Modelling and Testing of an Ultra-low Temperature sCO2 Opposing Piston Heat Engine

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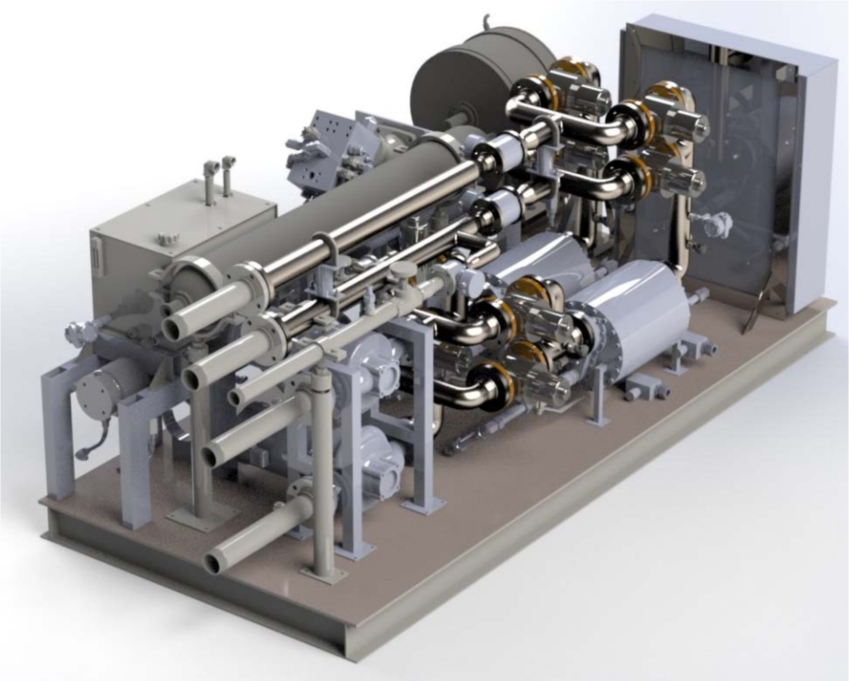
Partnered with: Thermal Tech Holdings and PwrCor, Inc.

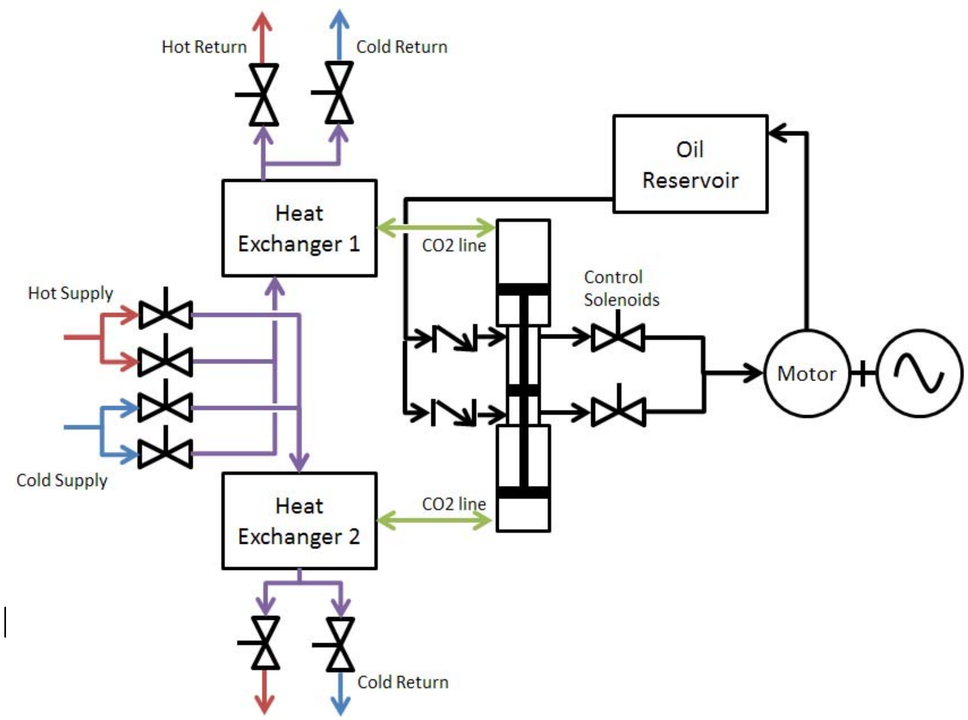
Background

- SwRI has a long history of understanding and developing CO2 compressors and engines
  - Design and testing of radial and axial turbomachinery and reciprocating machinery with CO2 as operating fluid
  - Multi-million dollar projects with industry and DOE to develop the technology
- SwRI contracted to conceptualize, model, design, assemble, and test a novel CO2 engine for low temperature heat inputs
  - Opposing piston design with expansive properties of CO2 as the driving force



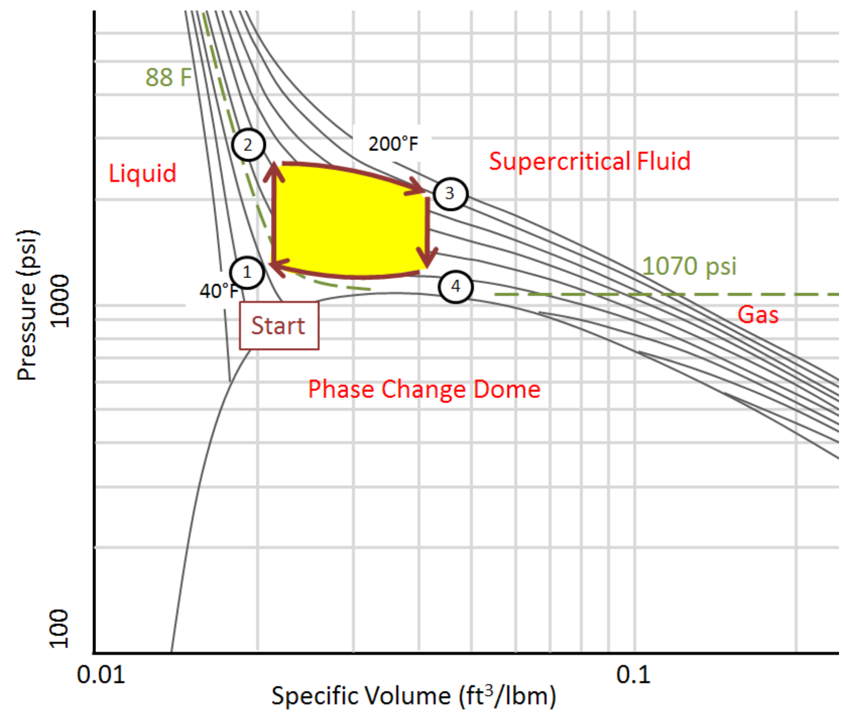
Working Principles

- CO2 experiences dramatic changes in density above the critical point for small changes in temperature
- Trapped CO2 in heat exchanger is heated with water which builds pressure that pushes a piston
- Opposing piston design compresses CO2 into a separate heat exchanger that is cooled
- Processes is rapidly reversed by switching water sources on heat exchangers with trapped CO2
- A central piston cylinder communicates pressurized hydraulic oil to a motor



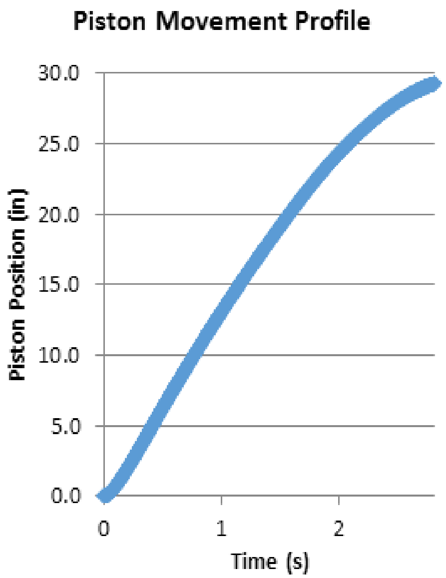
Engine Cycle

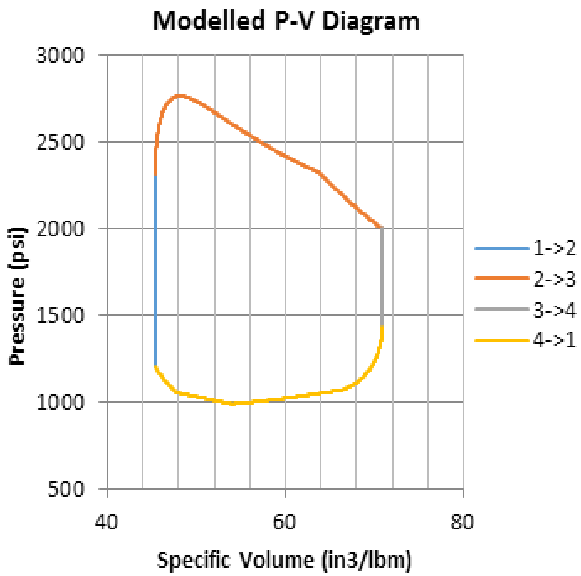
- Typically operates above the critical point of CO2
  - High pressures over 1100 psi
  - Low temperatures over 88 F
  - Can operate under the dome if enough cooling is available
- P-v diagram demonstrates how work is produced
  - Area between high and low pressure is available work
  - How fast this cycle repeats determines power output
- T-s diagram demonstrates the efficiency of the cycle
  - Area under heating line gives cycle heat load



Cycle Modelling

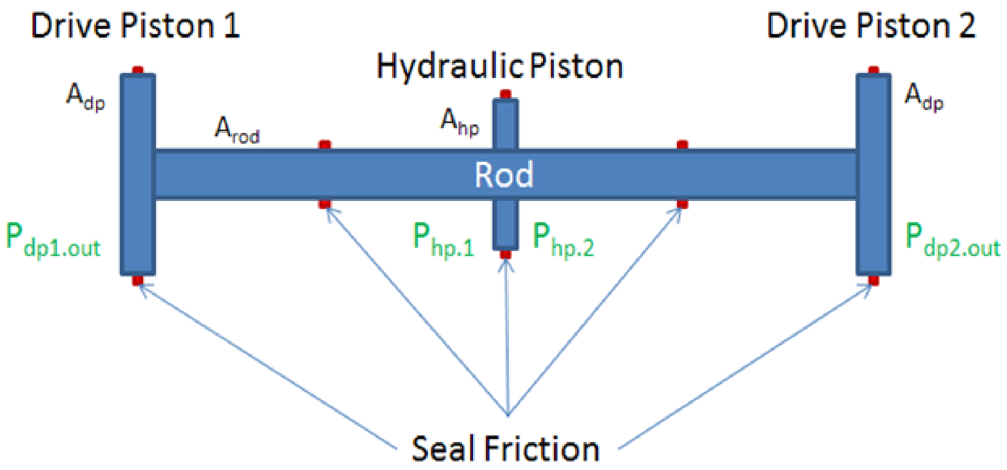
- CO2 properties pulled directly from REFPROP which is published by NIST
- Excel partially time dependent model
  - Estimates of piston movement and subsequent P-v
  - Work derived from P-v is path dependent which means that the value of pressure affects resulting work
- Matlab fully time dependent model
  - Control volume approach
  - Trading of CO2 between different volumes over small time steps
  - CO2 properties from REFPROP derived lookup tables for speed





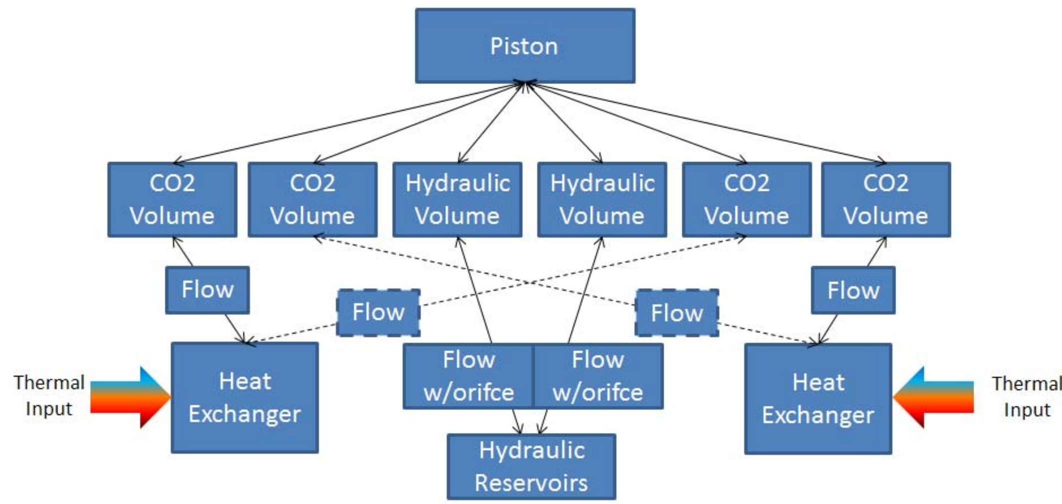
Force Balance Model in Matlab

- Piston balance of forces and acceleration determined by pressures and seal friction
  - Piston movement changes volume of each cylinder
  - Acceleration and velocity over small time step determines the piston displacement
  - 5 millisecond time steps used by the model



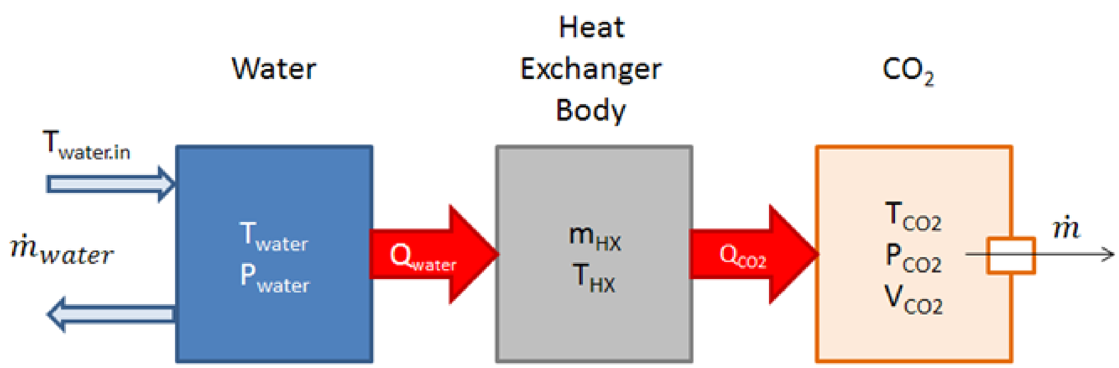
Modeled System in Matlab

- A network of possible exchanges developed based on connections
  - Volumes can exchange mass
- Mass heat addition or removal to a volume is tracked by enthalpy values
  - Table lookup developed to speed up code
  - 2-D property tables based on temperature and pressure
    - Temperature ranged from 20°F to 400°F,
    - Pressure from 500 to 5000 psi
    - The ranges were divided into 1000 equally spaced points



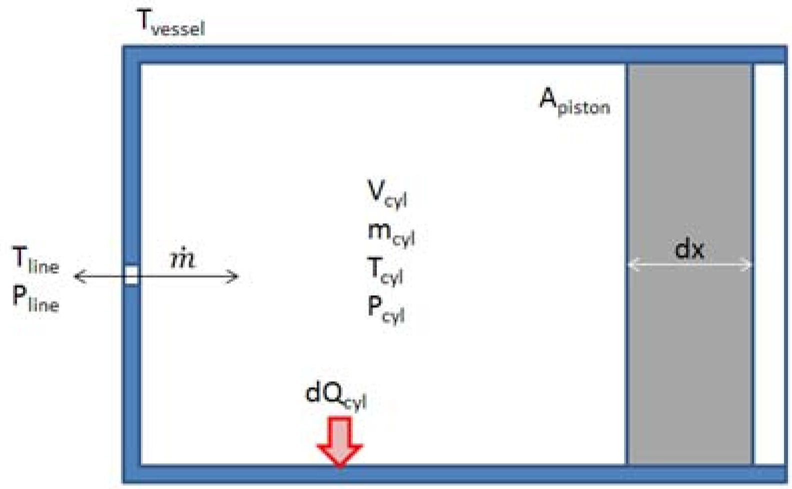
Matlab Heat Exchanger Model

- Water transfer of heat through metal body to CO_2 in the heat exchanger
- HX CO_2 volume is fixed but mass can be communicated to the piston CO_2 volume
- The new mass and volume creates a new density at each time step
- Using density and enthalpy from heat transfer, a new temperature and pressure is calculated

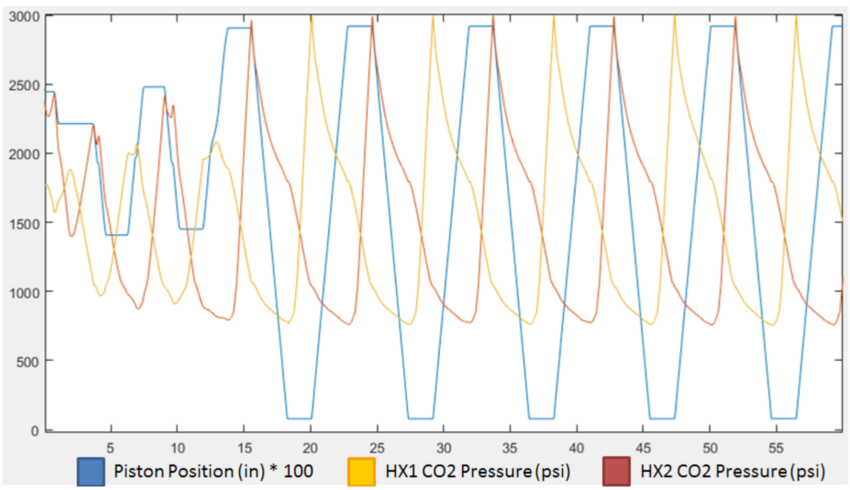


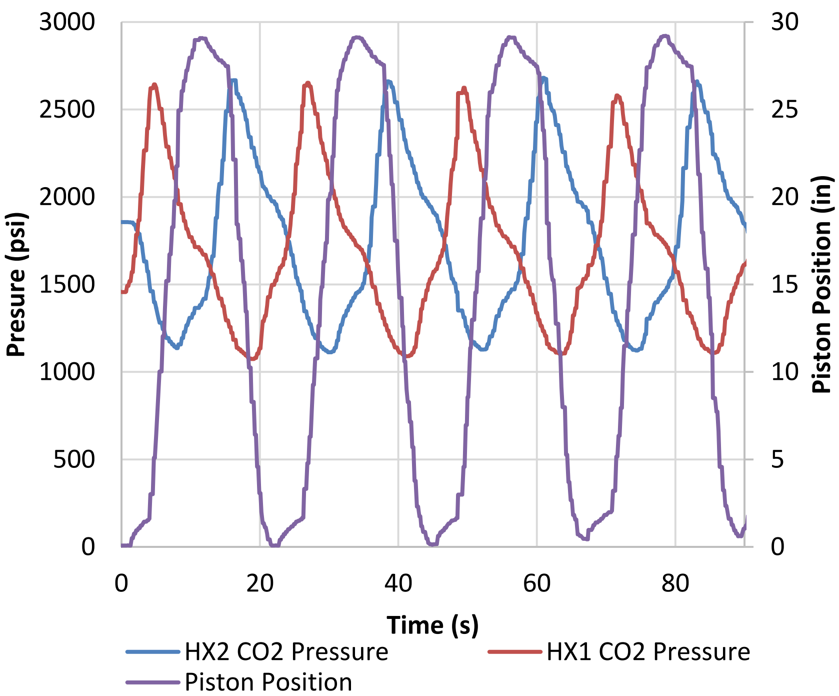
Matlab Model Cylinder CO2 Control Volume

- Moving piston head changes volume
- Mass transfer to and from cylinder based on balance of pressures between piston and HX CO2 volumes
  - Pressure loss of the lines communicating the CO2 is accounted for
  - Velocity driven by pressure difference at time step gives volume flow rate and mass flow rate
- Temperatures and pressures are recalculated as enthalpy and density change

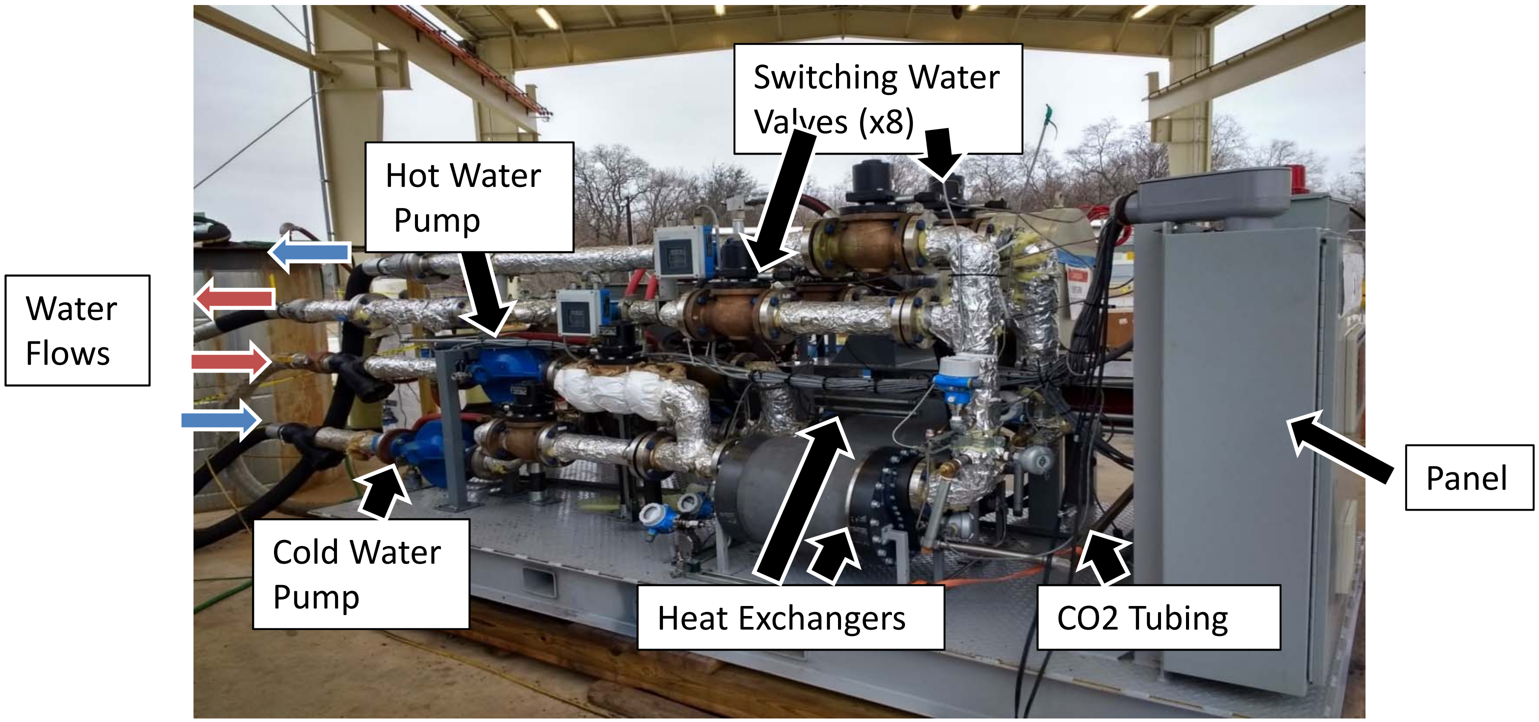


Matlab Model versus Recorded Data

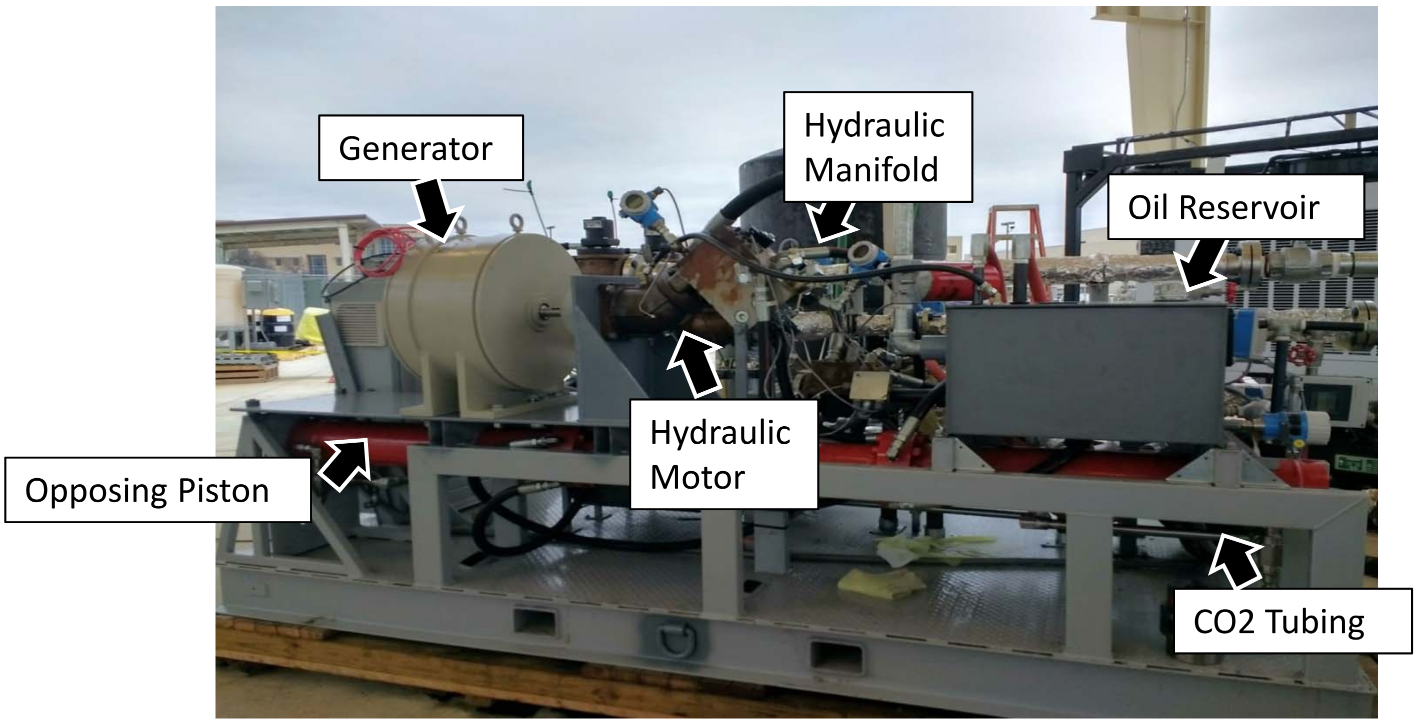




Component Overview (1)



Component Overview (2)



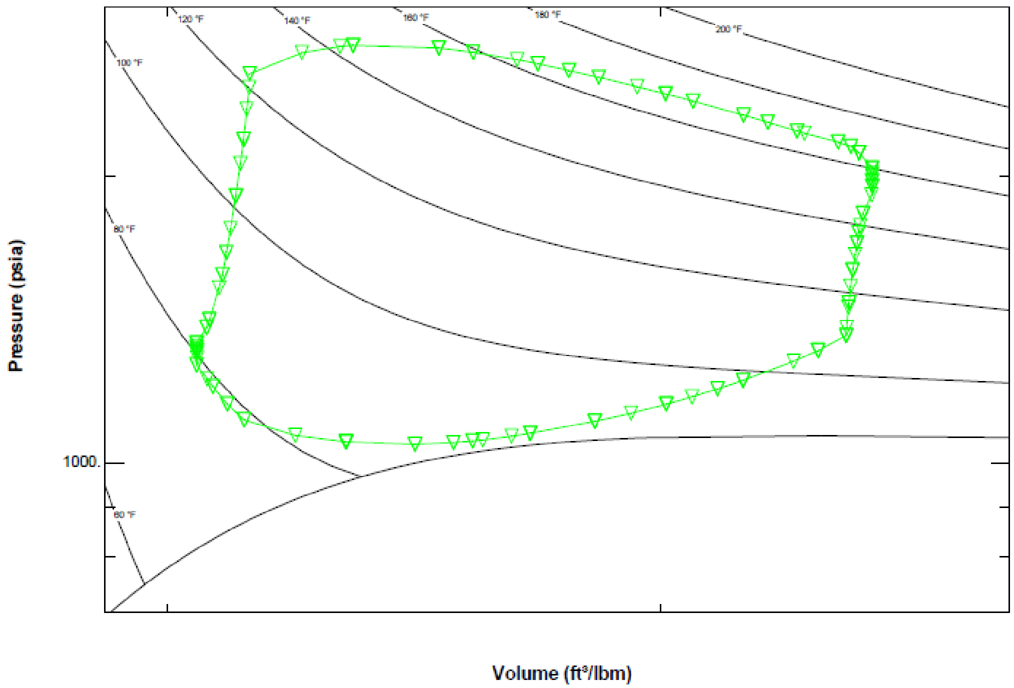
How Power is Calculated

- Pressure of oil
  - Direct measure of sensor at motor inlet
    - Good for constant supply of pressurized fluid (2 pistons or a pressurized reservoir)
    - Delay in input if pressure drops below a threshold when operation mode adjusted during testing
  - Calculation of oil pressure from CO2 pressure (Preferred)
    - CO2 response is responsive to abrupt changes because they are always pressurized
    - Calculated from static pressure ratio with dynamic pressure loss
- RPM of motor
  - Number of pulses over time
  - Time between pulses (Preferred)

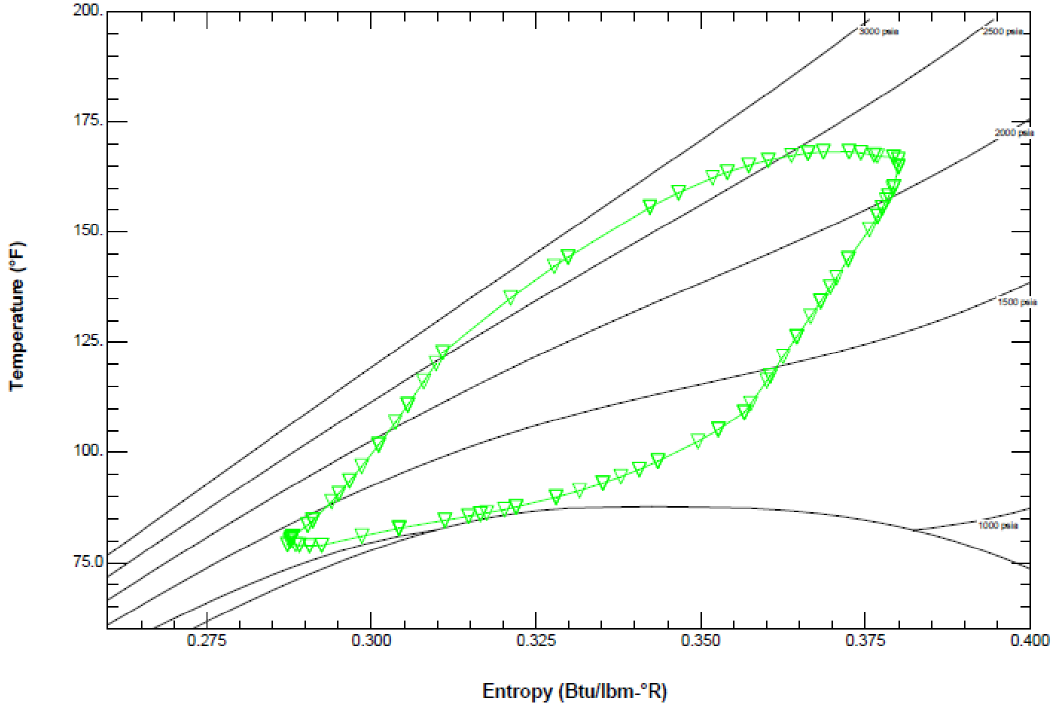
Accounting for Engine Losses and Inefficiencies

- Dynamic pressure loss from observed behavior when hydraulic pressure sensor "catches up" with CO_2-based calculation
  - Hydraulic flow kept constant with regulator, so this loss can be applied to the entire stroke
- Motor efficiency provided by manufacturer applied to calculate shaft power
- Calculating thermal efficiency ($\eta_{th} = \frac{P}{\dot{Q}_H}$)
  - Heat flow rate from CO_2 T-s diagram and power from motor shaft power out

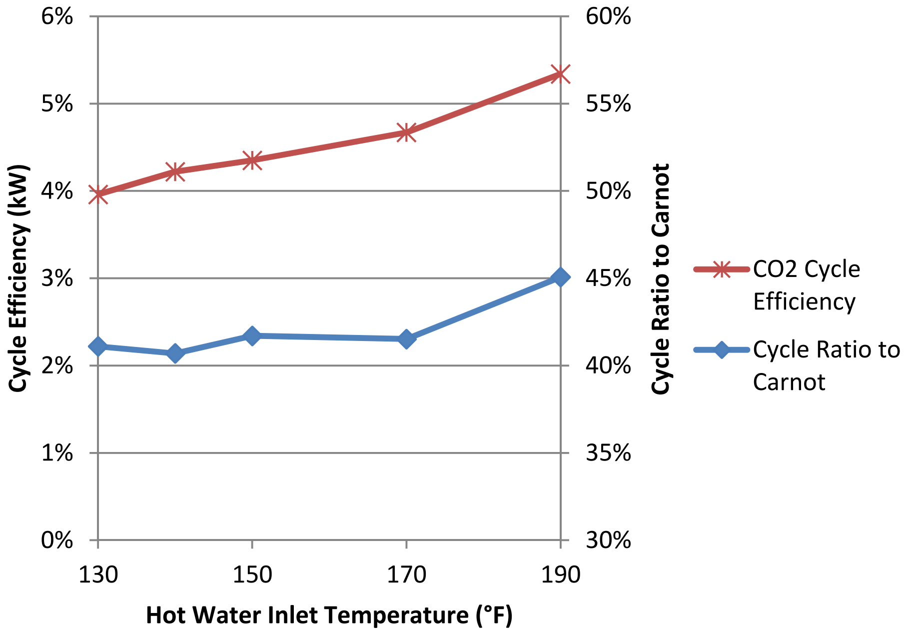
Best Case P-V (190°F hot, 45°F cold, 80 GPM)

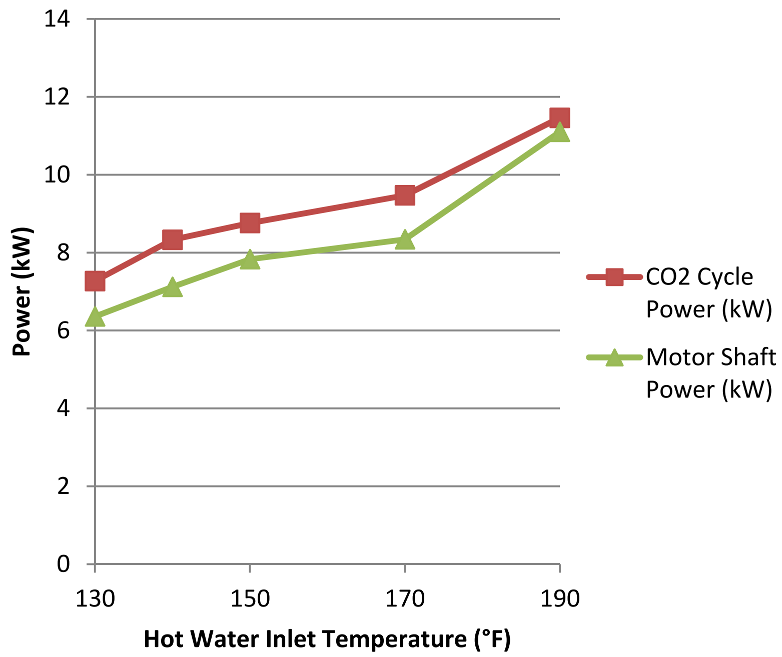


Best Case T-s (190°F hot, 45°F cold, 80 GPM)

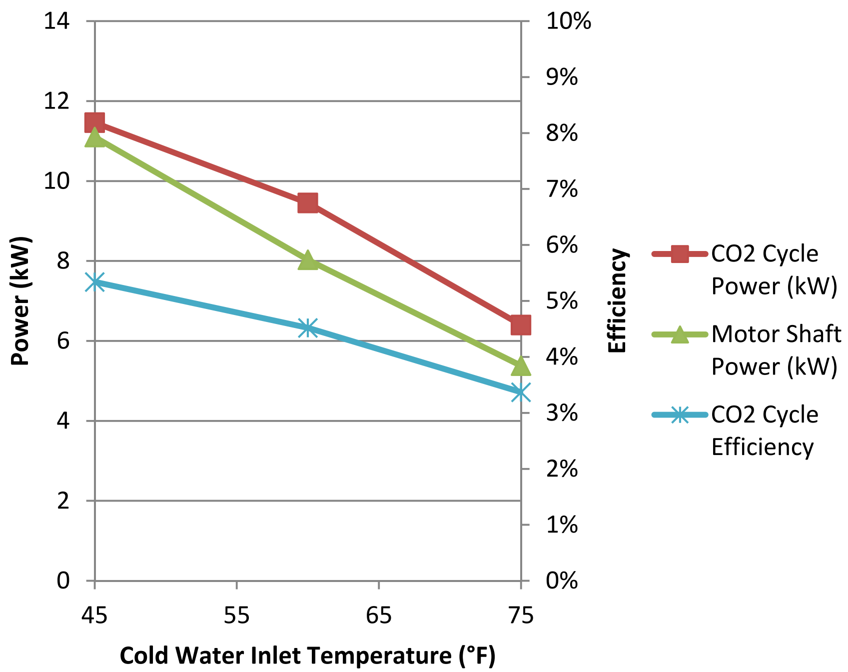


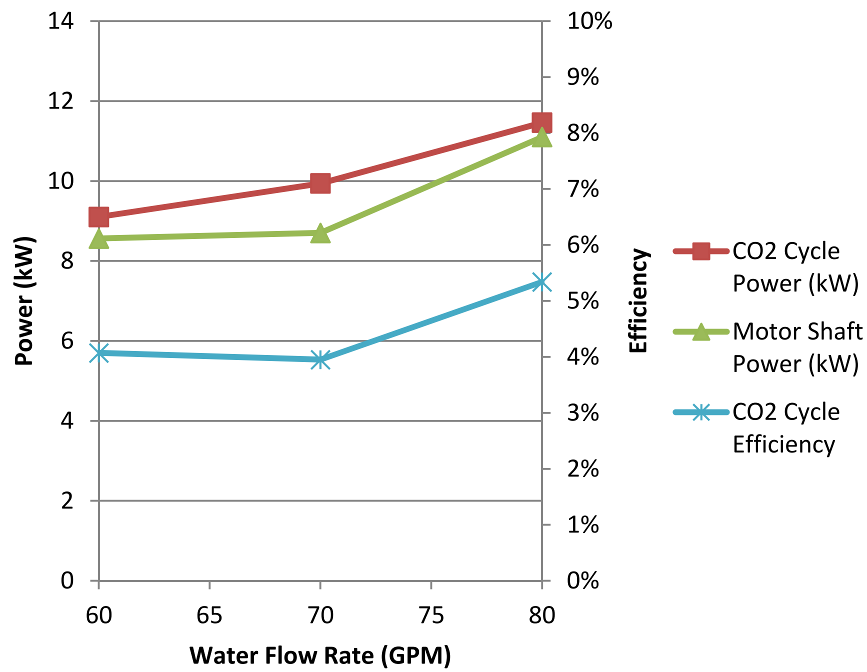
Power and Efficiency with Changes in Hot Water Temperature





Power and Efficiency with Changes in Cold Water Temperature and Flow Rates





Conclusions

- Conceptual cycle development showed the potential for utilizing ultra-low temperature heat sources to produce power
- The first models were moderately successful in predicting the behavior of the prototype but are in need of adjustments
- Tests of the prototype successfully demonstrated an engine producing power with hot inputs ranging from 130°F to 190°F
- Warmer cooling temperatures or less water flow decreases power output and efficiency
- Future engines will introduce cycle modifications to push the efficiency above 80% of the Carnot limit
  - Avoid the alternating of heat sources on the same heat exchanger

Thank You