Measurements and Modeling
Thermophysical Properties of Lubricants

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• History
  – 2014 NAVAIR (Naval Air Systems Command) contacted NIST; interested in thermophysical property data for gas turbine engine oil MIL-PRF-23699 (used in most military aircraft and 95% of commercial aircraft)
    • Needed accurate properties to assist in their Modeling and Simulation programs
      – Properties of interest include: viscosity, specific heat, density, thermal conductivity, enthalpy
    • Used software GFSSP (General Fluid System Simulator Program) developed by NASA. Desired ability to incorporate fluid properties for MIL-PRF-23699 into this software.
      – NIST did not have anything available at that time.
• **History**
  – 2015 NIST and NAVAIR entered into an agreement for NIST to provide
    • Highly accurate thermophysical property measurements of 3 pure fluid base stock components (POE5, POE7, POE9).
    • Highly accurate thermophysical property measurements of a fully formulated lubricant meeting MIL-PRF-23699.
    • Thermophysical property model within REFPROP software for a fully formulated lubricant.
    • A mini-course for up to 8 participants on the measurement and modeling of thermophysical properties.
  – 2018 Work completed and Final report submitted to NAVAIR.
Thermophysical Properties of Polyol Ester Lubricants

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Measurements Summary

- Completed measurements on 3 pure fluids (POE5, POE7, POE9) and the fully formulated lubricant MIL-PRF-23699
  - Thermal decomposition
  - Compressed liquid density (270 – 470 K, to 50 MPa, vib. tube, unc. <0.15%)
  - Ambient pressure density (278 – 343 K, vib. tube, unc. <0.18%)
  - Sound speed (283 – 423 K, up to 70 MPa, pulse-echo apparatus, unc. < 0.04%)
  - Ambient pressure sound speed (278 – 343 K, time of flight, unc. <0.2%)
  - Ambient pressure $C_p$ (208 – 503 K; DSC method, 2-3 % unc.)
  - Vapor pressure (gas saturation method, POE5 only)
  - Viscosity (275 – 450 K, up to 137 MPa, oscillating piston viscometer, unc. 5-10%)
  - Thermal conductivity (300 – 500 K, up to 69 MPa, transient hot wire apparatus, unc. 0.5%)

- All the gory details in NISTIR 8263
  https://doi.org/10.6028/NIST.IR.8263
 Modeling Summary

- Use density, $C_p$, sound speed, $\rho_{\text{sat}}$ data to develop an equation of state (EOS)
  - Can compute all thermodynamic properties from this equation
- Use viscosity and thermal conductivity data to develop individual correlations for viscosity and thermal conductivity as functions of density and temperature
- Initially tried to develop a “surrogate” fluid model for the lubricant
  - This had worked well in the past for complex fuels such as jet and rocket fuels, and diesel but did not work so well for the lubricant
- Successfully developed a pseudo-pure fluid model for the lubricant
  - EOS coefficients and coefficients for viscosity and thermal conductivity correlations are in the NISTIR 8263
  - Much better way to disseminate results - REFPROP
    - “fluid” files are in the NISTIR 8263 or email us
REFPROP Model  https://www.nist.gov/srd/refprop

- **REference Fluid Thermodynamic and Transport PROPerties (NIST23)** sold by NIST Standard Reference Data
  - Contains thermophysical properties of industrially important pure fluids (147 at present) and mixtures (up to 20 components)

- **Easy-to-use computer program**
  - Can provide tables or graphs of properties of fluids
    - Thermodynamic properties (density, sound speed, heat capacity, enthalpy, entropy, boiling point, etc.)
    - Transport and other properties (viscosity and thermal conductivity, surface tension)
  - Easy to add a new “fluid file” for the lubricant MILPRF23699
    - Just place the MILPRF23699.FLD file (a plain text file) in a specific directory where all files of type .FLD reside, then run the program

- **Source code (FORTRAN) included**
- **Can Interface with common applications (Excel, MATLAB, LabView, Python, C/C++, etc.) through wrappers and DLL**
  - Info on wrappers here: https://github.com/usnistgov/REFPROP-wrappers
Results for MIL-PRF-23699

Developed a Helmholtz-form EOS
All thermodynamic properties come from the EOS

\[
\frac{\alpha(\rho, T)}{RT} = \alpha(\delta, \tau) = \alpha^0(\delta, \tau) + \alpha^\tau(\delta, \tau) \quad \delta = \frac{\rho}{\rho_c} \quad \tau = \frac{T_c}{T}.
\]

\[
\alpha^0 = \frac{h_0^0}{RT_c} - \frac{s_0^0}{R} \cdot \left(1 + \ln \frac{\delta \tau_0}{\delta_0 \tau} - \frac{\tau}{R} \int_{\tau_0}^{\tau} \frac{C_p^0}{\tau^2} \, d\tau + \frac{1}{R} \int_{\tau_0}^{\tau} \frac{C_p^0}{\tau} \, d\tau \right).
\]

\[
\alpha^\tau(\delta, \tau) = \sum N_k \delta^d_k \tau^l_k + \sum N_k \delta^d_k \tau^l_k \exp(-\delta^l_k) + \sum N_k \delta^d_k \tau^l_k \exp(-\eta_k (\delta - \varepsilon_k)^2 - \beta_k (\tau - \gamma_k)^2).
\]

Uncertainties:
- density 0.2%
- sound speed 0.1%
- \(C_p\) 0.3%
Note on developing EOS

- Measurements, although seeming comprehensive, do not cover the entire fluid space

- Use a set of constraints during development to ensure appropriate behavior over entire fluid surface

$T_c$
Results for MIL-PRF-23699: density
Results for MIL-PRF-23699: speed of sound
Results for MIL-PRF-23699: heat capacity

All measurements at ambient pressure (0.083 MPa)
Results for MIL-PRF-23699: thermal conductivity

\[ \lambda(T, \rho) = \lambda^0(T) + \Delta \lambda^{\text{res}}(T, \rho) + \lambda^{\text{crit}}(T, \rho), \]

\[ \lambda^0(T) = \sum_{k=0}^{n} \alpha_k T^k \]

\[ \Delta \lambda^{\text{res}}(T, \rho) = \sum_{l=1}^{3} (\beta_{1,l} + \beta_{2,l}(T/T_c))(\rho/\rho_c)^l \]

\[ \lambda^{\text{crit}}(T, \rho) \] found with generalized method \( f(T_c, \rho_c, \rho_c, \text{MW}, \omega) \)
Results for MIL-PRF-23699: viscosity

\[ \eta(\rho, T) = \eta_0(T) + \Delta \eta(\rho, T) + \Delta \eta_c(\rho, T) \]

\( \eta_0(T) \) found from method of Chung et al. (1988)

\[ \Delta \eta(\rho, T) = (a_1 \Gamma + a_2 \Gamma^2 + a_3 \Gamma^3 + a_4 \Gamma^{11}) \sqrt{T} \rho_r^{2/3} \]

\( \Gamma = \rho_3^{3.36}/T \)

\( \Delta \eta_c(\rho, T) \) set to zero
Results for MIL-PRF-23699: PH chart generated by REFPROP
## Results for MIL-PRF-23699: tables generated by REFPROP

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<th>Density (kg/m³)</th>
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<th>Sound Speed (m/s)</th>
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Conclusions

• We developed, based on our experimental measurements, models for the thermophysical properties of MIL-PRF-23699 (and 3 pure POE’s)
  • including $\rho$, density, $T$, heat capacity, sound speed, vapor pressure, enthalpy, entropy, viscosity, thermal conductivity
• Models implemented in easy-to-use computer program REFPROP
• Details and REFPROP-compatible files in freely available publication
  https://doi.org/10.6028/NIST.IR.8263