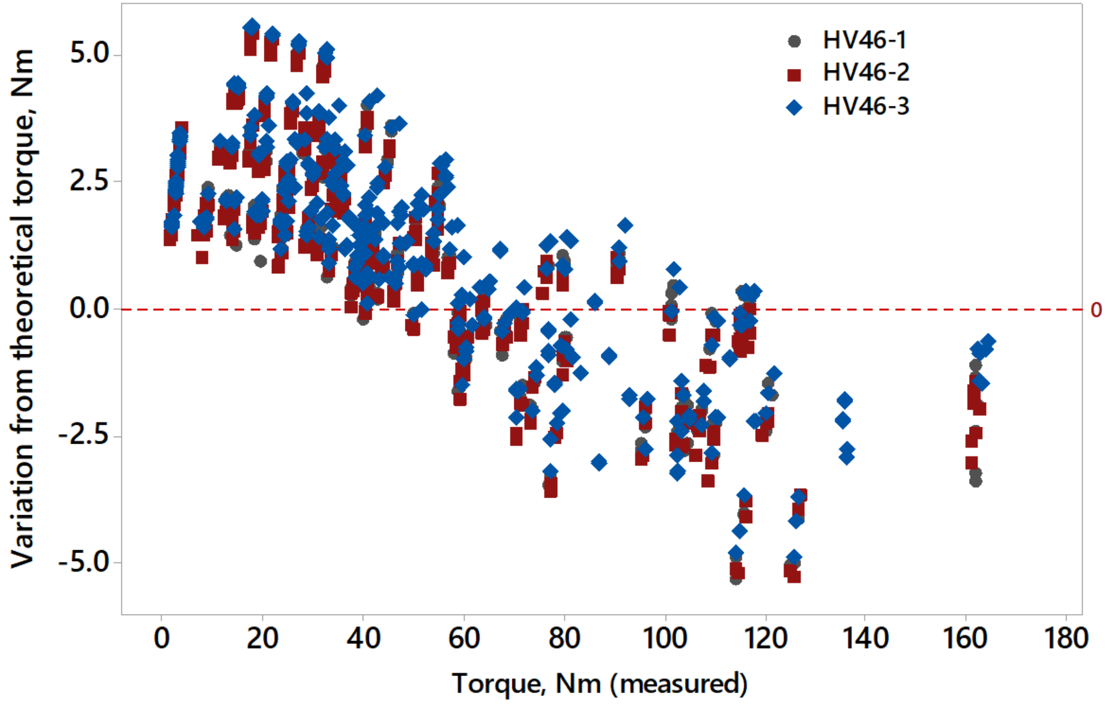
$$T = C_o + C_1 \frac{(V_i)p}{2\pi} + C_2 \mu\omega(V_i) + C_3 \frac{\rho(V_i)^{\frac{5}{3}}}{4\pi}\omega^2$$

Term	Form
Theoretical (1)	$T_o = \frac{(V_i)p}{2\pi}$
Viscous (2)	$T_l = \mu\omega(V_i)$
Turbulent (3)	$T_t = \frac{\rho(V_i)^{\frac{5}{3}}}{4\pi}\omega^2$

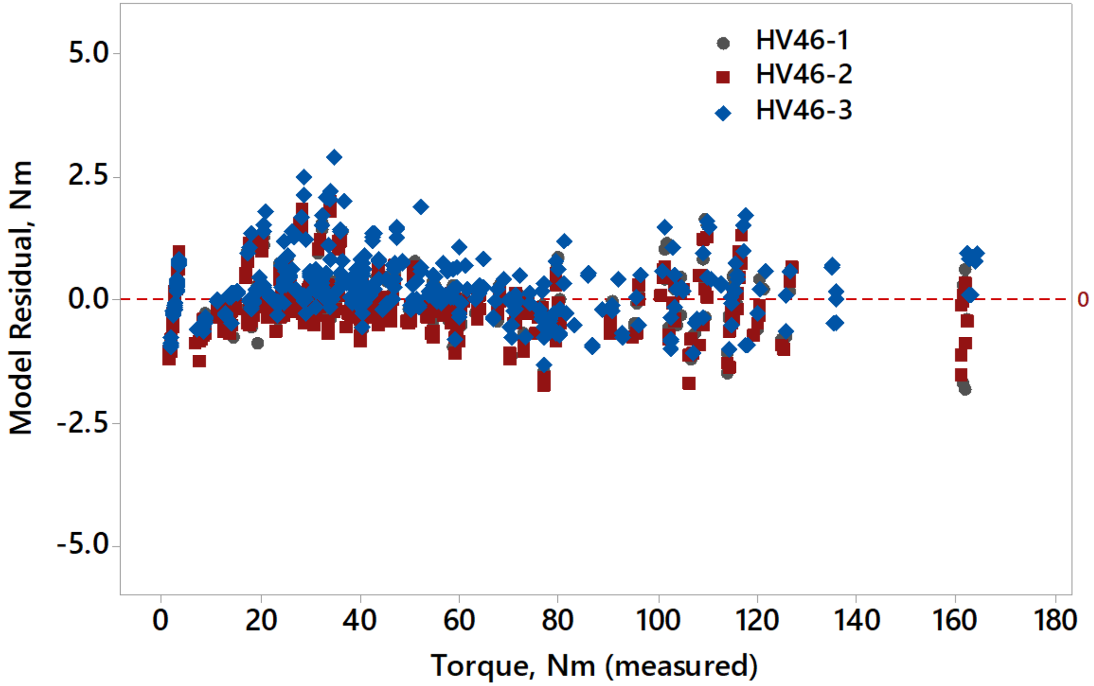


(1) Wilson, 1950
(2)Wilson,1950
(3)Thoma, J., 1969

Torque Residual Analysis

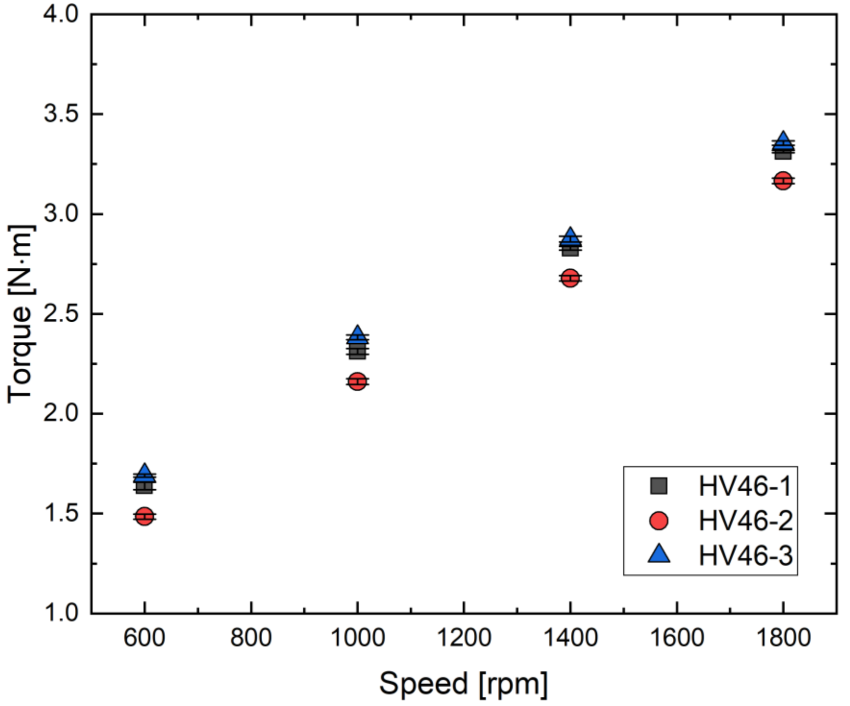


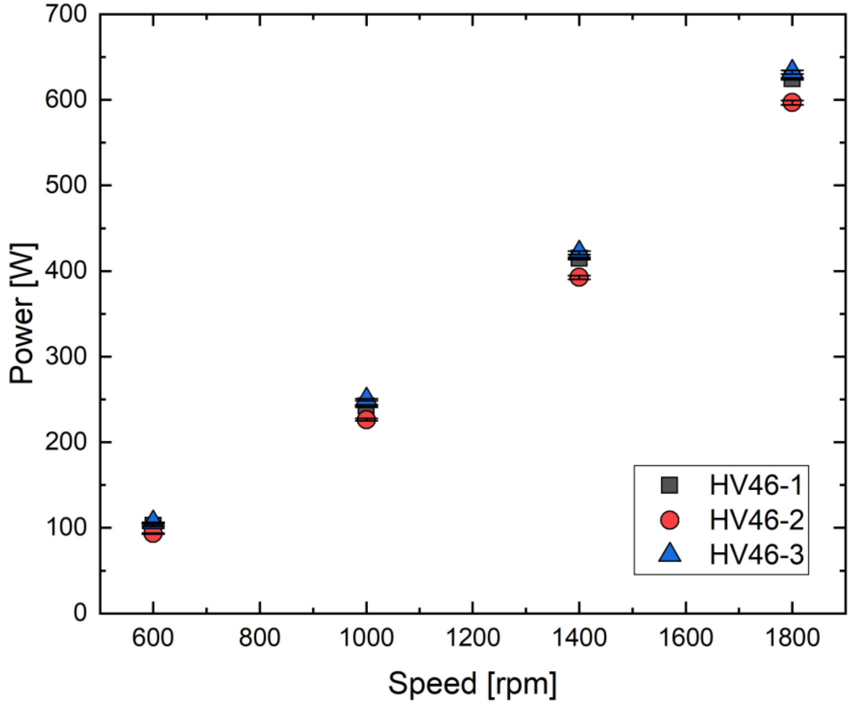
Residuals versus theoretical torque



Residuals versus 3-term model

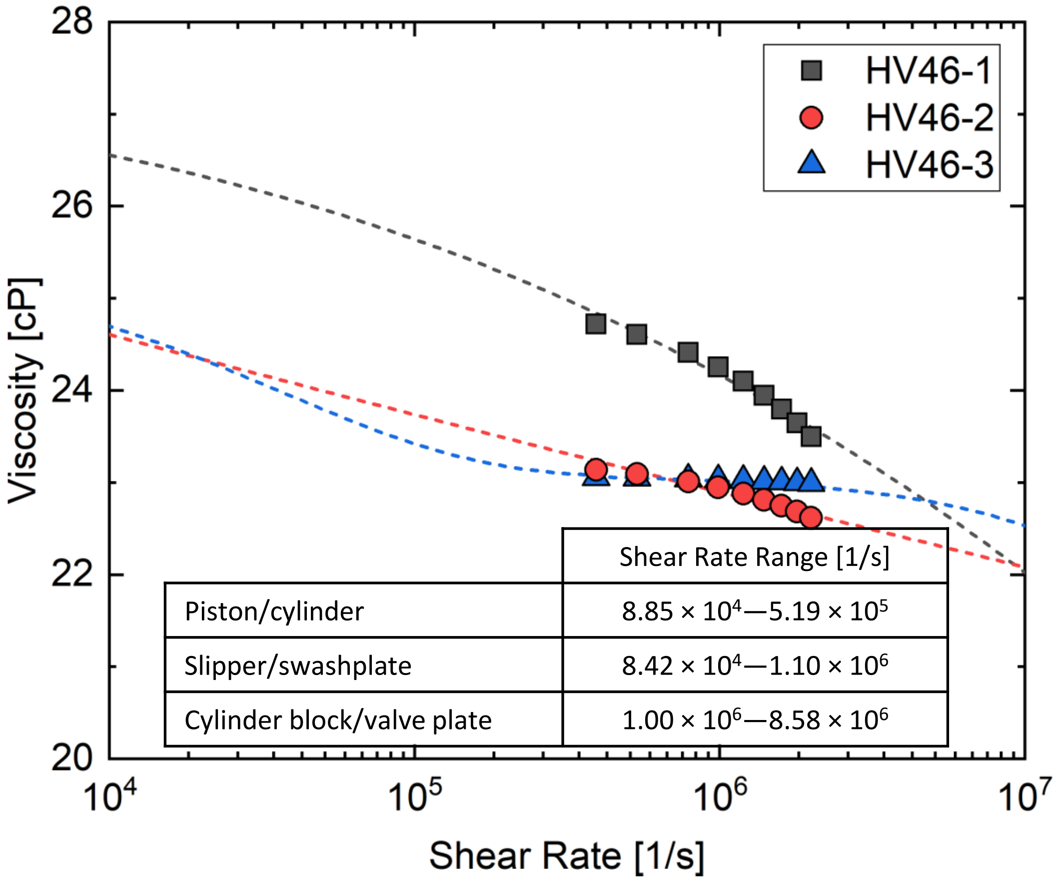
Dynamometer Results – Idling Losses





- It appears that HV46-2 required the least idle torque and power input, followed by HV46-1 and HV46-3
- *Hypothesis that reducing viscosity of the carrier base oil improves mechanical efficiency was not supported by the experimental results*

Viscosity at the Critical Shear Rate Range



- Recall: the critical shear rate range in an axial piston pump was between 10^4 and 10^7 1/s
- In this critical shear rate region,
  - HV46-1 has the highest viscosity and most shear thinning
  - HV46-2 has lower viscosity and moderate shear thinning
  - HV46-3 exhibits the least shear thinning

Summary

- The effect of VMs was studied using three fluids with varying concentrations of PIB but the same 40 and 100°C viscosities
- Experiments and simulations captured the shear thinning behavior of these fluids across ten decades of shear rates
- Preliminary idle pump tests showed that the HV46-2 performed the best with lower torque and input power
- The range of shear rates at regions of high viscous friction and leakage flow was identified for an axial piston pump
- Future work will correlate shear thinning to hydraulic efficiency

Thank You!

We acknowledge the Center for Compact and Efficient Fluid Power, the National Fluid Power Association Education and Technology Foundation and Afton Chemical for support of this research.

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9. Zhang, J., Li, Y., Xu, B., Pan, M., and Lv, F. (2017). Experimental Study on the Influence of the Rotating Cylinder Block and Pistons on Churning Losses in Axial Piston Pumps. Energies 10, 662; doi:10.3390/en10050662.