Helium-Hydrogen $P\rho T-x$ Measurements and Equation of State

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Liquid Hydrogen as a Rocket Fuel

- Liquid hydrogen ($\text{LH}_2$) tanks are pressurized with gaseous helium
- Small amounts of helium dissolve into the liquid hydrogen
- Current models assume pure LH$_2$ properties
- No real fluid helium-hydrogen mixture model exists

NASA's Space Launch System: Images from spacenews.com (above) and nasa.gov (right)
Ideal Models

- Dalton’s and Amagat’s law are approximations for real-gas mixtures

- Dalton’s law:
  \[ P_m = \sum_{i=1}^{k} P_i(Tm, Vm) \]

- Amagat’s law:
  \[ V_m = \sum_{i=1}^{k} V_i(Tm, Pm) \]
Binary Mixture Fluid Classifications

A – Type I Fluid (methane – ethane) – Simple two phase fluid.
B – Type II (water – phenol) Stable liquid-liquid phase.
C – Type III (helium – hydrogen) – Two distinct critical lines that never meet.

¹ C. L. Young, Pure and Appl. Chem. 68, pp. 1561-1572 (1986).
Type III Fluid Surface

- Complex fluid interactions require a real fluid model
- Need VLE and PpT-x experimental measurements

\[ C. \text{L. Young, Pure and Appl. Chem. 68, pp. 1561-1572 (1986).} \]
• Only Vapor-Liquid-Equilibrium (VLE) data available
• Need $P_T-x$ measurements
PpT-x Measurements

• Pressure: Paroscientific Digiquartz
• Composition: Gas Chromatography
• Temperature: Secondary Standard Germanium RTDs
• Density: Magnetic Suspension Microbalance

Liquid \( \text{pH}_2 \) \( P_pT \) measurements agree with \( \text{pH}_2 \) EOS\(^3\) within 0.06\% (above), early \( \text{LN}_2 \) agreed within 0.1\%\(^4\).

Conducted \( P_pT \)-x measurement on helium-hydrogen mixtures from 17 K to 29 K for pressures up to 2 MPa.

Mixture Equations of State

Helmholtz Free Energy Equation

\[ \alpha(\delta, \tau, x) = \alpha^0(\rho, T, x) + \alpha^r(\delta, \tau, x) \]

Ideal Equation

\[ \alpha^0(\rho, T, x) = \sum_{i=1}^{N} x_i \left( \alpha^0_{0i}(\delta, \tau) + \ln(x_i) \right) \]

Residual Equation

\[ \alpha^r(\delta, \tau, x) = \sum_{i=1}^{N} (x_i \alpha^r_{0i}(\delta, \tau)) + \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} (x_i x_j F_{ij} \alpha^r_{ij}(\delta, \tau)) \]

Reduced Density

\[ \delta = \frac{\rho}{\rho_c(x)} \]

Reduced Temperature

\[ \tau = \frac{T_c(x)}{T} \]
He-H$_2$ Equation of State Comparisons to Experimental Measurements

![Graph showing comparison between experimental measurements and calculated values for He-H$_2$ system.](image)
He-H$_2$ EOS Saturation Region
Future Work

- Does dissolved helium affect system level design and operation decisions?
  - Compare system performance assuming no helium dissolution and using the new He-H\(_2\) EOS.
- Use new capabilities to develop mixture models for other cryogens (neon-helium, neon-hydrogen, hydrogen-deuterium etc.)
Summary

• Conducted the first ever PpT-x measurements of He-H$_2$ mixtures.
• Developed a reference quality mixture equation of state.
• This EOS will be used to determine if dissolved helium affects system level decisions.
• This work will be continued for other cryogenic mixtures.
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THANK YOU
# PpT-x Measurements

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<th>Sample #</th>
<th>Temperature [K]</th>
<th>Pressure [PSI]</th>
<th>Density [kg/m^3]</th>
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