High Pressure Thermophysical Gas Property Testing, Uncertainty Analysis, and Equation of State Comparison for Supercritical CO2 Compression Applications

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Overview

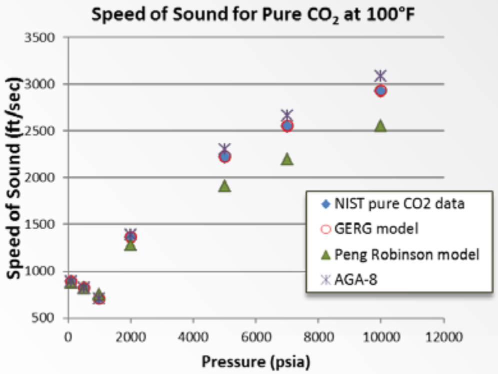
- Objective
- Characterization of Representative Gas Mixtures
- Test Description and Methodology
  - Uncertainty Analysis
- Test Campaign Results and Equation of State Comparisons
- Conclusions

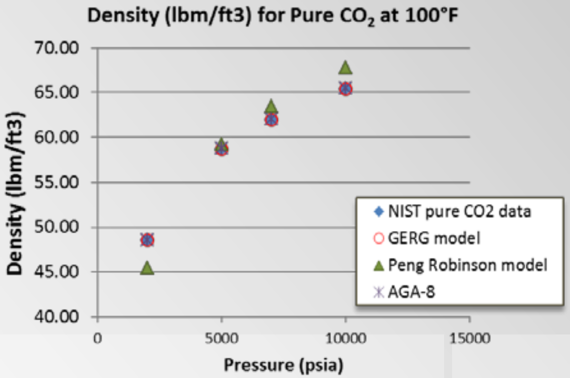
Interest in Supercritical Carbon Dioxide

- Continual increase of government regulations and international standards requiring lower acceptable release limits of greenhouse gases
- Investigation of sequestration, compression and transportation of CO_2 involving NGCC, IGCC, oxy-fuel and pulverized coal power plants
- Increased interest in compressed supercritical CO_2
- Limited data publically available to verify the results from the various equations of state (EOS) calculations for the range of pressures, temperatures and multi-species gas compositions relevant to compression and pipeline operations

Applications to Gas Compression

- Design and optimization of centrifugal compressor and turbomachinery
  - Density, compressibility, speed of sound, specific heat
- Mechanical design calculations
  - Relative gas velocity, temperature rise, flow rate for the stage-to-stage impeller geometry, material selection
- EOS models departure from Ideal Gas Behavior can be profound at extreme pressures and temperatures





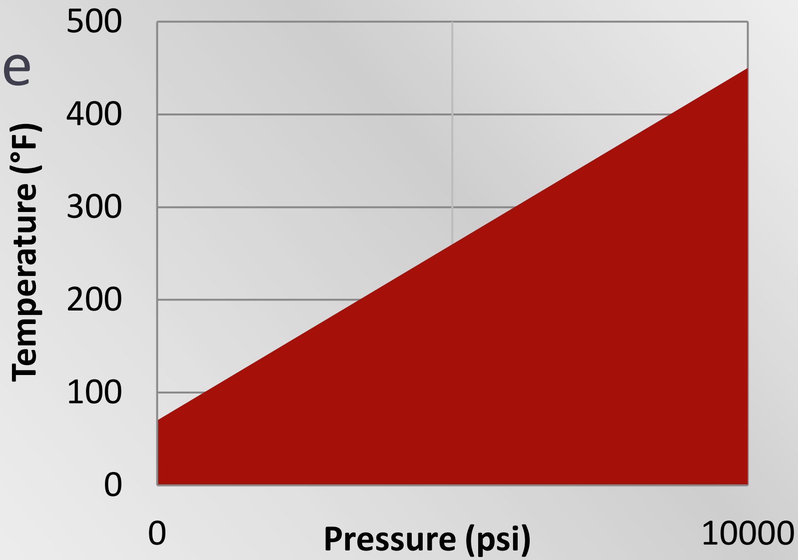
Representative Gas Mixtures and Ranges

Mixture	CO_2 %mol	N_2 %mol	O_2 %mol	Ar %mol	CH_4 %mol	Description
A	94.74	0	5.26	0	0	Membrane Separation
B	85.42	9.38	5.21	0	0	Oxy-Comb Lignite-Fired
C	95.96	2.02	0	1.01	1.01	Pipeline CO_2

Mix	Temperature	Pressure	Mix	Temperature	Pressure	Mix	Temperature	Pressure	Pressure
	°F	Psia		°F	Psia		°F	Psia	Psia
A	100	200	B	100	200	C	100	2000	2000
	100	800		100	800		100	4000	4000
	100	1250		100	1250		100	6000	4710
	100	1800		100	1800		100	8000	6280
	100	2500		100	2500		100	10000	7840
	200	200		200	200		200	2000	2000
	200	800		200	800		200	4000	4000
	200	1250		200	1250		200	6000	4710
	200	1800		200	1800		200	8000	6280
	200	2500		200	2500		200	10000	7840
	300	200		300	200		300	2000	2000
	300	800		300	800		300	4000	4000
	300	1250		300	1250		300	6000	4710
	300	1800		300	1800		300	8000	6280
	300	2500		300	2500		300	10000	7840
								*SOS	*Density

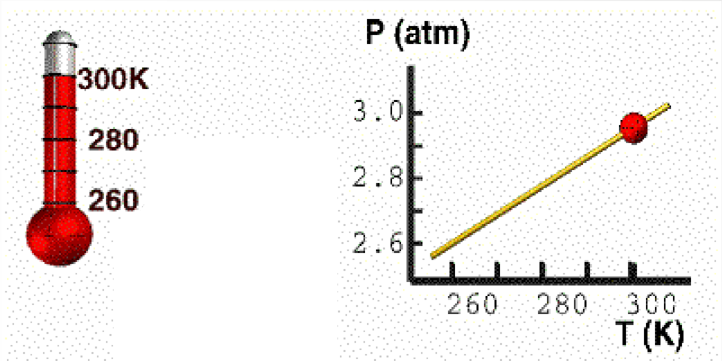
SwRI Gas Property Testing Laboratory: Current Testing Capabilities

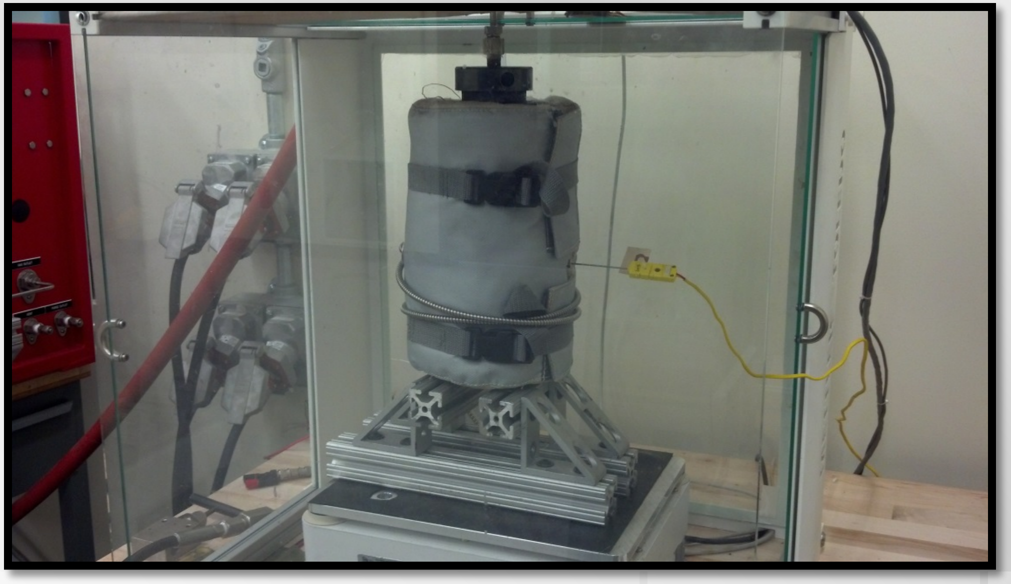
- Density (compressibility factor), Speed of Sound and Specific Heat at Constant Volume (Cv)
- Stable gas mixtures including CO_2, hydrocarbons, combustibles, non-combustibles and acid gas blends
- 0-10,000 psi pressure range
- Ambient to 450°F temperature range
- Gas sampling and species determination near critical point (gas chromatography)
- Determination of liquid formation



Density Measurement

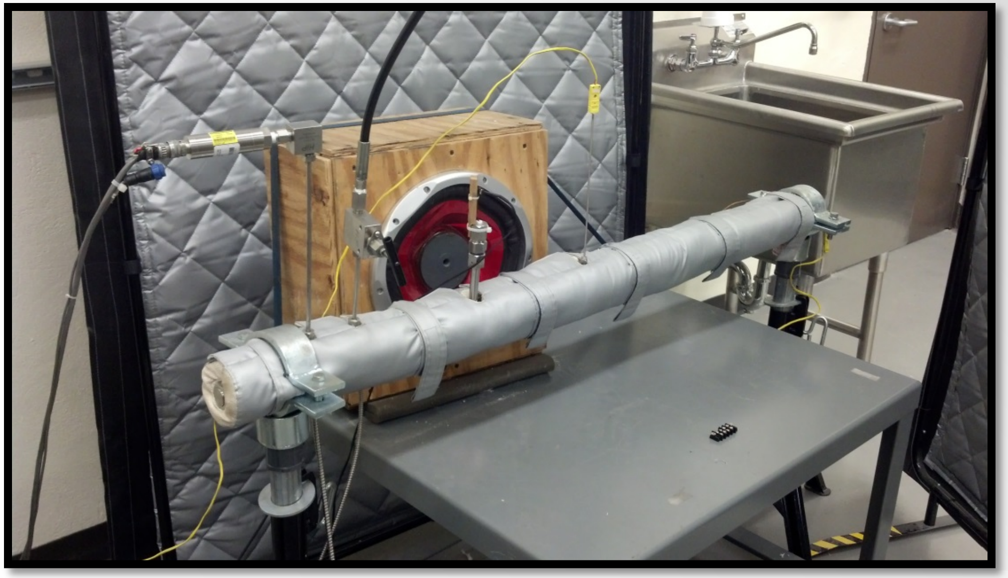
- Based on highly precise mass measurements at constant volume under controlled pressure and temperature conditions
  - High pressure autoclave and precision scale
  - All instruments calibrated by SwRI ISO certified laboratory (on site) with NIST traceability

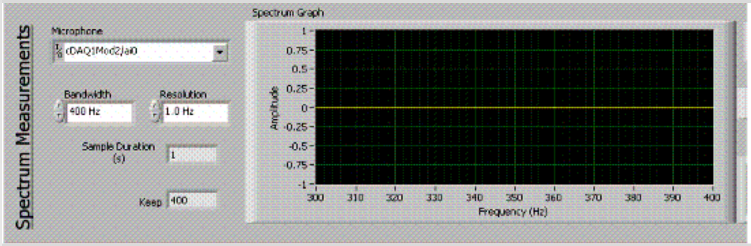




Speed of Sound Measurement

- Frequency measured using an acoustic-to-electric transducer at controlled temperature and pressure conditions
  - Acoustic resonance with a high pressure pipe with two closed ends
  - External speaker used to run a frequency sweep to determine length resonance frequency (half-wave response)





Calculation and Analyses of Uncertainties

- Primary measurements and reference conditions at each test iteration

Direct Measurement	Reference Condition

• Sensor Measurement Uncertainty
  • Scale Precision
  • Frequency Resolution
• Geometry
  • Internal Volume
  • Length
	• Pressure Uncertainty
	• Temperature Uncertainty
	• Gas Mixture Analytical Uncertainty
	• EOS Model Predictions

Application of the Perturbation Method

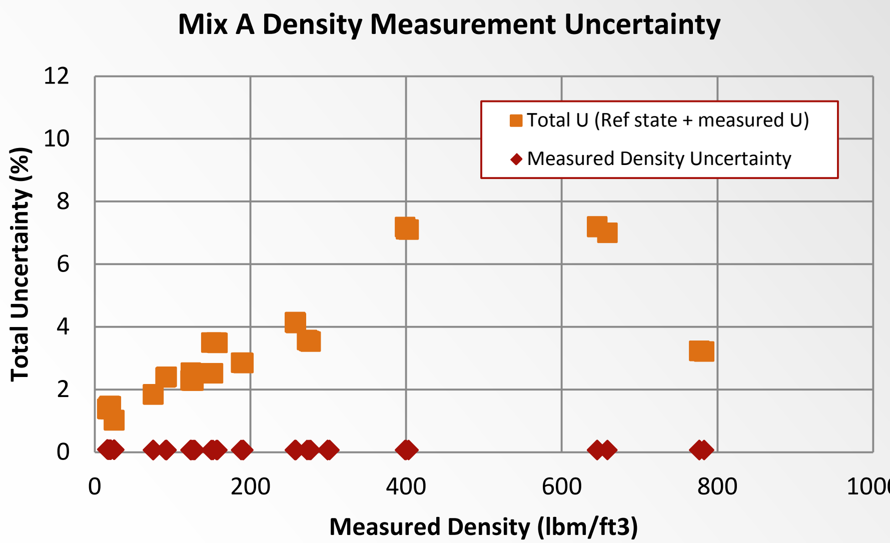
- Determination of total uncertainty of dependent measurement systems
- Does not require linearity assumptions

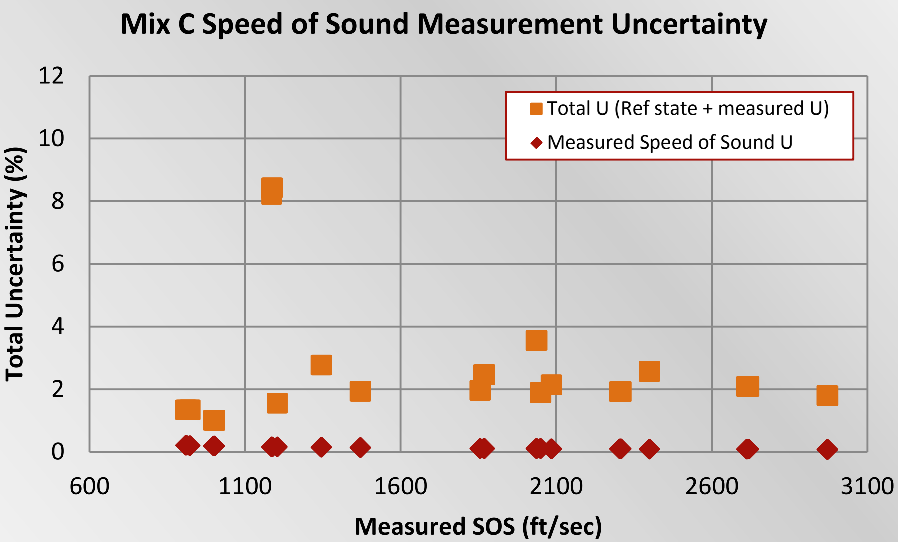
$$\Delta F = \Delta F(\Delta x_1) + \Delta F(\Delta x_2) + \Delta F(\Delta x_3) + \ldots \Delta F(\Delta x_n)$$
$$= \left|F(x_1) - F(x_1 + \Delta x_1)\right| + \left|F(x_2) - F(x_2 + \Delta x_2)\right| + \left|F(x_3) - F(x_3 + \Delta x_3)\right| + \ldots \left|F(x_n) - F(x_n + \Delta x_n)\right|$$
$$= \sum_{i=1}^{n} \left|F(x_i) - F(x_i + \Delta x_i)\right|$$

- Sequentially perturbing (altering) input values by their respective uncertainties
  - Use of NIST REFPROP program
  - GERG EOS Model

Final Test Uncertainties – Density & SoS

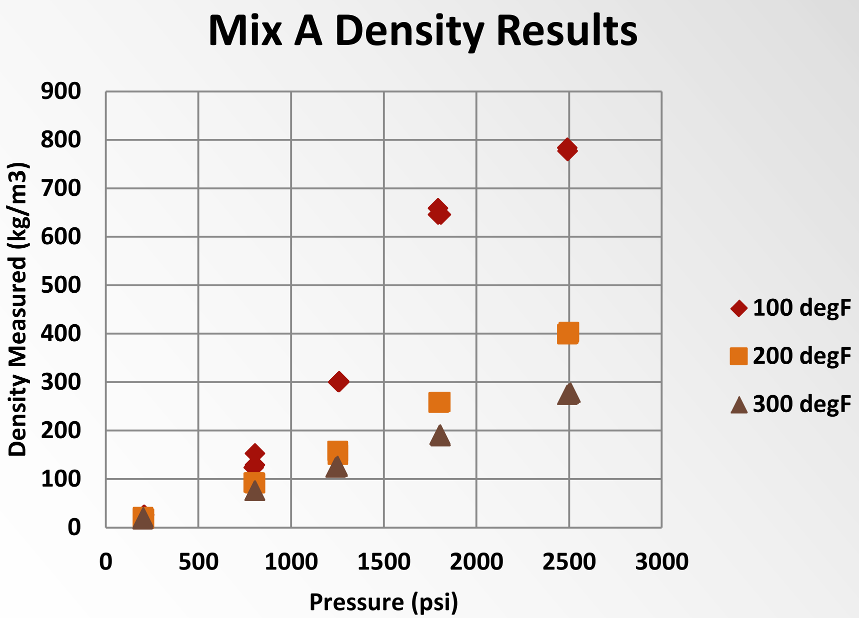
- Largest component towards total uncertainty – gas mixture component (analytical) uncertainty
- Reference uncertainties that could not be calculated
  - Mix A: 1250 psi & 100 °F
  - Mix B: 1800 psi & 100 °F



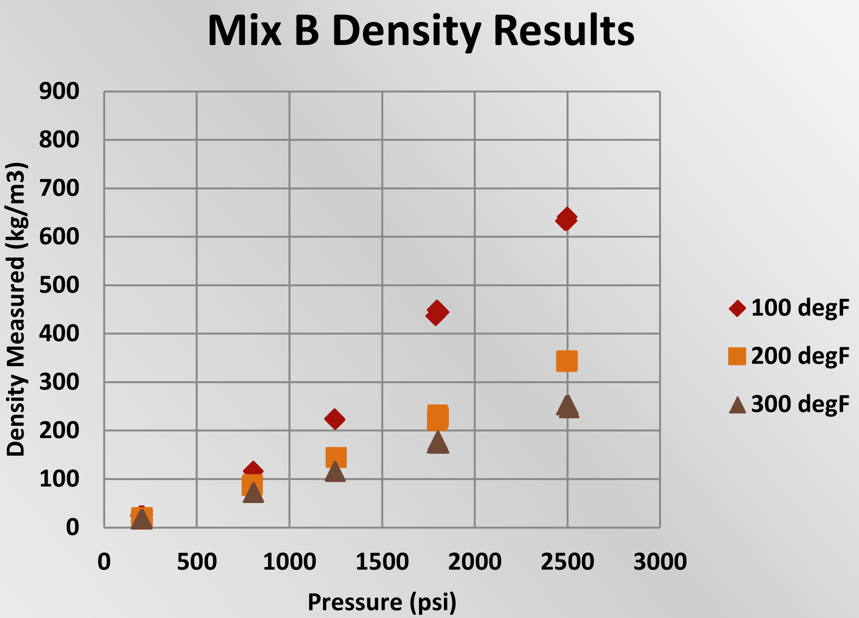


Mix A & B Density Results

- Greater influence of density due to pressure at lower temperatures
- Larger difference with Mix A



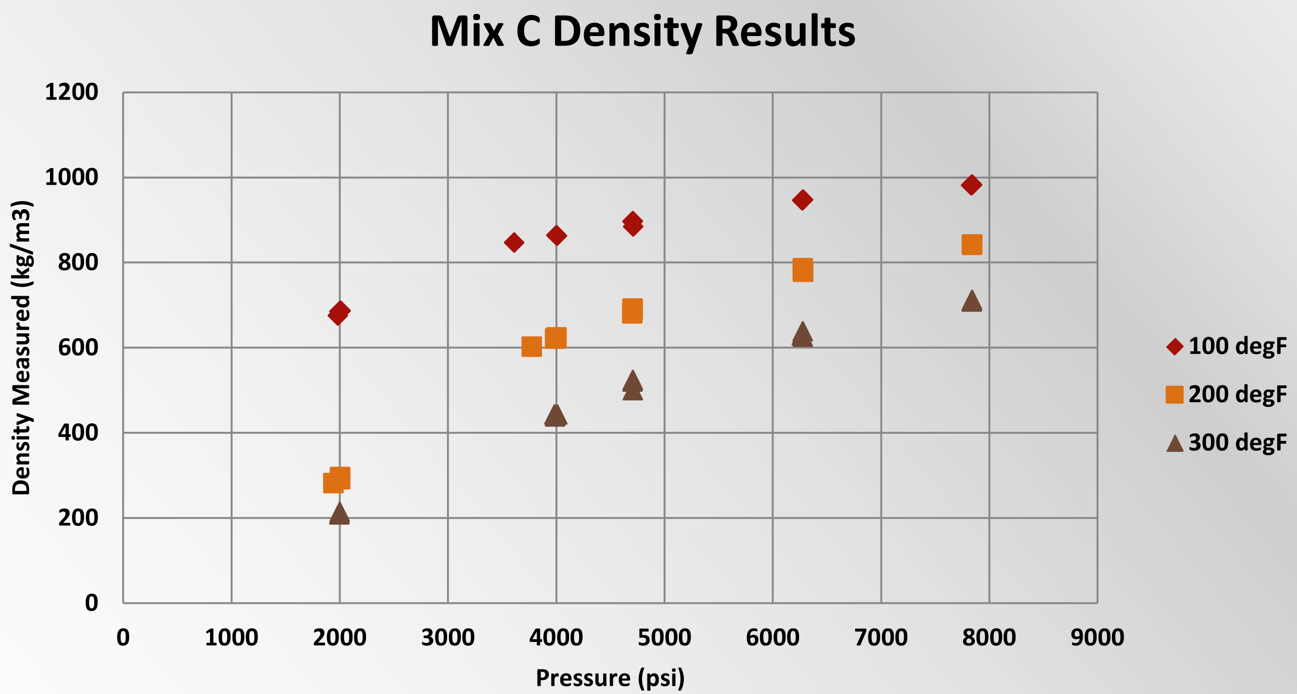
Mixture	CO_2 %mol	O_2 %mol
A	94.74	5.26



Mixture	CO_2 %mol	N_2 %mol	O_2 %mol
B	85.42	9.38	5.21

Mix C Density Results

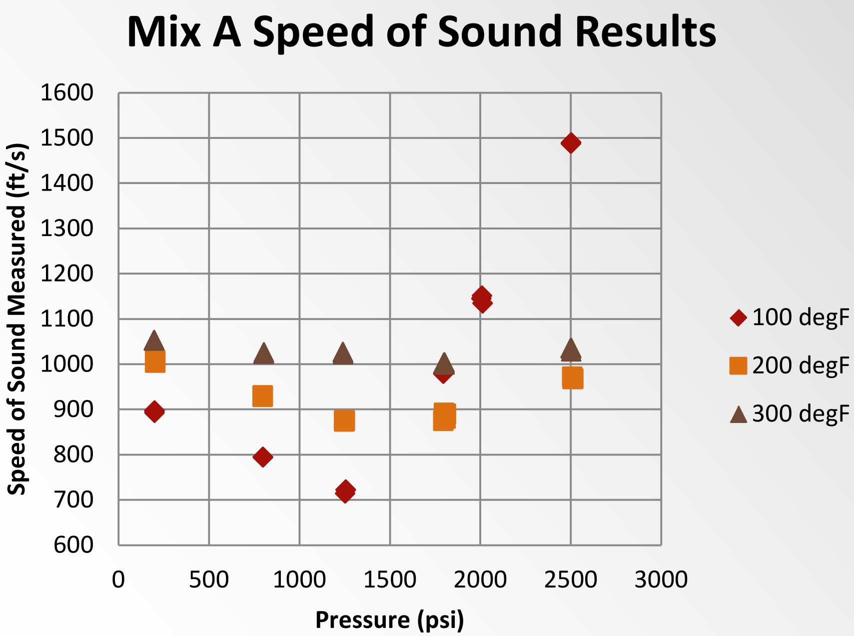
- Less influence of density due to pressure changes at elevated pressures regardless of temperature.



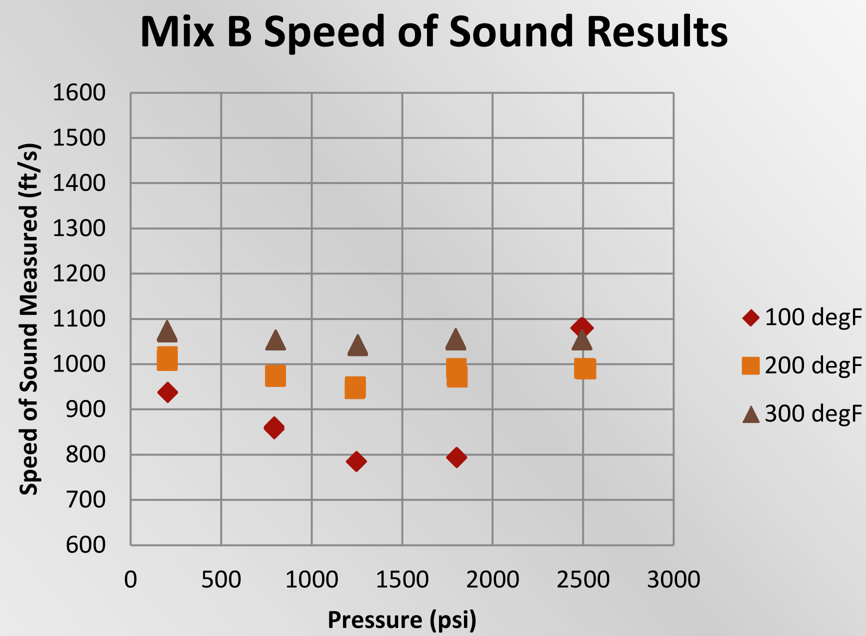
Mixture	CO_2 %mol	N_2 %mol	Ar %mol	CH_4 %mol
C	95.96	2.02	1.01	1.01

Mix A & B Speed of Sound Results

- Greater influence of speed of sound due to pressure at lower temperatures
- Impact of the critical point



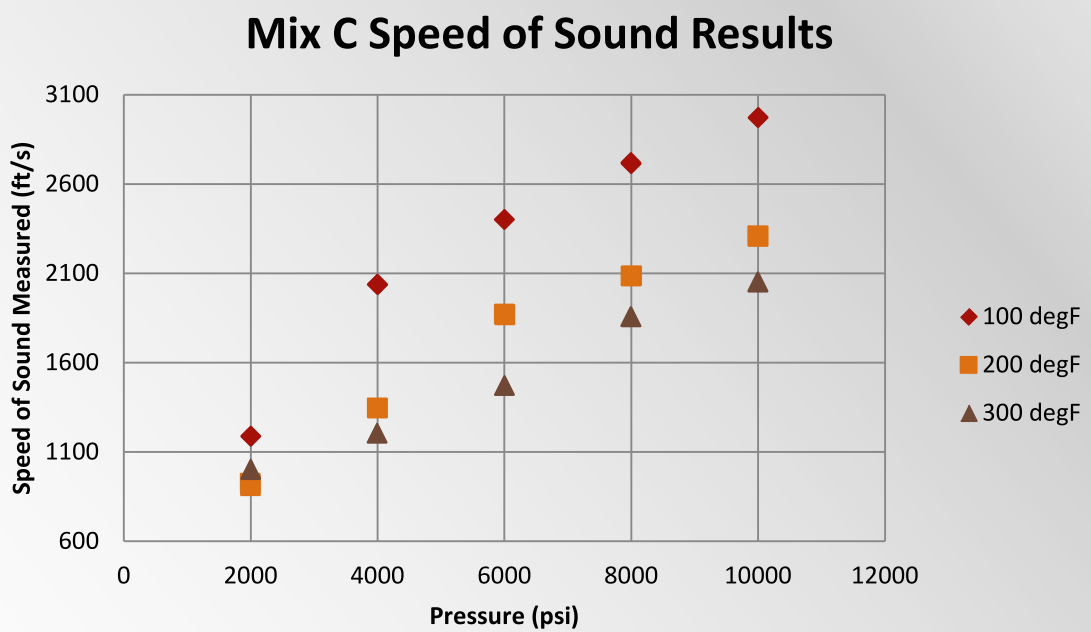
Mixture	CO2 %mol	O2 %mol
A	94.74	5.26



Mixture	CO2 %mol	N2 %mol	O2 %mol
B	85.42	9.38	5.21

Mix C Speed of Sound Results

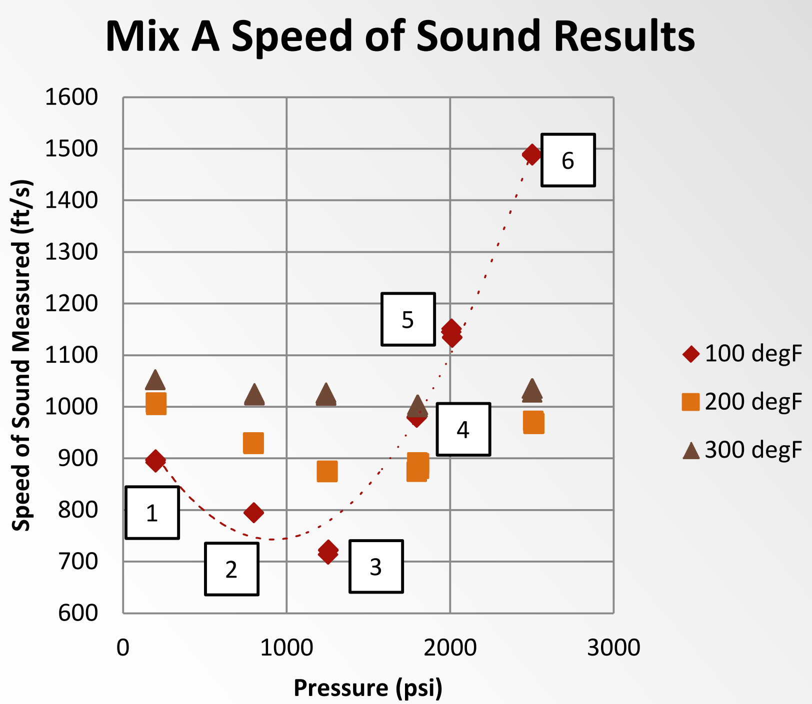
- Similar influence of speed of sound (slope) due to pressure changes at elevated pressures for all tested temperatures.

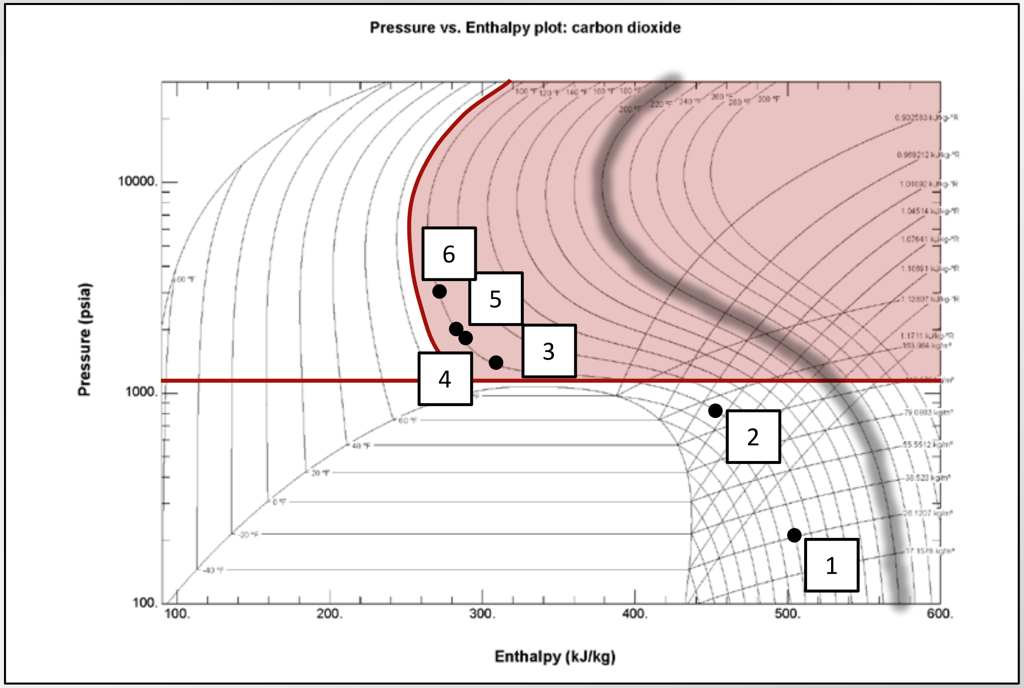


Mixture	CO_2 %mol	N_2 %mol	Ar %mol	CH_4 %mol
C	95.96	2.02	1.01	1.01

Mix A Speed of Sound Results

- Increase of speed of sound when approaching and surpassing the critical point.





Mixture	CO2 %mol	O2 %mol
A	94.74	5.26

Equations of State (EOS) Comparison

- GERG 2008 Wide-Rage EOS
  - Based on 21 natural gas components
    - Methane, nitrogen, carbon dioxide, oxygen and argon
- Default NIST EOS
- Predict similar density and speed of sound values for all the mixtures at most test points

Predicted Density Differences

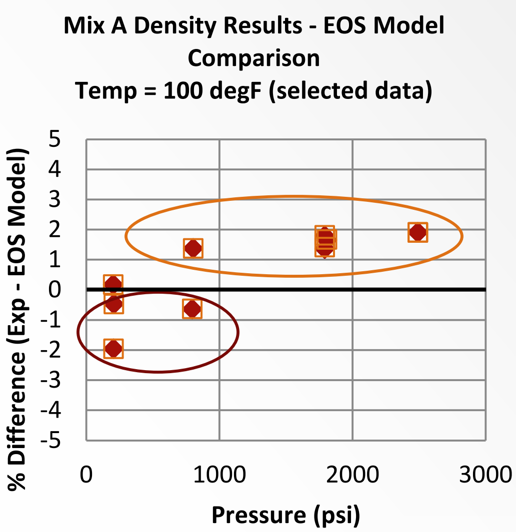
- A: 0.54% kg/m3
- B: 1.72% kg/m3
- C: 0.21% kg/m3

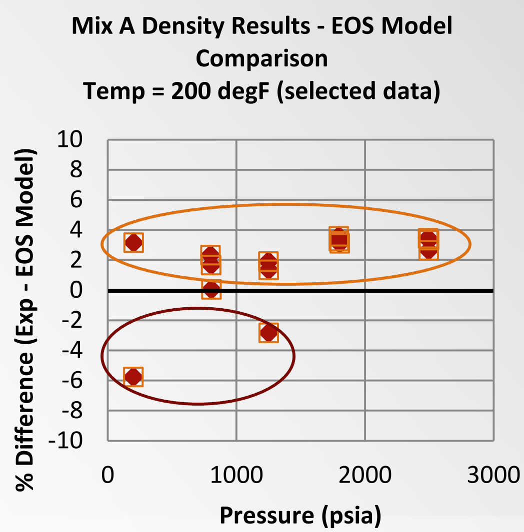
Predicted Speed of Sound Differences

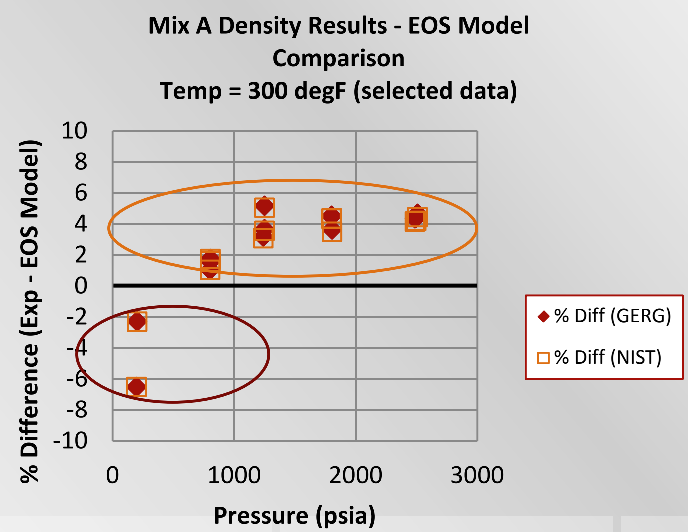
- A: 0.28% ft/s
- B: 0.03% ft/s
- C: 0.19% ft/s

Mix A Density EOS Model Comparison

- Both GERG and Default NIST EOS models match experimental data within +/- 4%
- Lower pressures – EOS models predict higher values (max ~6%)
- Higher pressures – EOS models predict lower values (max ~6%)
- Similar results for Mix B

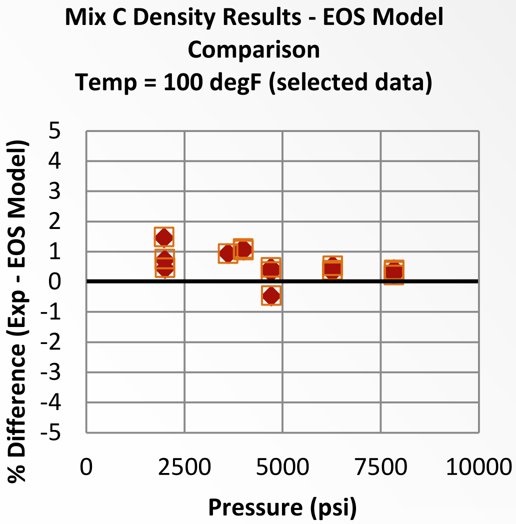


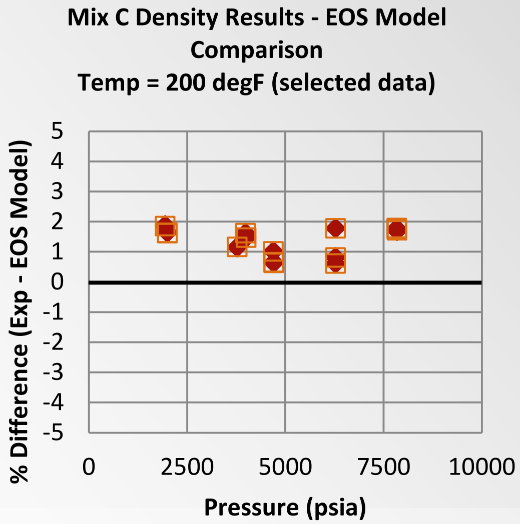


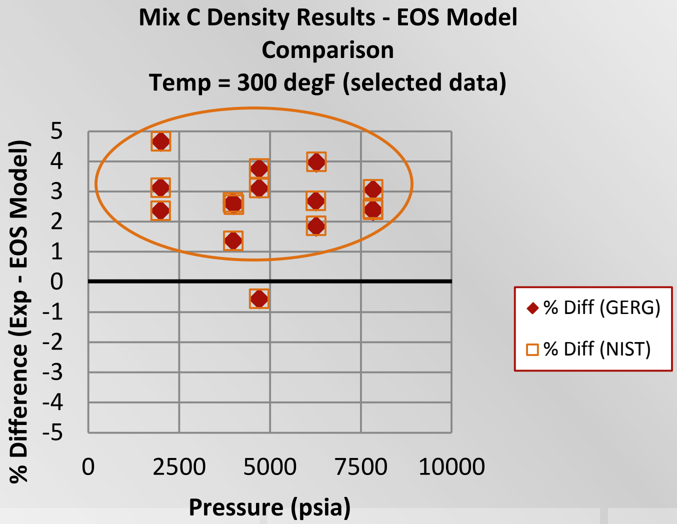


Mix C Density EOS Model Comparison

- Both GERG and Default NIST EOS models match experimental data within +/- 2% for lower temperatures (100 °F & 200 °F)
- Larger differences at 300 °F
- Higher temperatures – EOS models predict lower values (max ~5%)

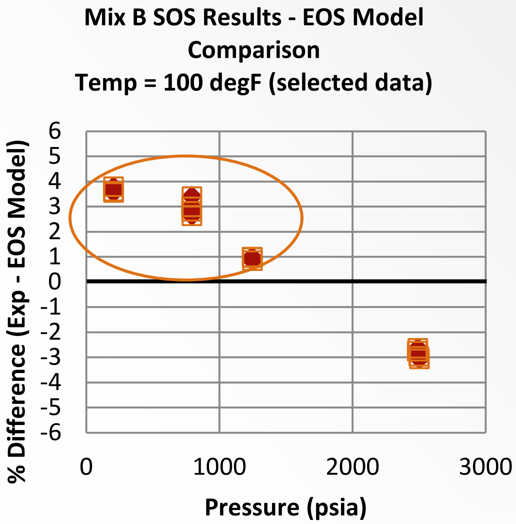


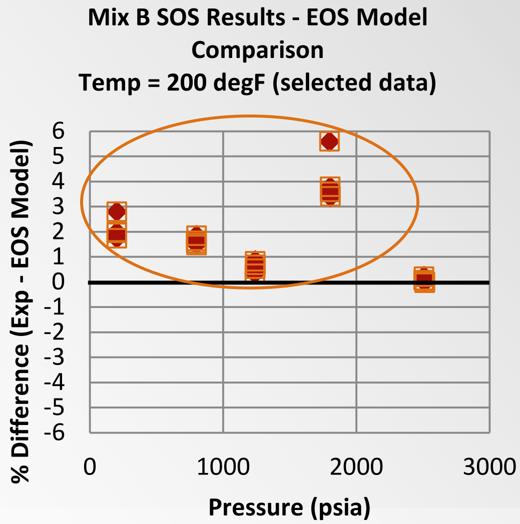


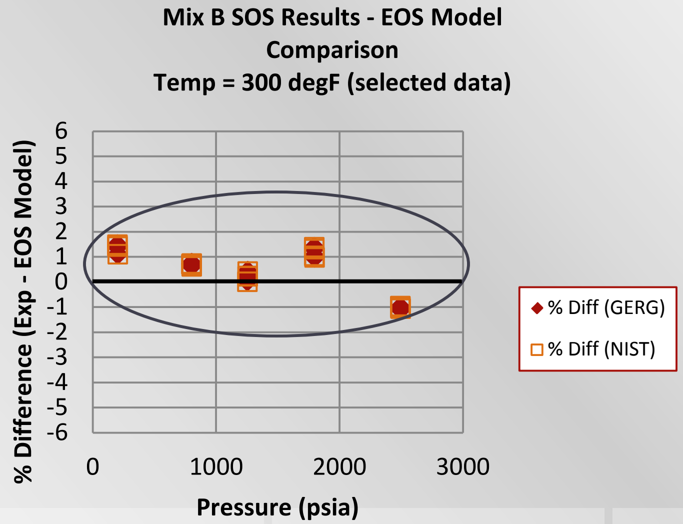


Mix B SoS EOS Model Comparison

- Both GERG and Default NIST EOS models match experimental data within +/- 5%
- Smaller differences in EOS models and experimental data at 300 °F
- Lower temperatures – EOS models predict lower values (max ~6%)
- Similar results for Mix A and Mix C







EOS Model Conclusions

- GERG and default NIST EOS models predict similar density and speed of sound values for all the mixtures at most test points
  - Max 1.7% density difference
  - Max 0.3% speed of sound difference
- In general, both GERG and default NIST EOS models match experimental data within +/- 5% for most test points
- Density (pressure influenced)
  - Lower pressures – EOS models predict higher values
  - Supercritical regime – EOS models predict lower values
- Speed of Sound (temperature influenced)
  - Smaller differences in EOS models and experimental data at 300 °F
  - Lower temperatures – EOS models predict lower values

Thank You

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