Comparison of sCO_2 Compressor Performance Test Results Using Temperature-, Density-, Or Torque-based Measurements

Paper #053

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SCO2 offers many benefits

- Reduced machinery size
- High cycle efficiencies
- Heat source independency
- Abundant and relatively benign

SCO2 also poses many challenges

- High pressures
- High temperatures (at high pressures)
- Low temperatures (Joule-Thomson effect with leaks)
- **Property changes near critical point**

Density varies rapidly near critical point

- At 74 bar, a **2ºC shift** in temperature from 32ºC to 30ºC results in a fluid density **more than double** its original value.
- If conditions drop into vapor dome, liquid will form, posing hazard to machinery.

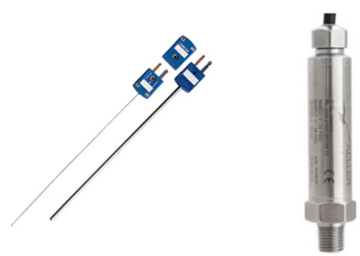
Temperature control near critical point is…critical

- But direct temperature measurement is prone to error
- Thermocouple accuracies +/- 1 K typical
- Thermowells disturb the flow, and recovery coefficients not well documented for sCO2

$$T_t = T_s + R\frac{u^2}{2c_p}$$

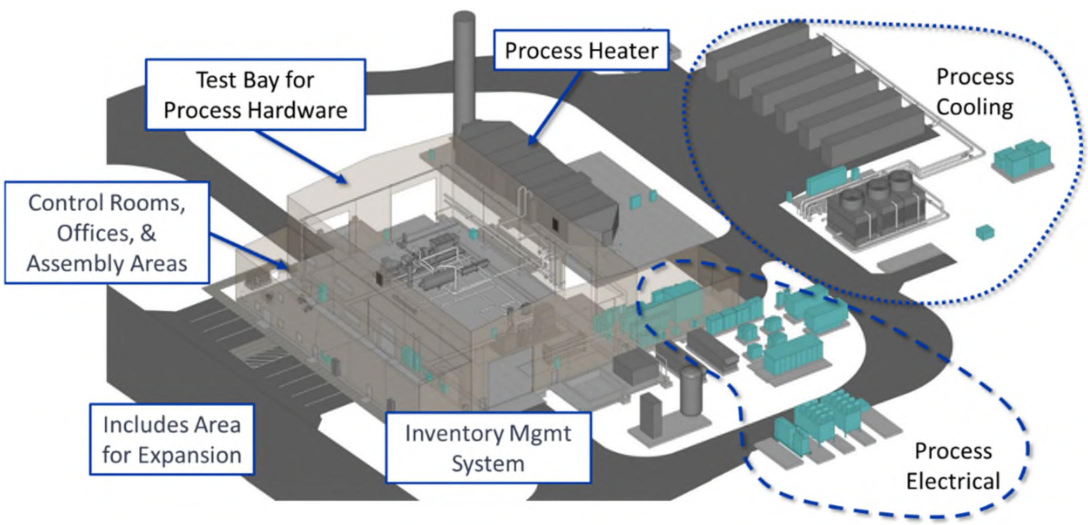
Can density and pressure measurement perform better than temperature and pressure?

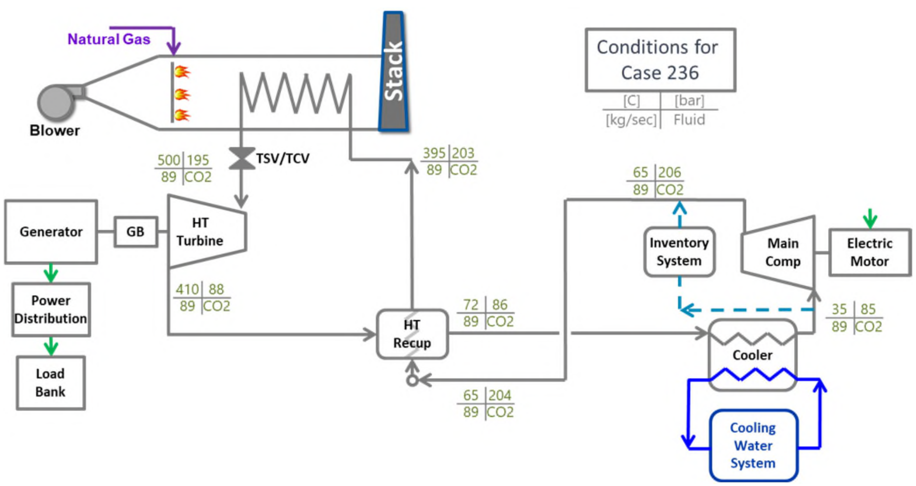
Enthalpy(T,P) vs Enthalpy(D,P)



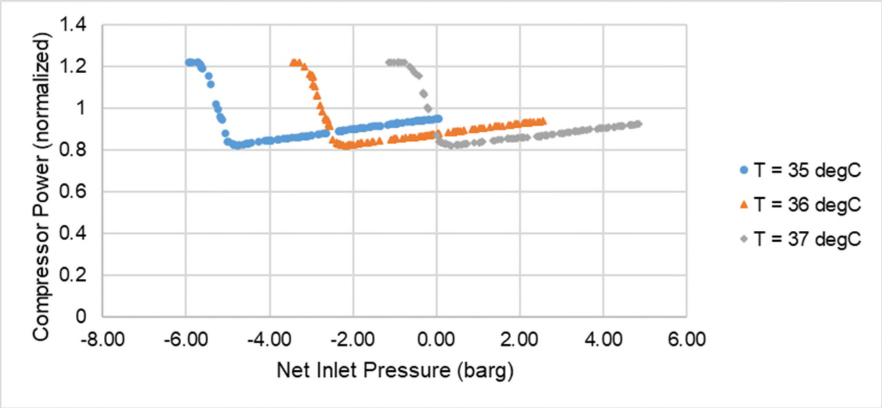
Could torque/speed measurement
also be a substitute for temperature?

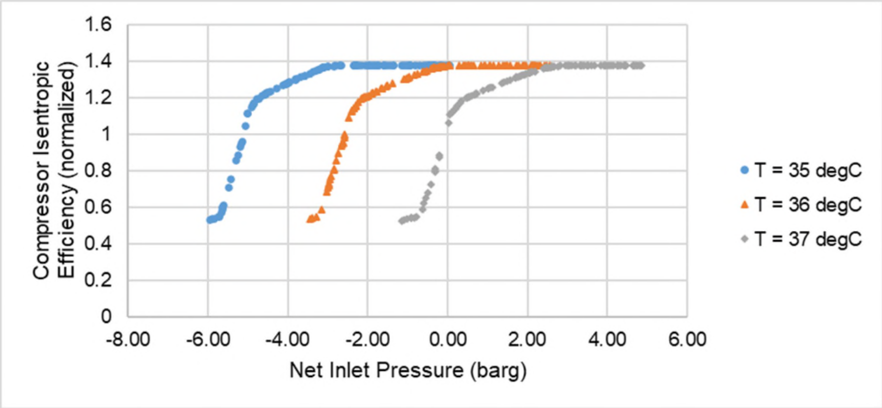
The STEP Demo facility operated at 4MWe in October 2024

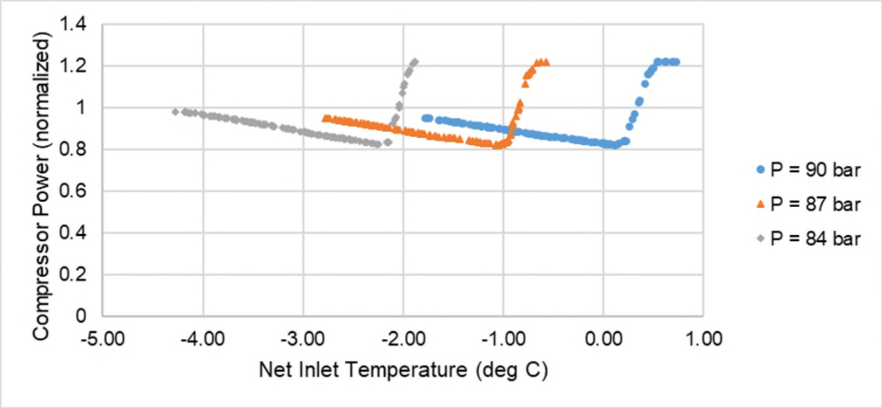


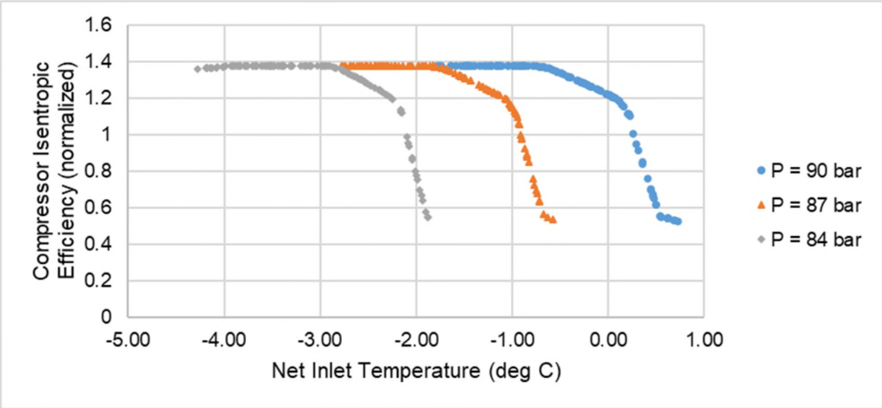


Drastic changes in simulated performance for small T/P changes

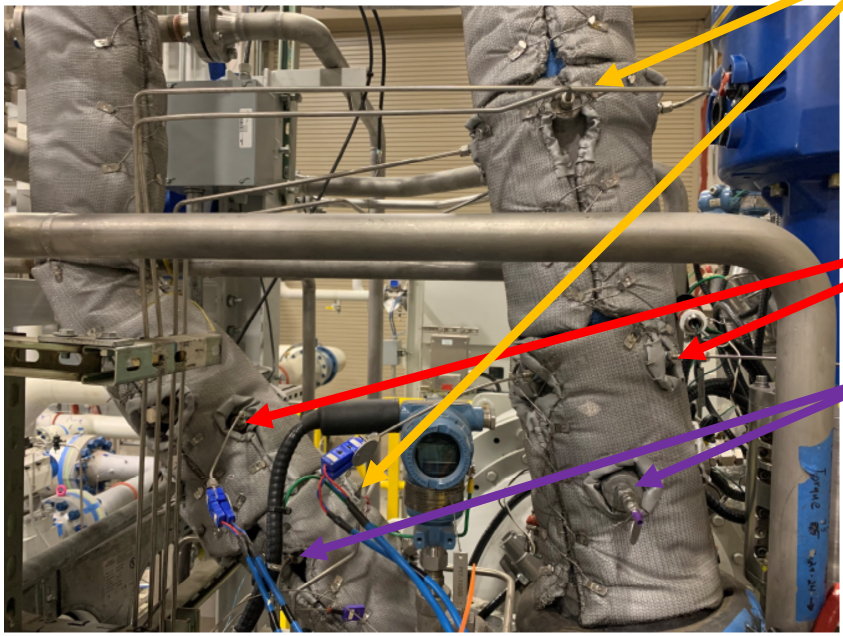






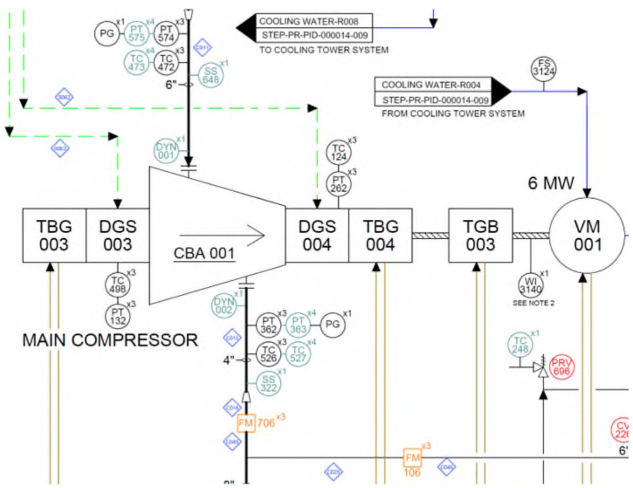


The main compressor inlet was instrumented per ASME PTC-10*

*As much as possible

Instrument uncertainties were determined from calibration or manufacturer data



Measurement	Average End-to-End Uncertainty
Compressor Inlet Temperature	0.45%
Compressor Inlet Pressure	0.28%
Compressor Outlet Temperature	0.19%
Compressor Outlet Pressure	0.14%
Compressor Mass Flow Rate	0.64% (ASME MFC-3M estimate)
Compressor Low Speed Shaft Torque	0.02% (manufacturer's rating)
Compressor Speed Keyphasor	0.03% (manufacturer's rating for nominal compressor speed)
Compressor Inlet Density	0.1 kg/m3 (manufacturer's rating)

Performance calculations utilized REFPROP for property lookups

- $\dot{W} = \dot{m}(h_2 - h_1)$ Power
- $\eta_s = \frac{h_{2s} - h_1}{h_{2a} - h_1}$ Isentropic Efficiency

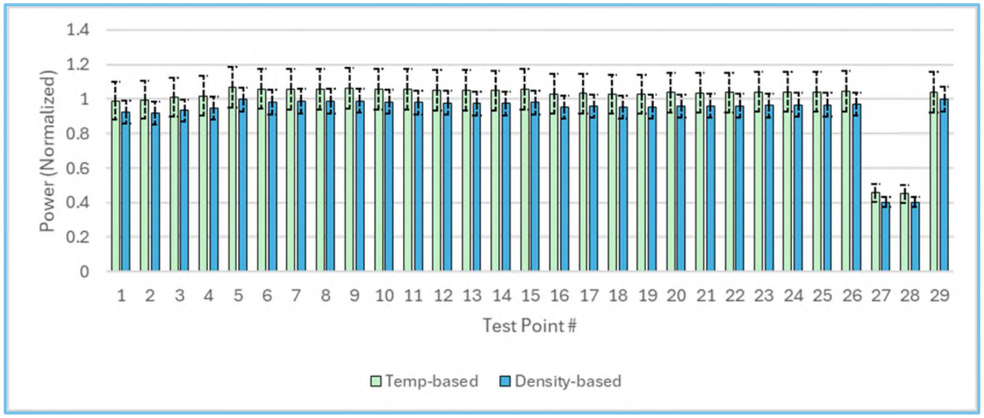
- Kline-McClintock used for uncertainty of calculated values.
- Uncertainty for property lookups utilized Monte Carlo simulation for variation due to inputs.
- Flat 0.5% uncertainty added to property lookups for REFPROP uncertainty.

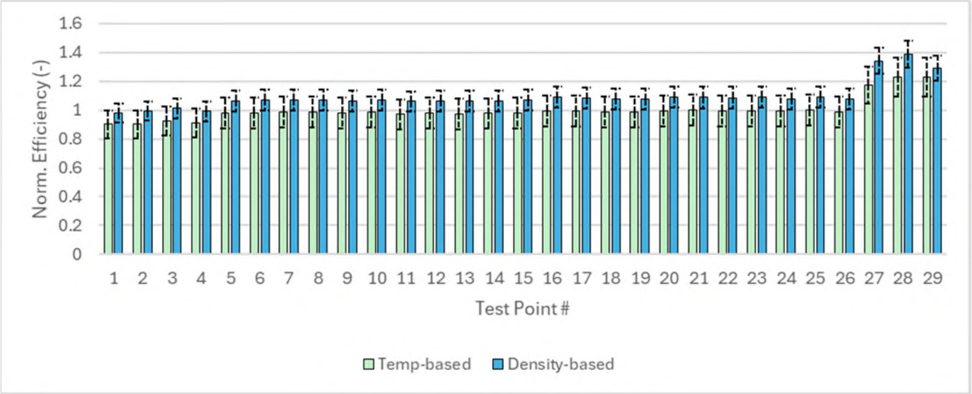
$$f = f(x_1, x_2, \ldots, x_n)$$

$$u_f = \sqrt{\left(\frac{df}{dx_1} u_{x_1}\right)^2 + \left(\frac{df}{dx_2} u_{x_2}\right)^2 + \cdots + \left(\frac{df}{dx_n} u_{x_n}\right)^2}$$

Density-based measurements reduced power uncertainty

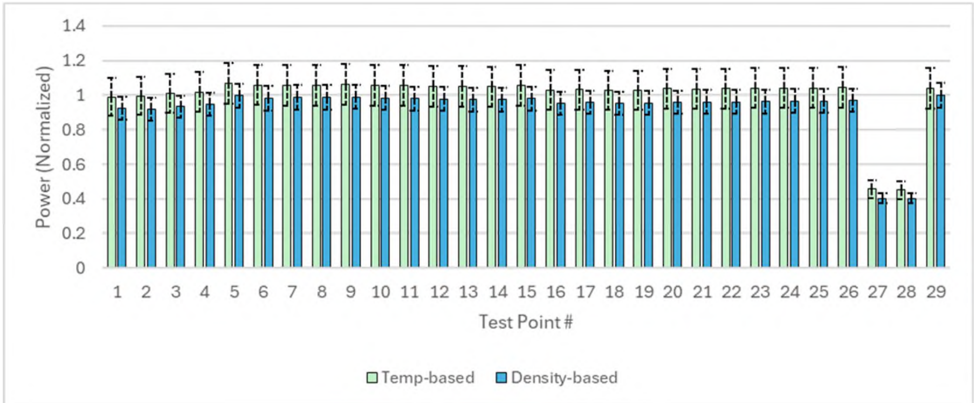
- Density-based power estimates were 7.3% lower on average.
- Uncertainties:
  - Density-based:
    - 7.0%
  - Temperature-based:
    - 11.1%

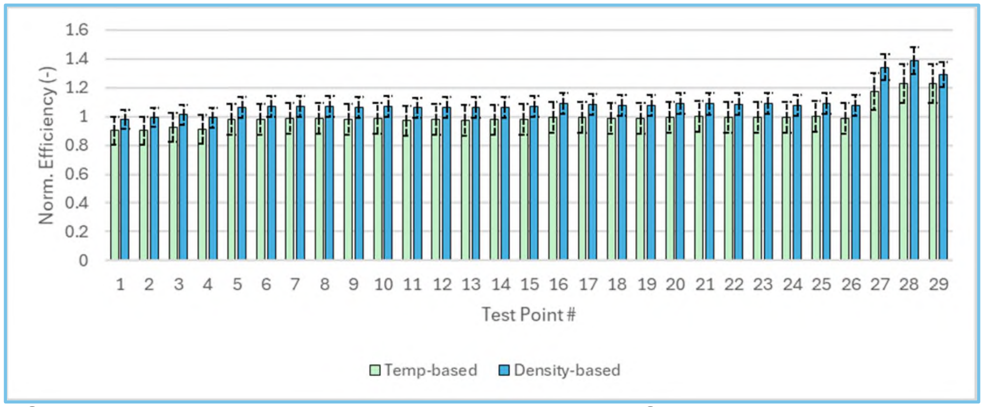




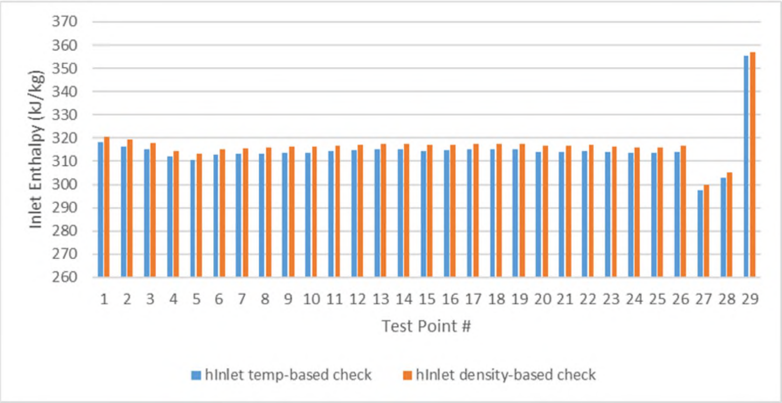
Density-based measurements reduced efficiency uncertainty

- Density-based efficiency estimates were 5% higher on average.
- Uncertainties:
  - Density-based:
    - 6.7%
  - Temperature-based:
    - 10.7%





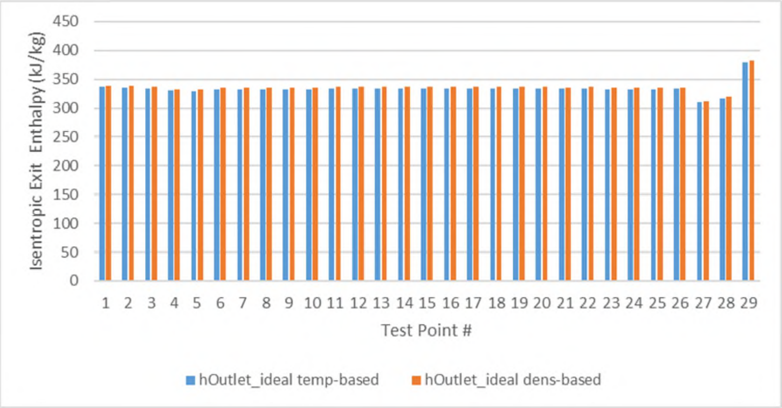
Examining enthalpy differences explains higher efficiency and lower power



Density-based 0.8% higher on average
Results in actual enthalpy change 7.3% smaller for density-based measurement

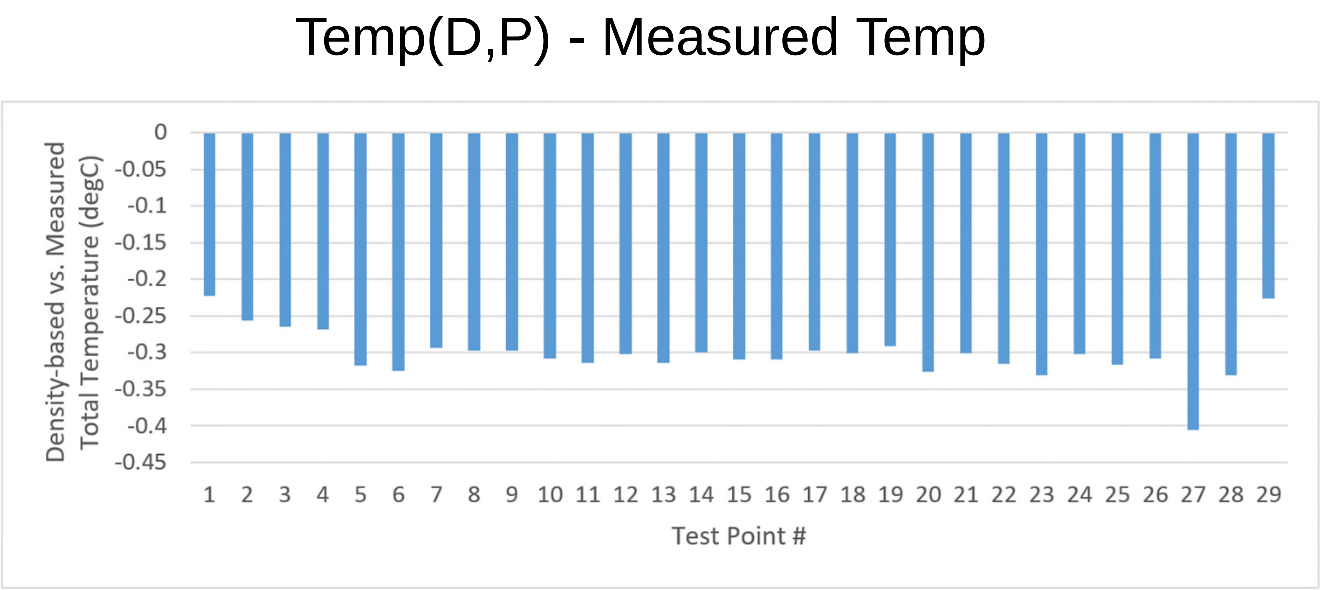
$$\eta_s = \frac{h_{2s} - h_1}{h_{2a} - h_1}$$

Same outlet enthalpy both bases



Density-based 0.8% higher on average
Results in 1.2% higher isentropic enthalpy change

Density-based temp estimates consistently lower than measured temps



- Recovery coefficient of 0.7 estimated for thermowells
- Data implies actual recovery coefficient is likely lower than 0.7 (if density-based data is more accurate)

Shaft torque and speed measurement allow power estimation

- $\dot{W}_{torque} = \tau\omega$

1. Calculate exit enthalpy : $h_{2a}(T_2, P_2)$
2. Use torque power to calculate inlet enthalpy:

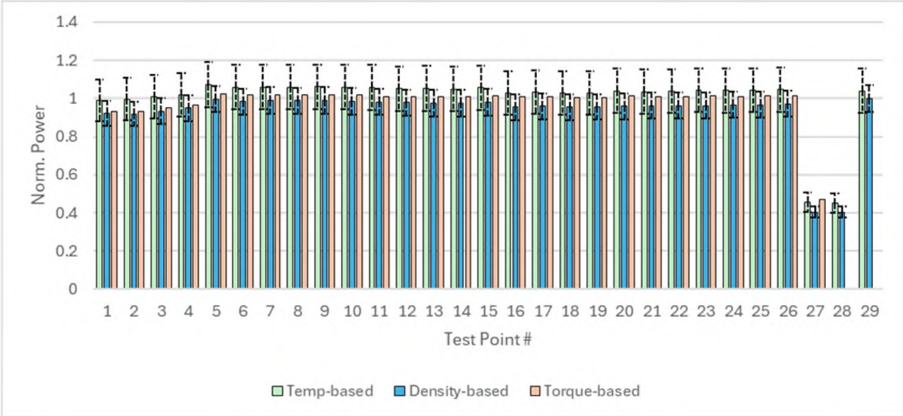
$$h_1 = h_{2a} - \frac{\dot{W}_{torque}}{\dot{m}}$$

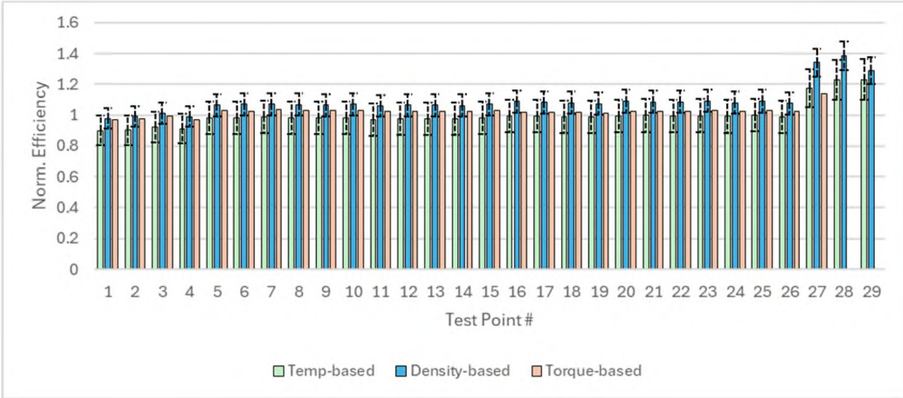
3. Calculate inlet entropy: $s_1(h_1, P_1)$
4. Calculate isentropic exit enthalpy: $h_{2s}(s_1, P_2)$
5. Calculate isentropic efficiency using equation 2: $\eta_s = \frac{h_{2s} - h_1}{h_{2a} - h_1}$

Torque-based power and efficiency estimates are similar to other methods*

- *Torque measured on low-speed coupling. 95% efficiency for both gearbox and high-speed coupling assumed
- Because of major assumptions/unknowns, no error bars shown.
  - Transmission efficiencies
  - Windage losses
  - Bearing losses
- However, low instrument uncertainty could make attractive if measurement and windage loss estimates are better.

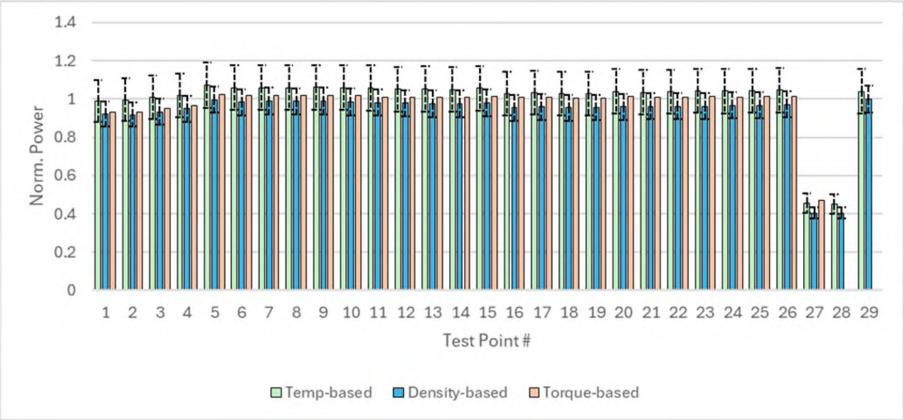
Compressor Low Speed Shaft Torque	0.02% (manufacturer's rating)
Compressor Speed Keyphasor	0.03% (manufacturer's rating for nominal compressor speed)

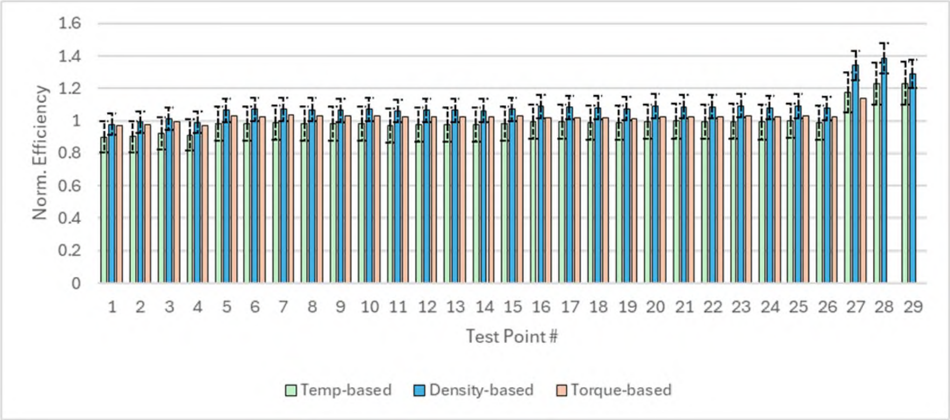




Overall, density-based measurements showed reduced uncertainty

- 37% reduction in uncertainty relative to temperature-based measurement
- Density measurement requires specific installation depending on manufacturer and best practices.
  - This study used a side stream, which could result in temperature differences.
  - Gamma ray densitometer or other indirect density measurement may show improved results.
- Torque-based measurements may helpful for a quick estimate but require proper installation and accurate determination of windage and bearing losses.





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