Polymer-Enhanced Fluid Effects on Mechanical Efficiency of Hydraulic Pumps

University of California Merced, Department of Mechanical Engineering
Ashlie Martini  Michelle Len  Pawan Panwar

Milwaukee School of Engineering, Fluid Power Institute
Ninaad Gajghate  Paul Michael
Pump Efficiency and Viscosity Modifiers

- Increased viscosity reduces leakage flow but increases pump torque
- Viscosity modifiers exhibit complex behavior that depends on shear rate

- Can we leverage viscosity modifier behavior to optimize overall efficiency?


Our Approach

Molecular Simulations

Viscosity Measurements

Pump Performance Tests

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

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

Dynamometer showing Coriolis flow meter before the pump inlet which enables measurement of the fluid density
First 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 the VM to be isolated.

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

* All formulated with the same commercial anti-wear additive package.
Viscosity vs Shear Rate Results at 50°C
Pump Torque at 50°C Inlet Temperature

- No difference between the fluid when averaged across the operating range
- Torque is lower with the polymer enhanced fluids at the highest flow rates and pressures

3000 psi, 2200 rpm, 100% displacement
Axial Piston Pump: Critical Shear Rates

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

Significant viscous friction occurs at the following shear rates:

<table>
<thead>
<tr>
<th>Shear Rate Range [1/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piston/cylinder</td>
</tr>
<tr>
<td>$8.85 \times 10^4 - 5.19 \times 10^5$</td>
</tr>
<tr>
<td>Slipper/swashplate</td>
</tr>
<tr>
<td>$8.42 \times 10^4 - 1.10 \times 10^6$</td>
</tr>
<tr>
<td>Cylinder block/valve plate</td>
</tr>
<tr>
<td>$1.00 \times 10^6 - 8.58 \times 10^6$</td>
</tr>
</tbody>
</table>

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

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

• To minimize leakage and pump torque, an ideal hydraulic fluid should have:
  1. High viscosity at low shear rates (minimize leakage)
  2. Low viscosity at high shear rates (minimize torque loss)
  3. Shear thin at the critical region for the pump, i.e. \(\sim 10^5\) 1/s
Ideal Fluid Design

Design Constraints:
• Onset of shear thinning at $10^5 - 10^7$ 1/s
• Negligible permanent viscosity loss during machine operation
• Dynamic viscosity $\sim 8$ cP at 100°C for an efficient hydraulic fluid
• Molecular weight of the polymer < 10 kg/mol for modeling

Fluids Considered:
• Base oil: PAO2, PAO4, and PAO8
• Viscosity modifier: PIB of MW up to commercially available maximum of 6 kg/mol
• VM concentration: between 10 and 20 wt.%
Theoretical Approach

Einstein – Debye Equation:

\[ \lambda = \frac{(\mu - \mu_s)M}{c\rho RT} \]

Density or Specific Gravity of Blend:

\[ \frac{1}{SG_{blend}} = \frac{c_A}{SG_A} + \frac{c_B}{SG_B} \]

Viscosity of Blend using Kendall-Monroe:

\[ \nu_{blend} = \left( x_A \nu_A^{1/3} + x_B \nu_B^{1/3} \right)^3 \]

\( \mu \) and \( \mu_s \) = viscosity of blend and solvent
\( M \) = molecular weight of solute
\( c \) = weight concentration polymer
\( \rho \) = density of blend
\( R \) = universal gas constant
\( T \) = temperature
\( \dot{\gamma}_{cr} \) = \( 1/\lambda \) critical shear rate

High Pressure Rheology for Quantitative Elastohydrodynamics by Dr. Scott Bair
Ideal Fluid Identification

**Concentration of PIB**
- 10%
- 14%
- 18%
- 12%
- 16%
- 20%

**PAO 8**

Critical Shear Rate [1/s]

Viscosity [cP]

Molecular Weight [g/mol]

×10^7

7

6

5

4

3

2

1

0.5

1

1.5

2

2.5

3

×10^4

10

15

20

5

10
Current Activities

• Working with Afton Chemical to formulate and measure the high shear viscosity behavior of the “hypothetical” PAO-PIB fluid

• Developing dynamic testing methods for the dynamometer to better capture real machine duty cycles

• Developing coarse grain modeling approaches to enable the simulations to capture higher molecular weight VMs
Dynamic Testing – Backhoe Trenching
Coarse Grain Modeling for Higher MWs

- Dimer, trimer and tetramer of 1-Decene

[Diagram showing molecular structures of dimer, trimer, and tetramer of 1-Decene with labels for carbon and hydrogen atoms.]
Summary

• Studied shear response of viscosity over 10 orders of magnitude.
• Critical shear rate in the pump was 80,000 to 8,000,000 /s.
• A polymer that was stable at the critical shear rates was evaluated.
• Low viscosity base oil in combination with the polymer did not significantly affect pump mechanical efficiency.
• Future work to examine fluids under dynamic operating conditions and polymers that shear in the critical zone.
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.

Additional details are available in our recent publication: