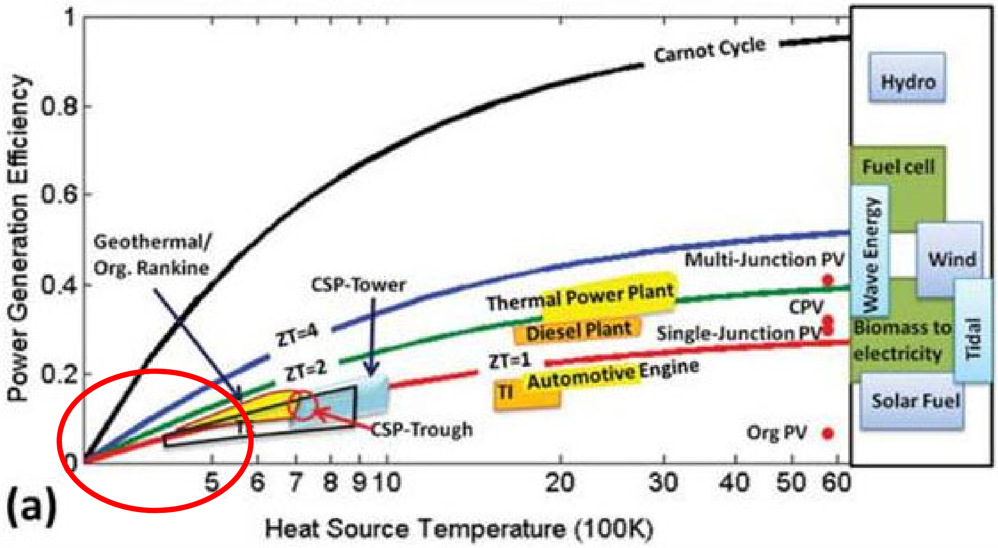
Low-Cost, Low-Grade Waste Heat Recovery Using sCO_2 Natural Convection

SOUTHWEST RESEARCH INSTITUTE®

Kelsi M. Katcher
Tim Allison, Ph.D.
Michael Marshall
Natalie R. Smith, Ph.D.

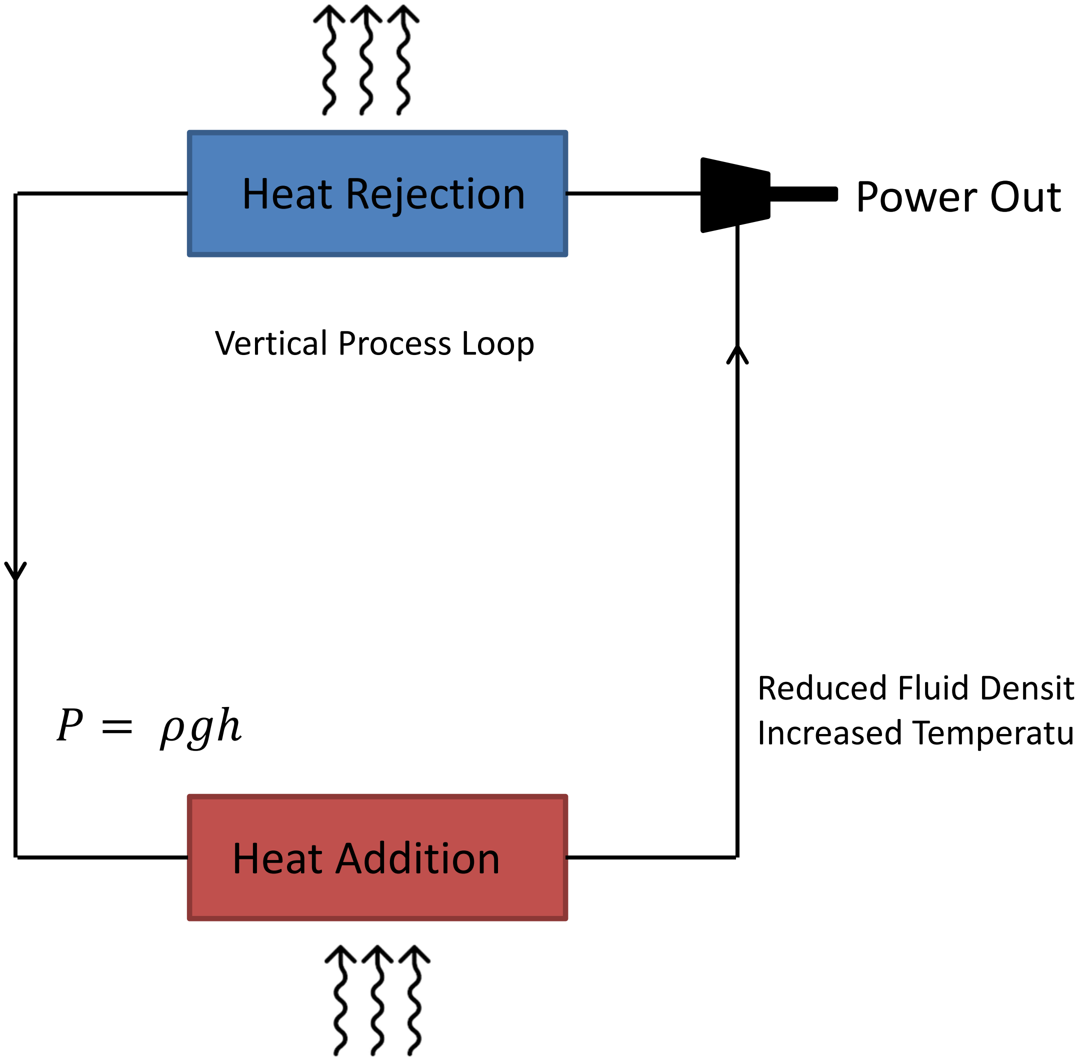
Low-grade Heat Rejection

- <100-300°C [<212-572°F]
- Accounts for as much as 80% of total waste heat available
- Inherently low thermal efficiencies result in prohibitively high cost of electricity
- Existing technologies in this space: Organic Rankine Cycles (ORC) or Kalina cycles relying on multiple pumps and expanders for power generation
- Capital cost of installed processes must be reduced to make low-grade WHR commercially viable



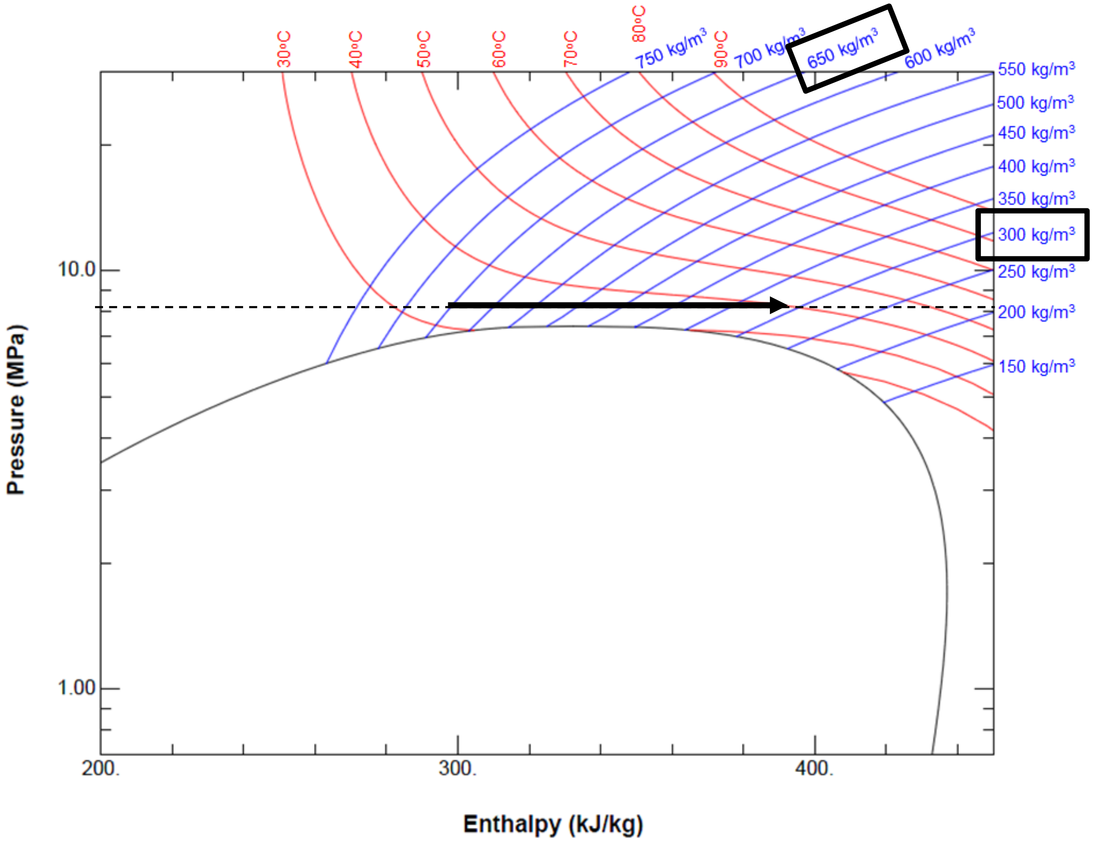
R. Kishore and S. Priya, "A Review on Low-Grade Thermal Energy Harvesting: Materials, Methods, and Devices," Materials, 2018.

Proposed Technology: Natural Convection Power Cycle



- Differences in density create pressure gain (thermosiphon)
- Relatively constant pressure throughout loop
- No pump or compressor required to drive mass flow
- Employing a sealed power-conversion concept minimizes the need for auxiliary systems

Supercritical CO_2

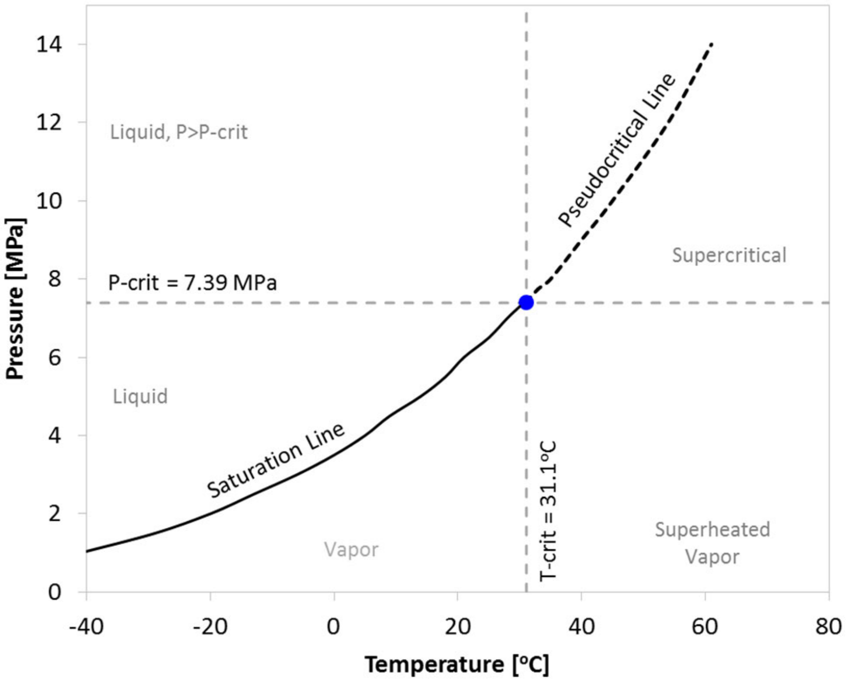


Inherently large density swings near the critical point

Temperature change from 32°C to 40°C at 8.25 MPa yields 54% reduction in density

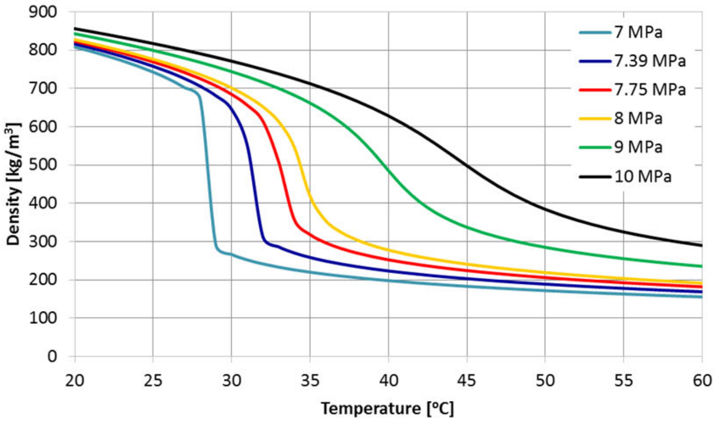
High fluid density and low viscosity provide a large mass flow potential

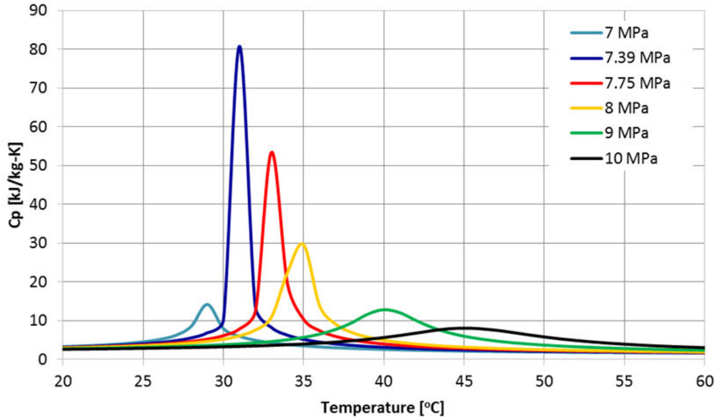
Supercritical CO_2

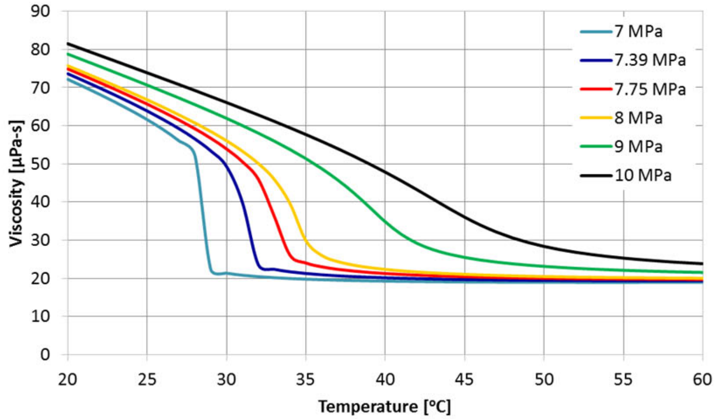


Significant change in thermophysical properties near the critical point and especially as the fluid crosses the pseudocritical line

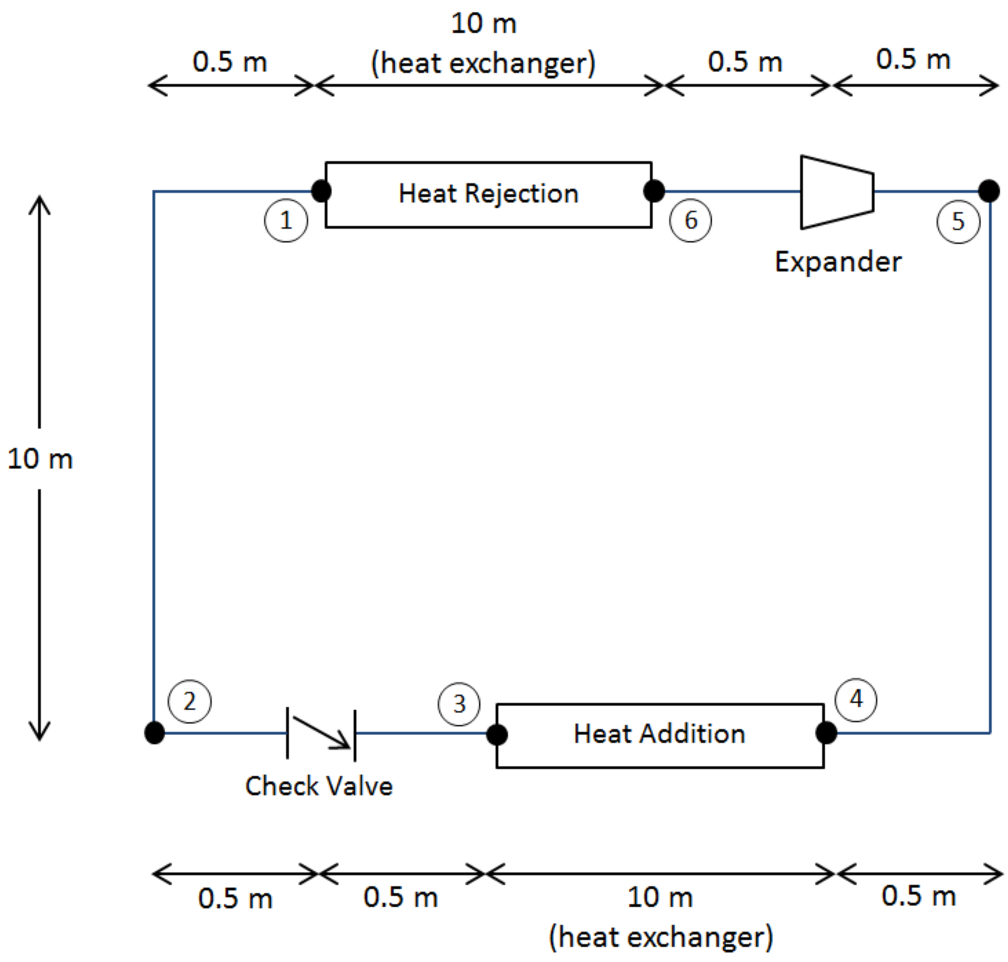
Pseudocritical temperature - where the specific heat at a constant pressure reaches a local maximum







Natural Convection Loop Studied



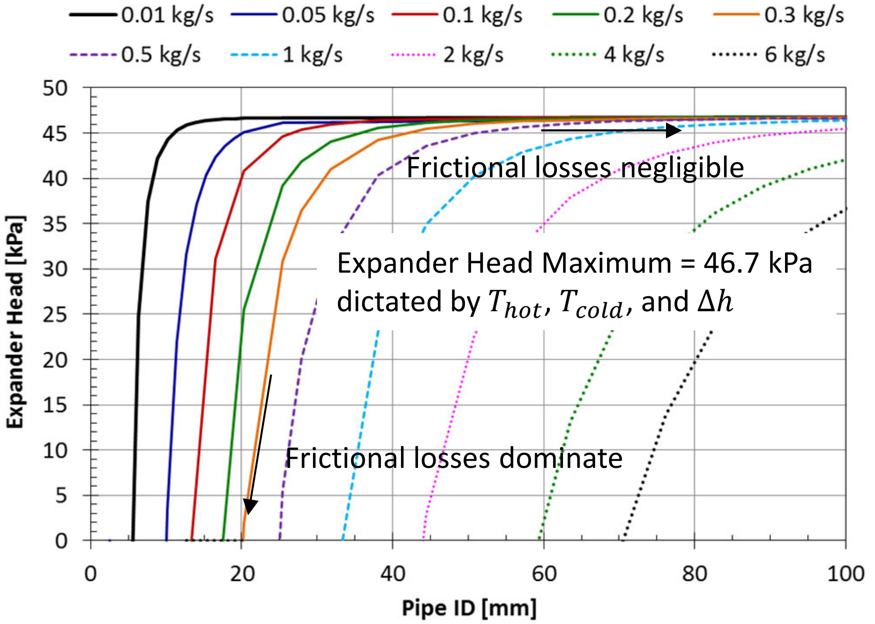
State Point	Property	Value
1 - Cooler Outlet	Temperature	32°C
4 - Heater Outlet	Temperature	60°C
6 - Expander Outlet	Pressure	8.5 MPa

Pipe Inner Diameter = 73.66 mm (NPS3, Sch. 80)

These dimensions and state points were varied independently to determine the effects on the available power and available expander head.

Sensitivity Study: Pipe Sizing & Mass Flow Rate

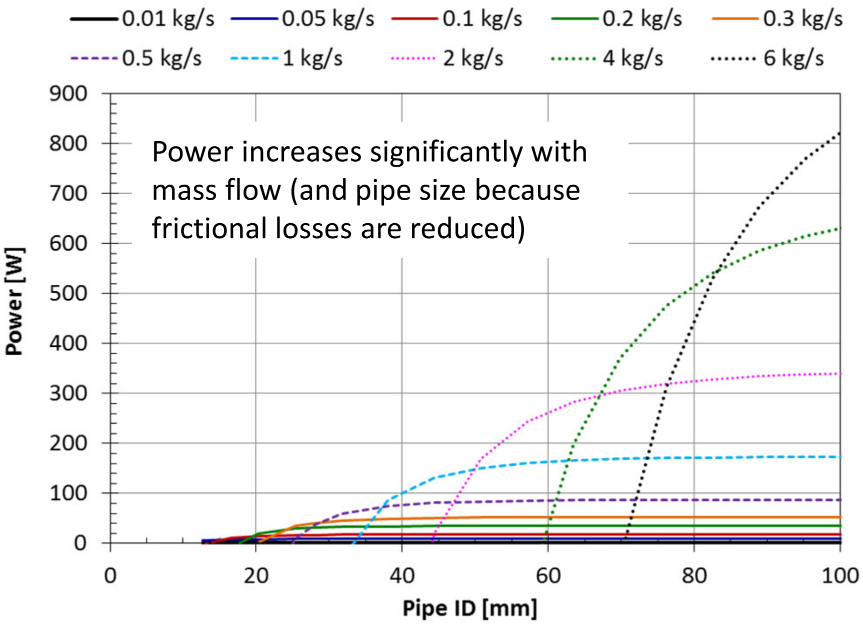
- It is expected that the specific WHR application will define
  - source temperature
  - sink temperature
  - general size constraints
- The required expander head and the target mass flow could then be used to define the required pipe size for the loop.



Frictional losses negligible

Expander Head Maximum = 46.7 kPa dictated by T_{hot}, T_{cold}, and Δh

Frictional losses dominate

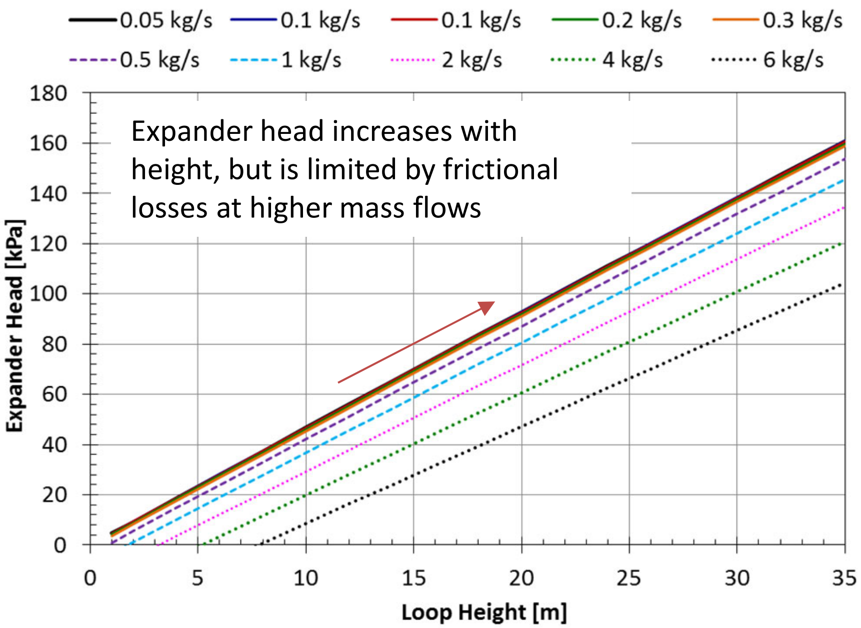


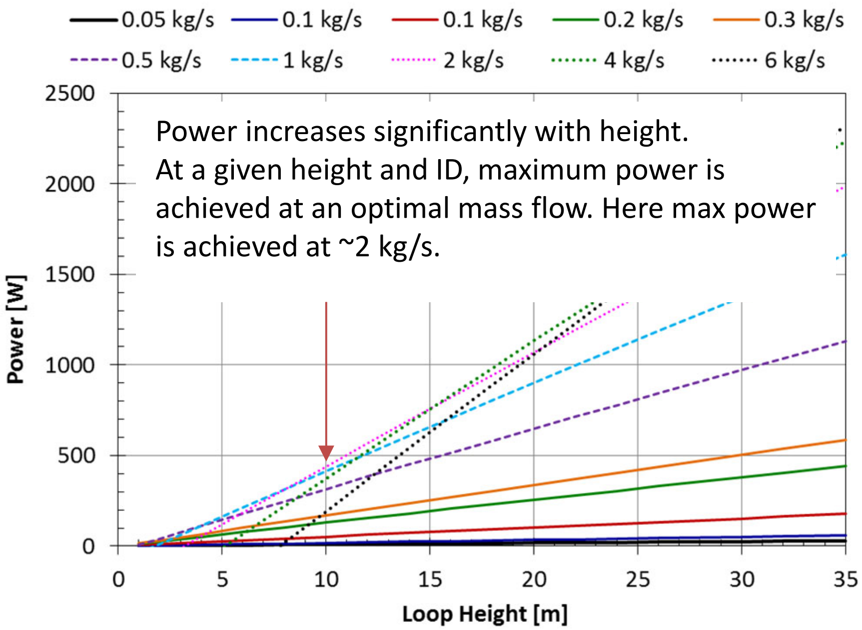
Power increases significantly with mass flow (and pipe size because frictional losses are reduced)

Assuming: $T_{hot} = 60°\text{C}$, $T_{cold} = 32°\text{C}$, $\text{P} = 8.5\ MPa$,
Loop Height = $10\ m$

Sensitivity Study: Loop Height & Mass Flow Rate

- Expander power can be increased by increasing the hydrostatic pressure gain across the loop (allowing for a higher expander head or a larger mass flow).
- This can be achieved by increasing loop height or increasing CO_2 temperature change across the loop


Expander head increases with height, but is limited by frictional losses at higher mass flows


Power increases significantly with height. At a given height and ID, maximum power is achieved at an optimal mass flow. Here max power is achieved at ~2 kg/s.

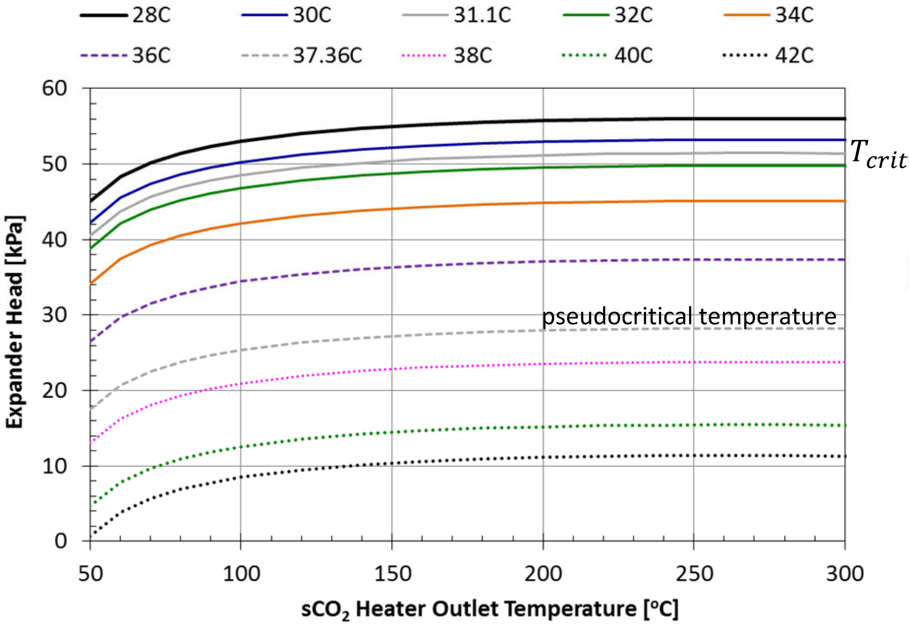
Assuming: $T_{hot} = 60°C, T_{cold} = 32°C$, $P = 8.5\ MPa$,
Pipe Size = NPS3, Sch 80 (Pipe ID = 73.66 mm)

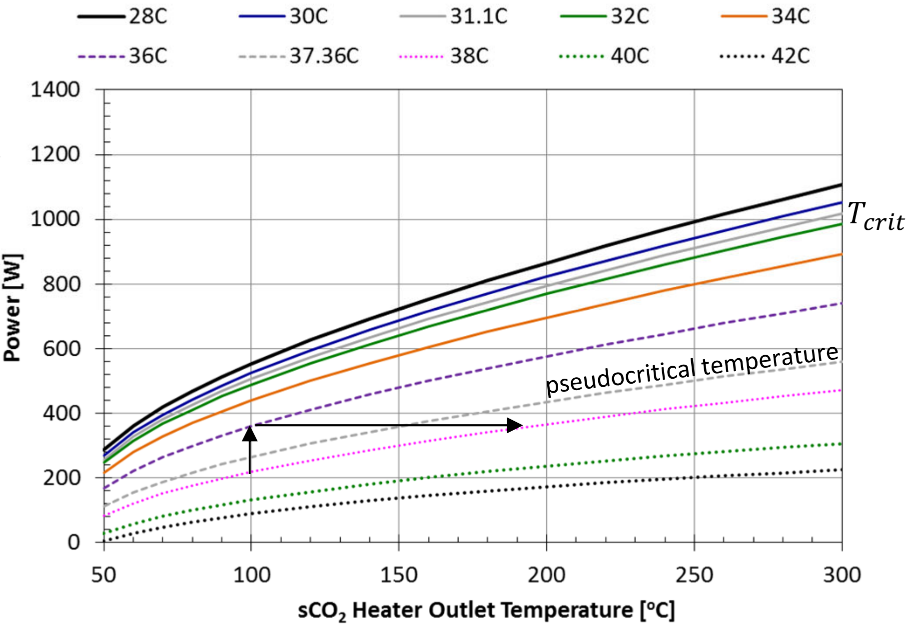
Sensitivity Study:
Hot-Side & Cold-Side Temperature

- Expander power can be increased by increasing the hydrostatic pressure gain … expander head or a larg…
- This can be ac… ncreasing CO_2 tempera…

Gains are more significant with reduction in T_{cold} than a corresponding increase in T_{hot}

Gains are most significant as the temperature crosses the pseudocritical temperature but become less significant as the temperature drops below the critical temperature (into liquid phase)

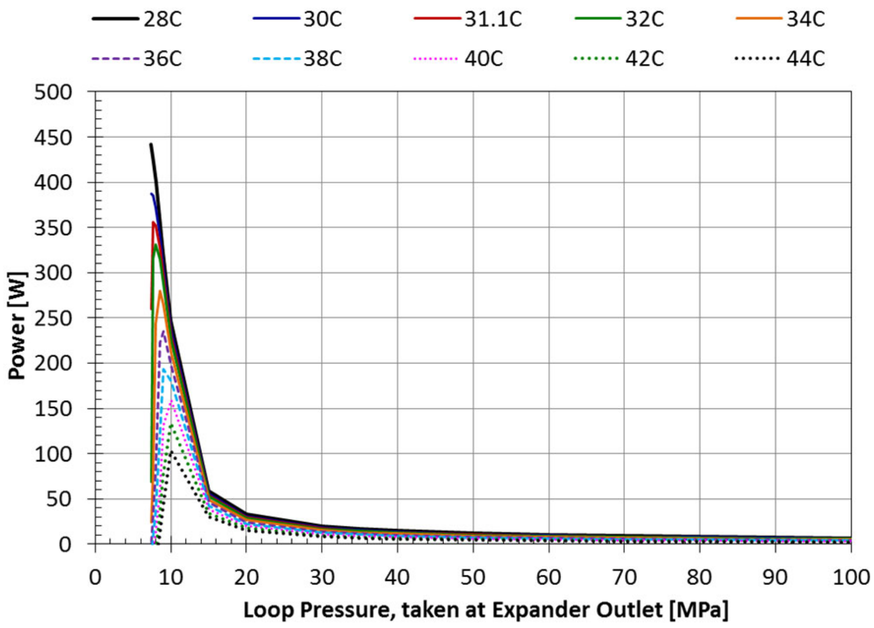


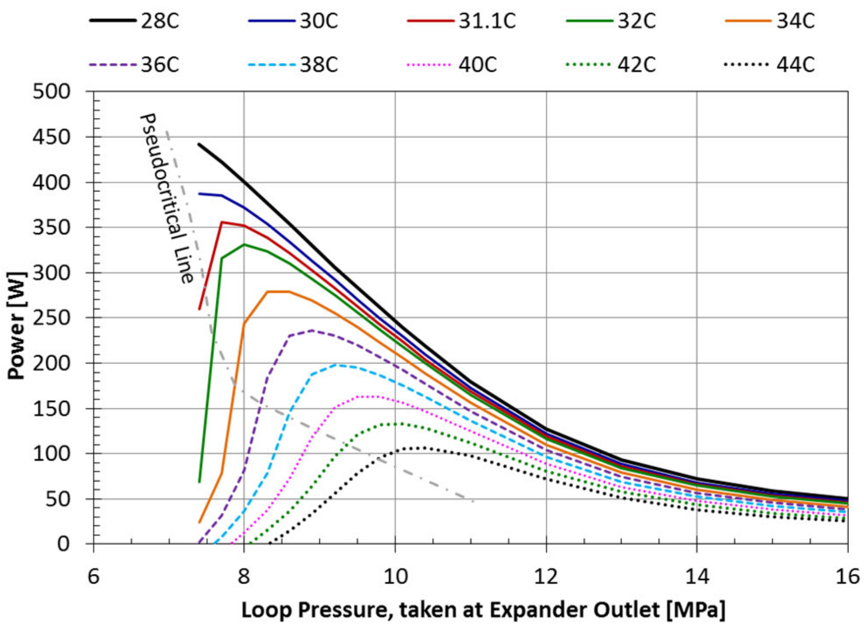


Assuming: $P = 8.5\ MPa,\ \dot{m} = 2\ kg/s,$ Loop Height = $10\ m$
Pipe Size = NPS3, Sch 80 (Pipe ID = 73.66 mm)

Sensitivity Study: Loop Pressure & Cold-Side Temperature

- The optimal pressure, in general, is very near the critical pressure but varies with cold side temperature
- The optimal pressure follows the trend of the pseudocritical line

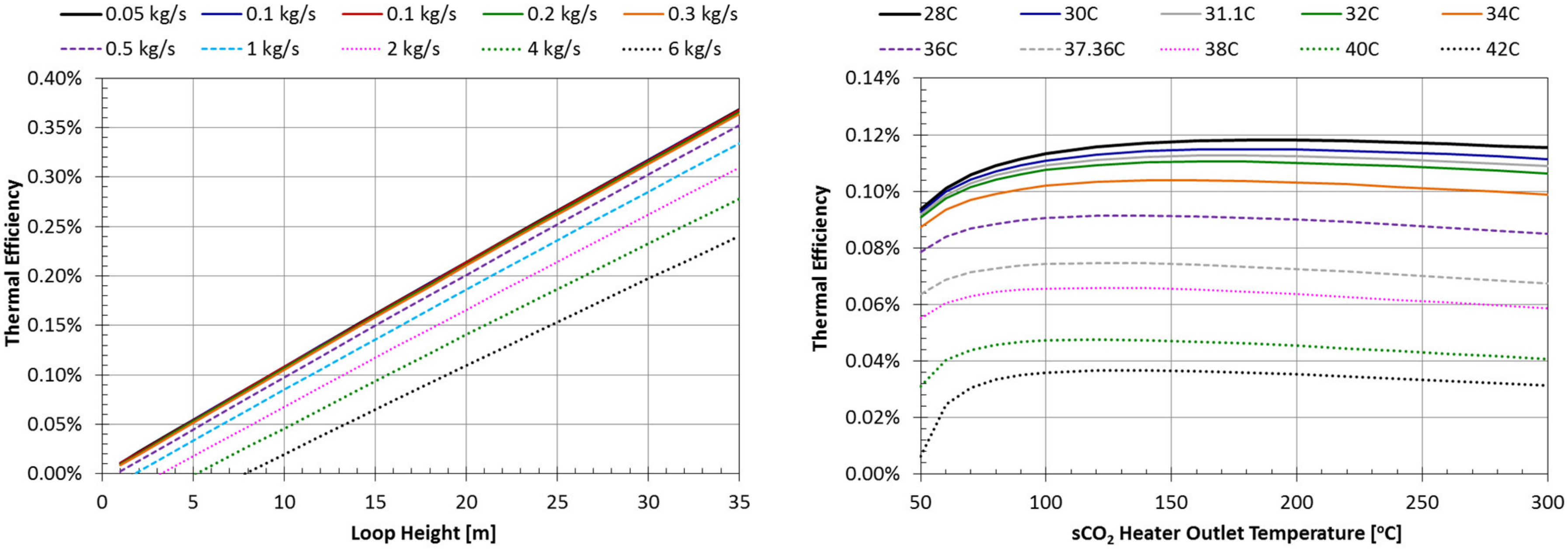




Assuming: $T_{hot} = 60°\mathrm{C}$, $\dot{m} = 2\ kg/s$, Loop Height = $10\ m$
Pipe Size = NPS3, Sch 80 (Pipe ID = 73.66 mm)

Sensitivity Study:
Thermal Efficiency

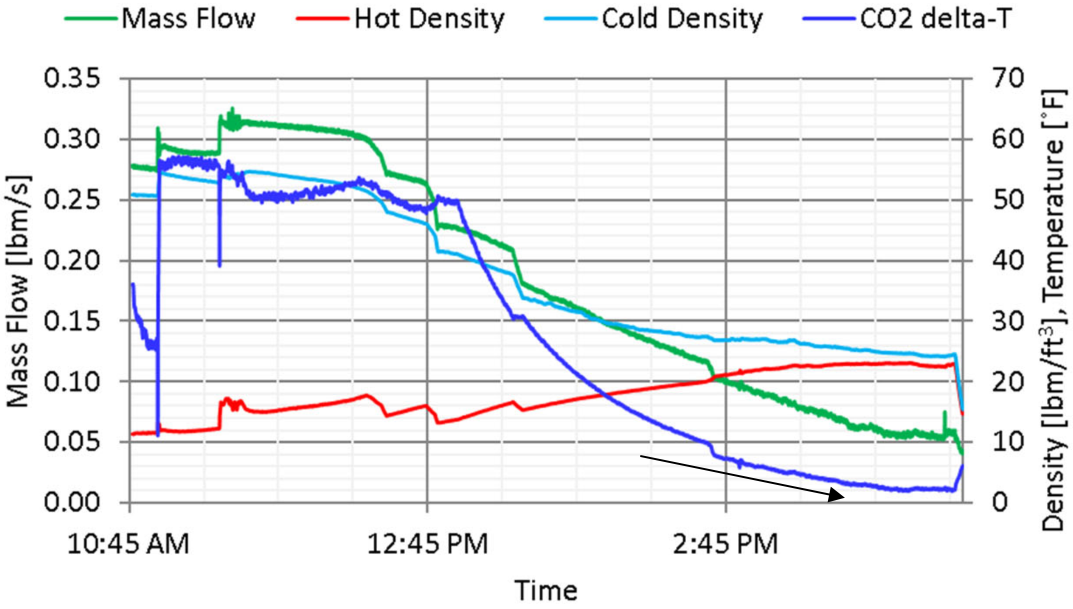
- For this simplified cycle, the thermal efficiency followed the trend of the available expander head
- Increasing loop height and decreasing cold-side CO_2 temperature produced the largest improvements in thermal efficiency
- Efficiency does not significantly increase with hot-side temperature (contrary to what is typically expected)



Lab-Scale Validation Testing

- Thermosiphon is very stable
- Able to operate smoothly with phase change in heat exchangers (trans-critical, subcritical, and supercritical)
- Measurable mass flow continues with CO_2 temperature difference less than 0.5˚C.
- Promising results for autonomous, low-maintenance operation

Transient testing, demonstrating source/sink temperatures converging ▶



Conclusions

- The most significant increases in power and efficiency are achieved by increasing loop height (elevation change)
- Small gains can be achieved by increasing the hot-side CO_2 temperature, but more significant gains can be achieved by reducing the low-side CO_2 temperature
- Optimal cycle performance occurs when the cold-side temperature is below the pseudocritical temperature
- Cycle performance can be optimized by selecting the correct operating pressure
- Available power increases significantly with mass flow, so limiting pressure losses through the piping, valves, and heat exchangers is critical to obtaining cost-competitive power generation potential
- Because the loop design and performance is very application specific, a techno-economical analysis should be performed on a case-by-case or scale-specific basis to further evaluate merit

Questions?

Kelsi M. Katcher
Research Engineer
Southwest Research Institute
(210) 522-2306
kelsi.katcher@swri.org

Michael P. Marshall
Engineer
Southwest Research Institute
(210) 522-6409
michael.marshall@swri.org