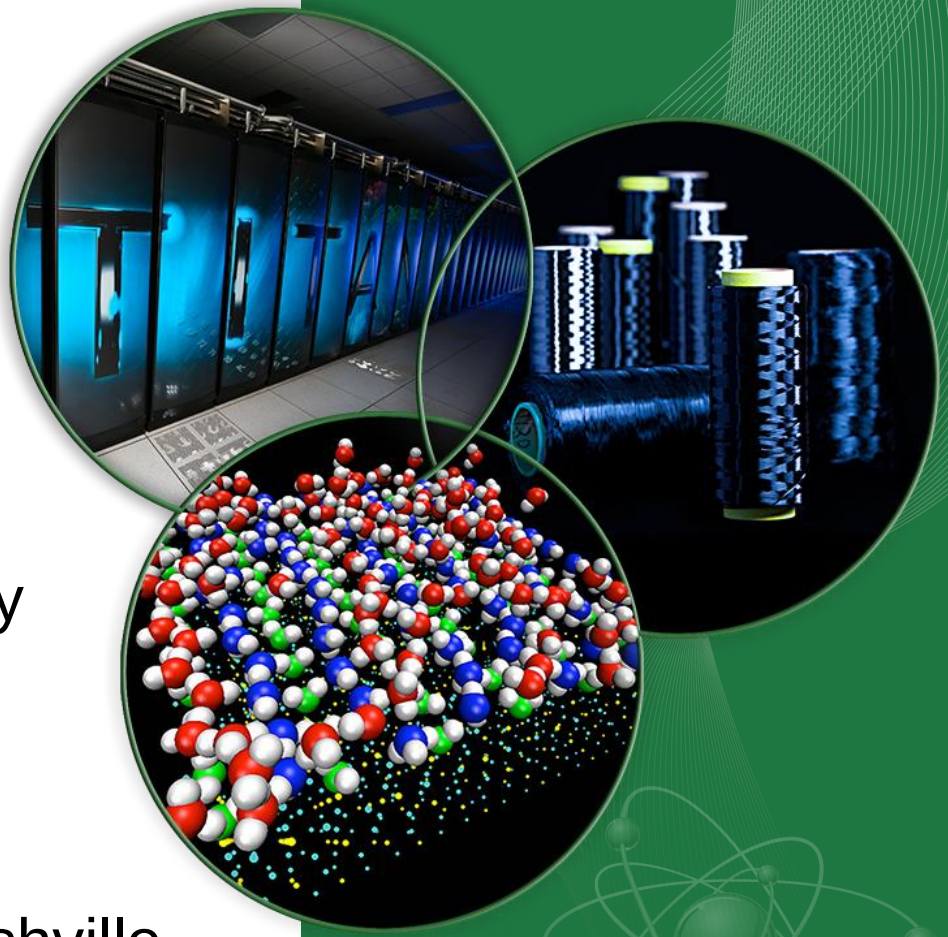
Development of Low-cost ENERGY STAR®-Qualified Residential CO_2 HPWH Prototype



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Oak Ridge National Laboratory

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ACEEE Hot Water Forum, Nashville

Session 3A

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Outline

- Project goals
- Considerations specific to transcritical heat pumps
  - Temperature glide in hot refrigerant
  - Importance of tank stratification
- Design method – wrap around gas cooler
- Results to date

Acknowledgments

- DOE Building Technologies Office, Emerging Technologies – Antonio Bouza
- GE Appliances (CRADA partner) – Craig Tsai

Goals

US has Presidential commitment (Climate Action Plan) to phase out HFCs:

- **Demonstrate a more affordable path to ENERGY STAR®-qualified residential CO_2 HPWH**
  - Low GWP, no direct environmental impact
  - Configured for price point appropriate to US market
  - Evaluate system for FHR, EF
- Also cooler climate potential: evaluate EF_{NC} (NEEA Northern Climate specification)

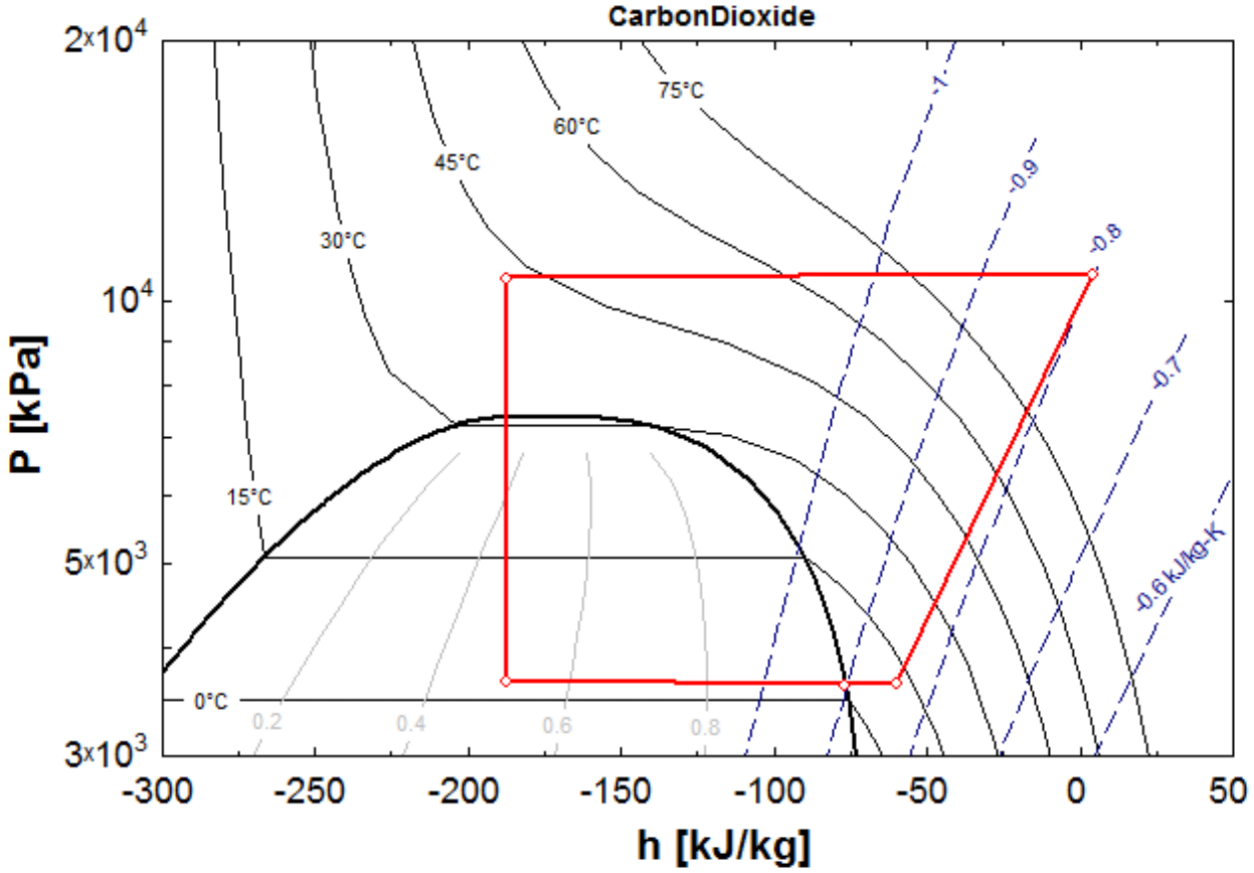
ENERGY STAR Criteria

For electric water heaters:

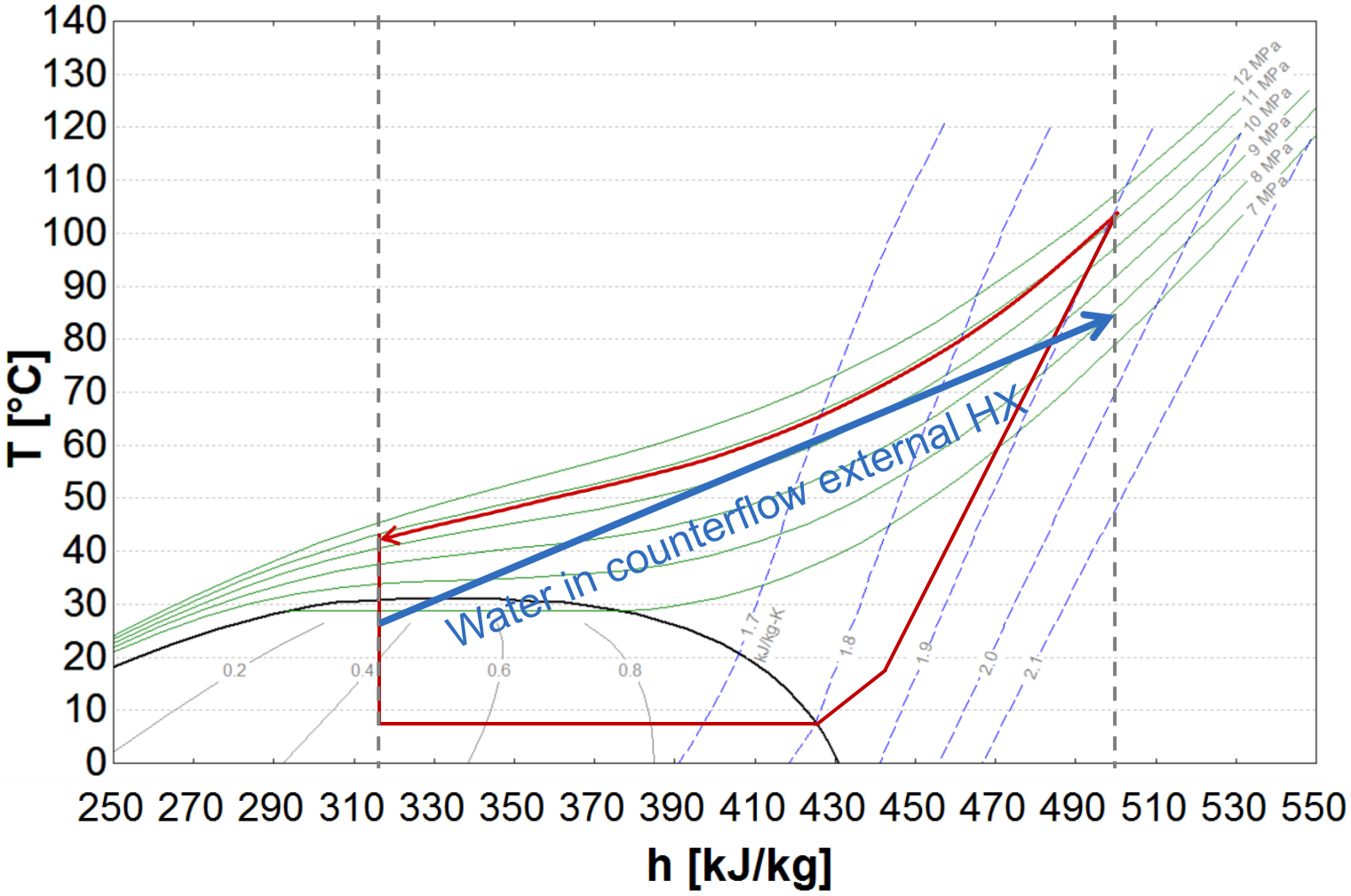
- EF ≥ 2.0
- FHR ≥ 50 gallons
- Must report low ambient temperature at which compressor shuts off

Transcritical Heat Pump – P-h

- Supercritical gas does not condense, so “condenser” is called a “gas cooler”
- Temperature glide of supercritical gas

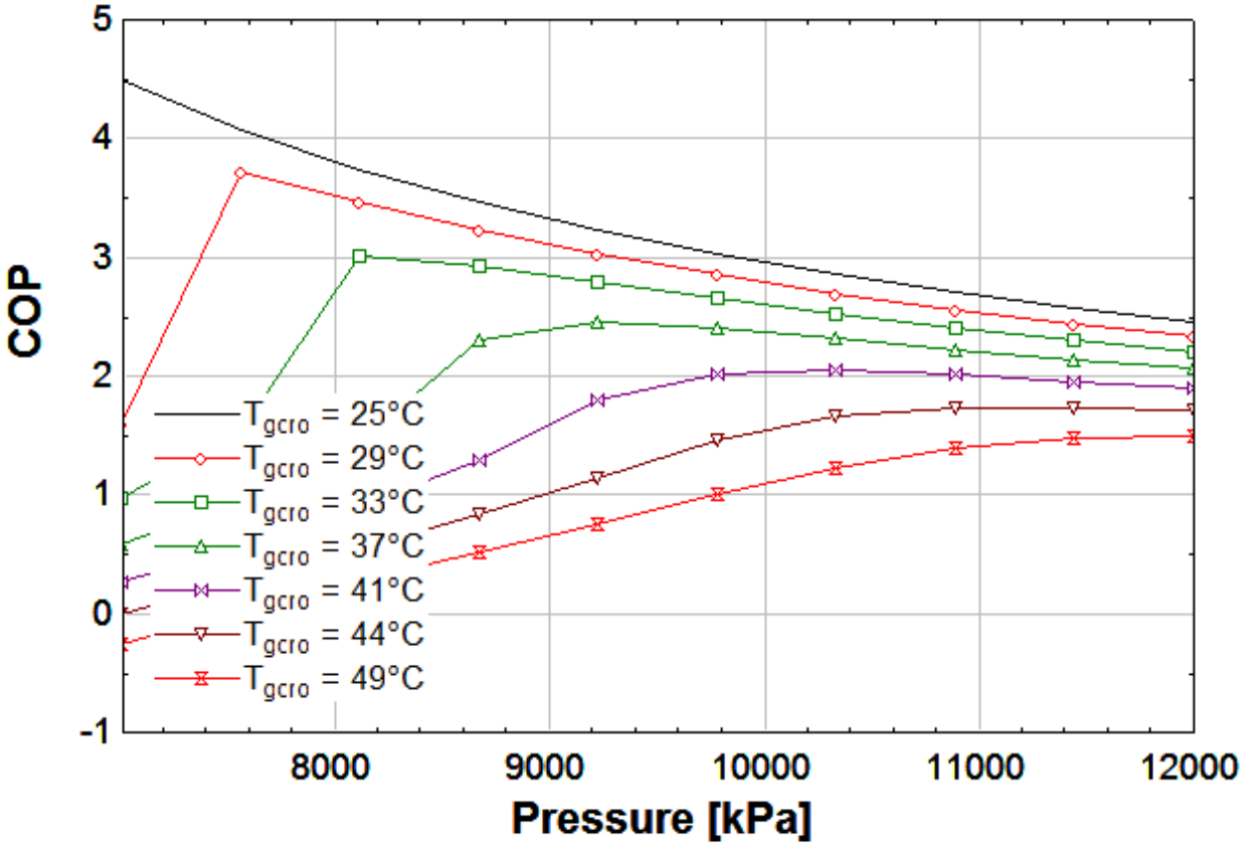


Transcritical Heat Pump – T-h



High Side Pressure Optimization

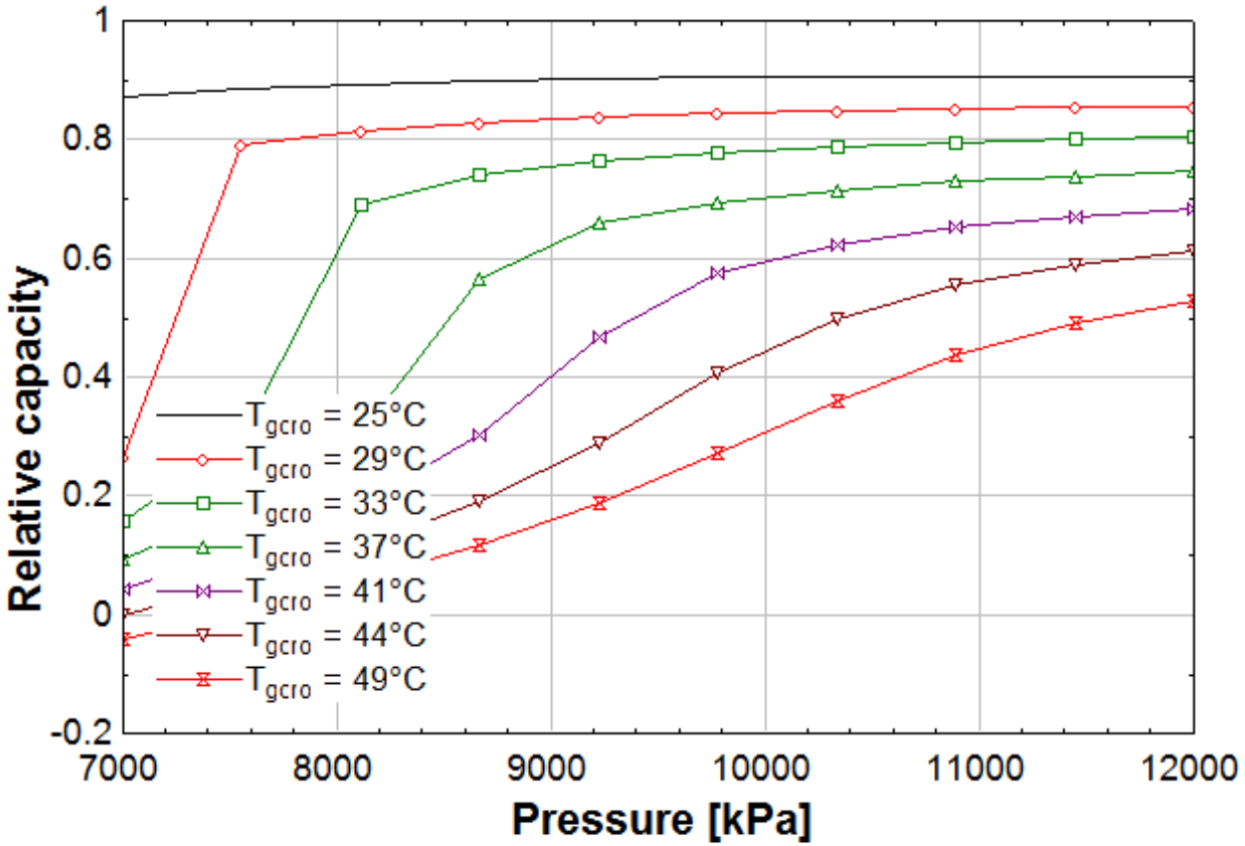
- For a given gas cooler outlet temperature:
  - A COP-optimum high side pressure exists



Based on cycle model, assuming simple reverse transcritical cycle (no suction line heat exchanger); CO_2 refrigerant; 2°C saturation temperature in evaporator; 100 kPa pressure drop in gas cooler; 50 kPa pressure drop in evaporator.

High Side Pressure Optimization

- For a given gas cooler outlet temperature:
  - Capacity increases with increasing pressure



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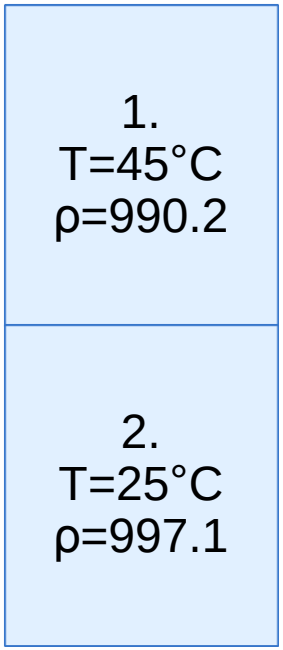
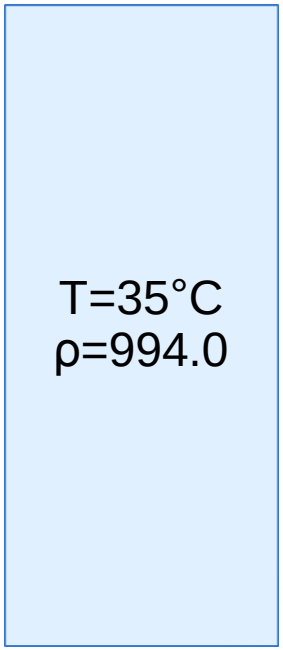
Water Heater Tank – Stratification

Stratification minimizes gravitational potential energy



$PE = m_1gh_1 + m_2gh_2$
$PE = 1378.0$ J



$PE = mgh$
$PE = 1380.9$ J

Difference in gravitational potential energy = 2.9 J
3 gpm flow through ½" pipe has 0.2 J/s

Water Heater Tank – Stratification Principles

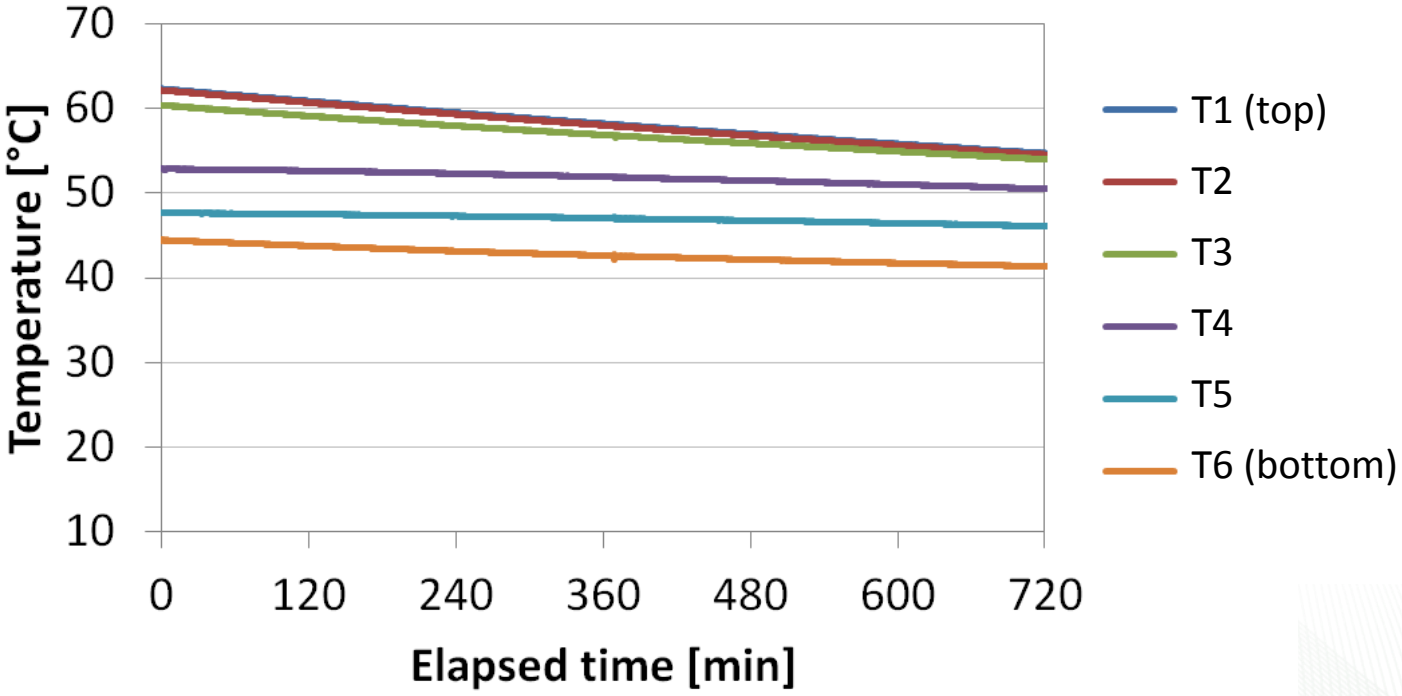
- Warmer water on top of colder (“positive” gradient) is stable (for fluids with positive coefficient of thermal expansion, like liquid water above 4°C)
- An “inversion” (negative gradient) is unstable and will “overturn”
- A strong positive gradient resists external forces
- A weak positive gradient is susceptible to external forces

Water Heater Tank – Stratification Phenomena

Phenomenon	Storage systems to which phenomenon is relevant :
Stratification due to cold inflow at bottom	All
Mixing due to high velocity inlet	All
Stratification due to hot inflow at top	Sidearm; external heat exchanger systems
Mixing above, and stratification below, a heat source	Systems with a burner or immersed electric element; HPWH WAHX with bottom-up refrigerant flow
Stratification due to temperature glide of external heating source	**Transcritical HPWH with WAHX**; Condensing HPWH with top-down refrigerant flow

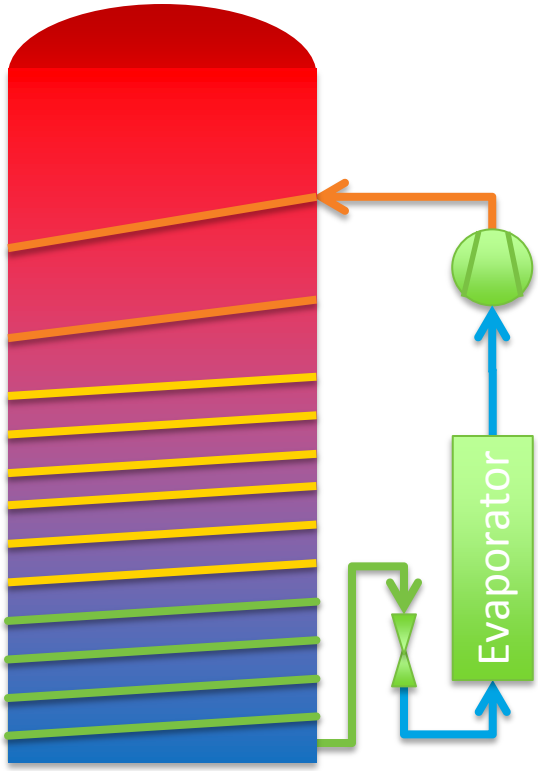
Water Heater Tank – Stratification

- Stratification empirical results (50 gallon tank)
  - 12 hours standby losses (no draws)

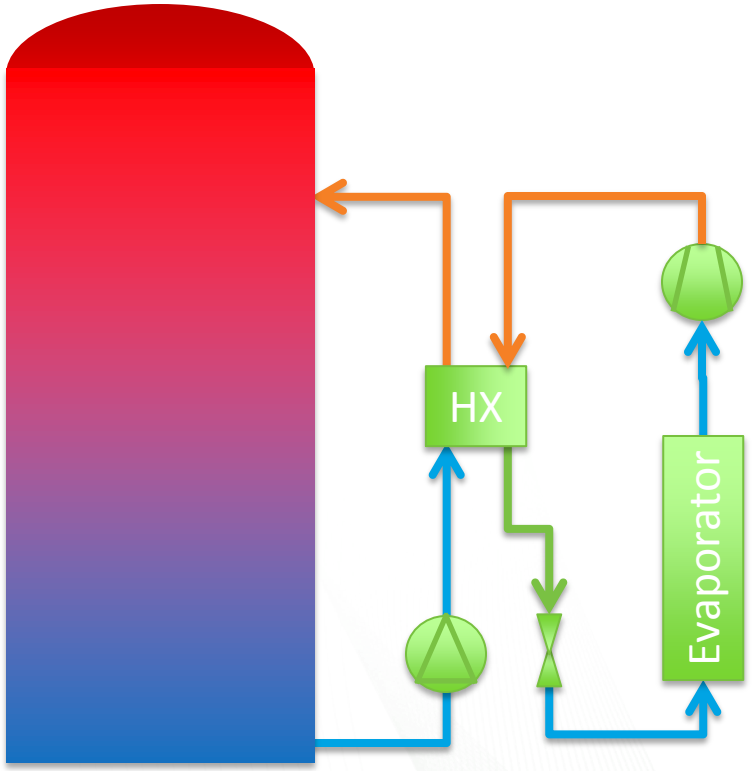


Gas Cooler Options

Wrap-around:



External:



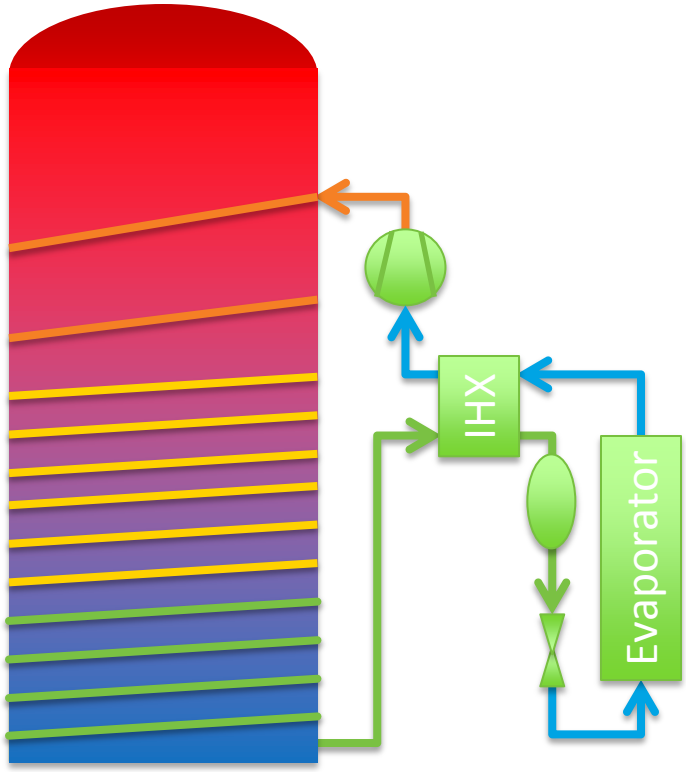
Gas Cooler Type

Wrap-around vs. external (e.g. plate or tube-in-tube)

Characteristic	External heat exchanger	Wrap-around heat exchanger
Cost	✗ High	✓ Low
Water fouling	✗ Significant challenge	✓ None
Water pump	✗ Required	✓ Not required
Additional tank water inlet/outlet ports	✗ Required	✓ Not required
Performance	✓ Good	? Needs research

Approach

This project:



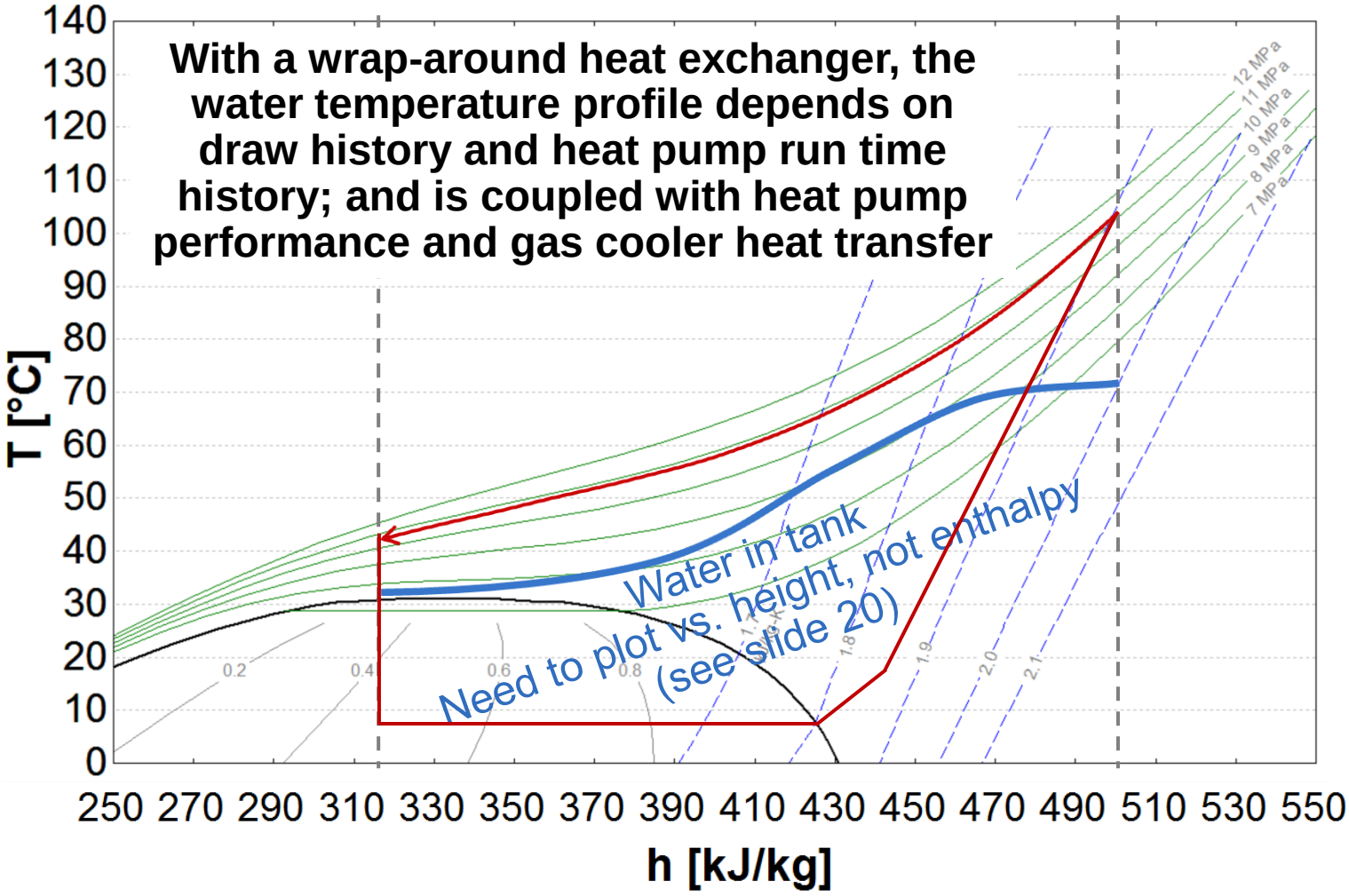
Note: Heat pump to be packaged on top of tank, but shown here spread out for visual clarity

EcoCute:

Additional elements (cost):

- Split system (high installation cost)
- Inverter-driven compressor
- Electronic expansion valves
- Variable speed pump
- External gas cooler

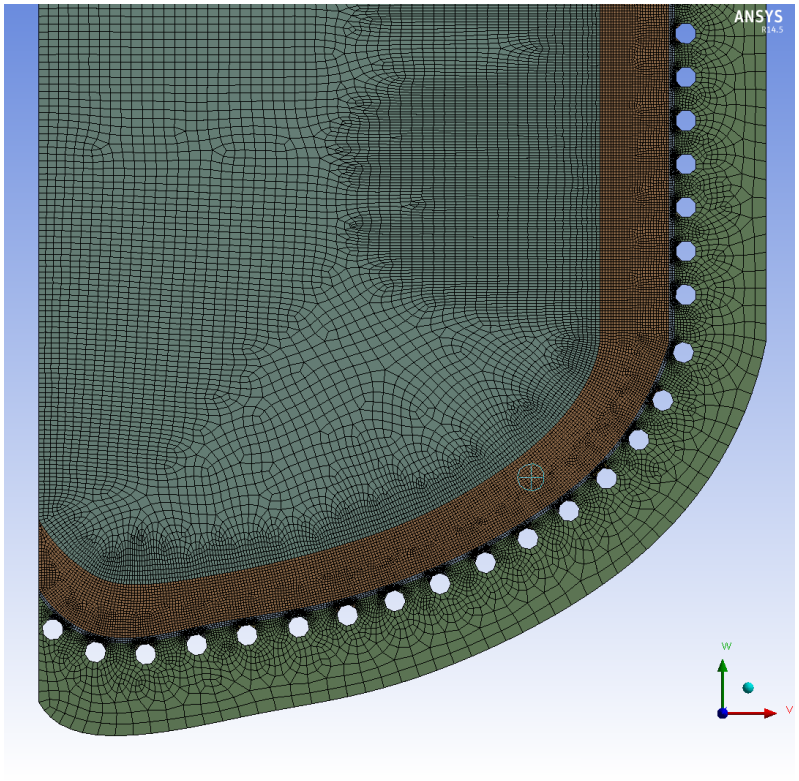
Transcritical Heat Pump – T-h

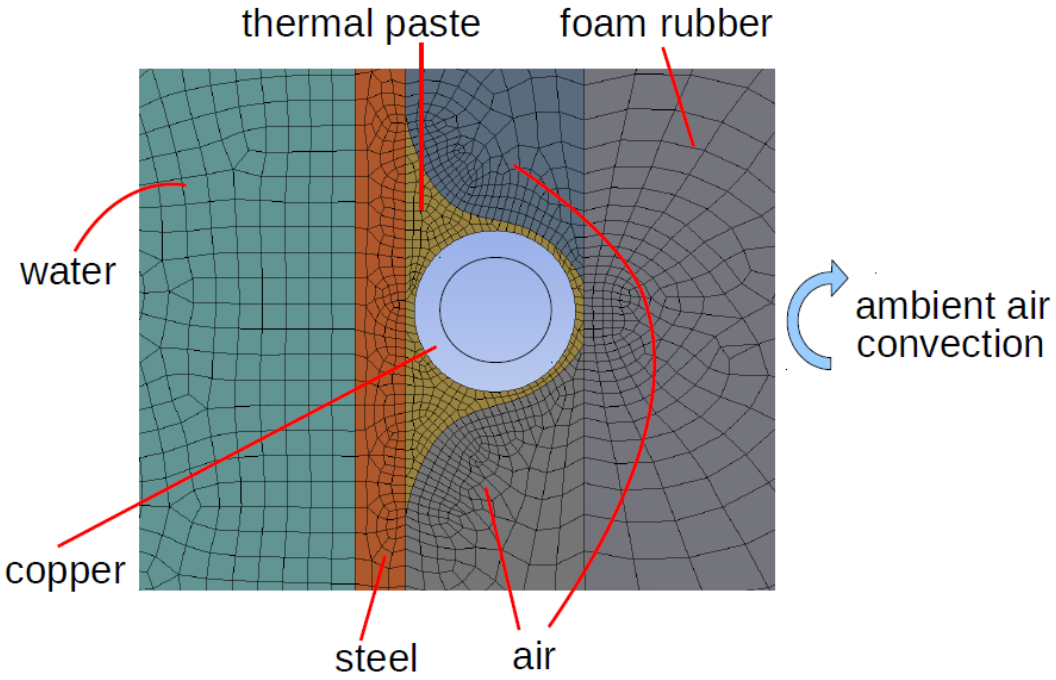


Gas Cooler Design Tool in ANSYS

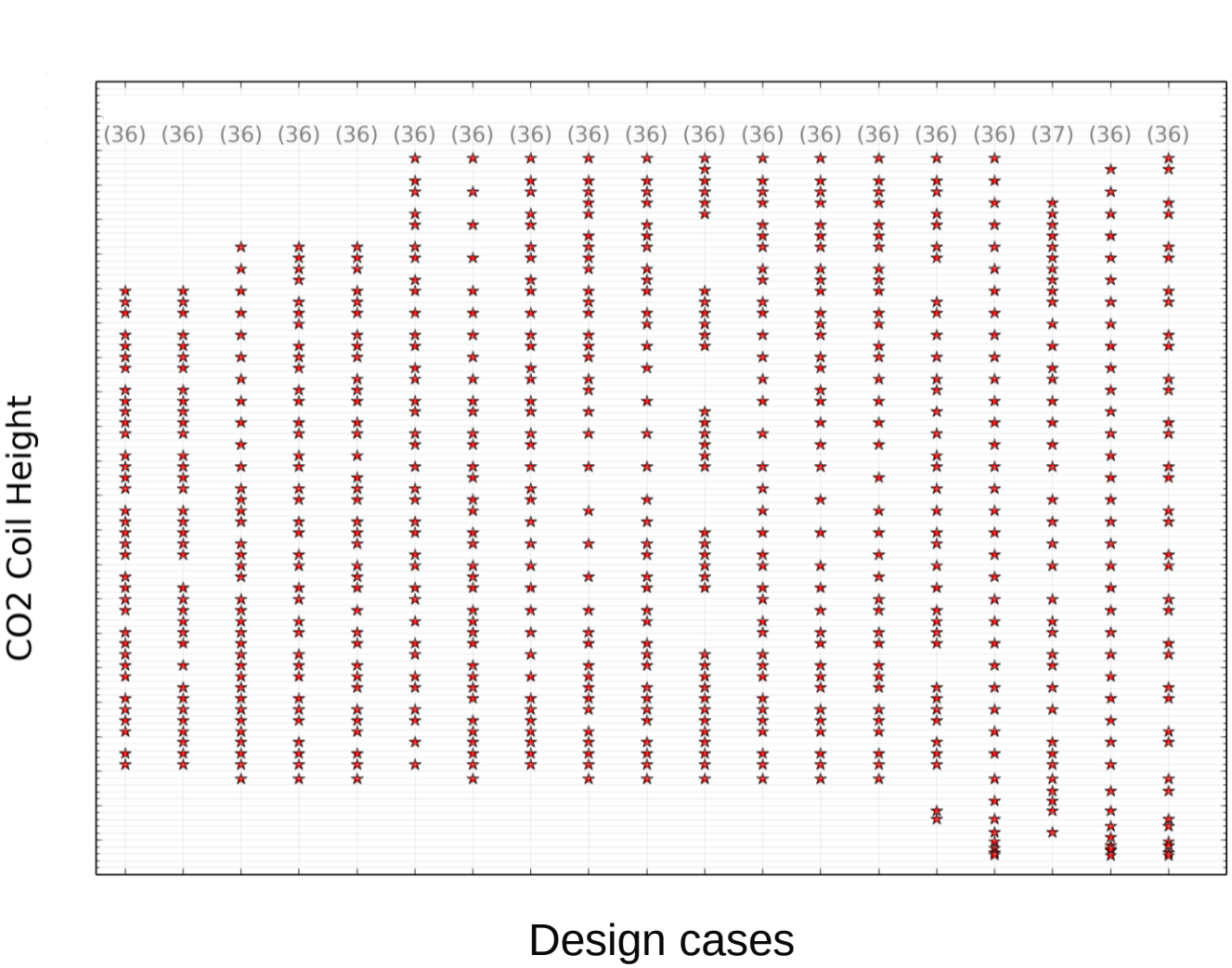
Coupled models of:

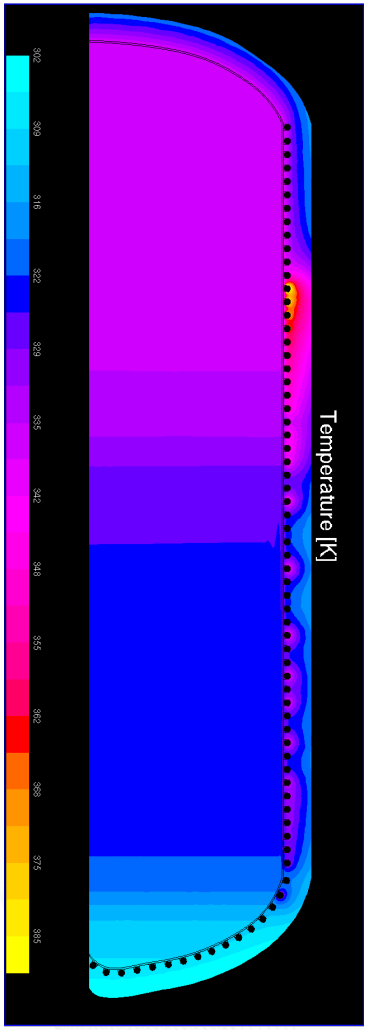
- Heat pump performance (mass flow, discharge T and P)
- Heat transfer (convection and multi-material conduction)
- Natural convective fluid flow in tank





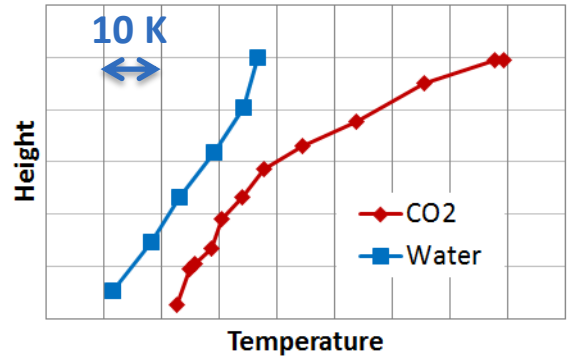
Gas Cooler Design with CFD





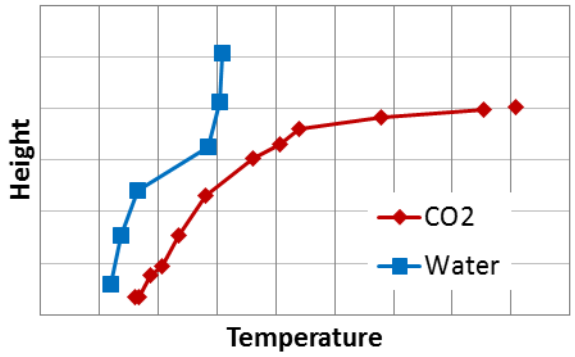
Design Improvements to Gas Cooler

Accomplishments: Progressive improvements in wrap-around gas cooler



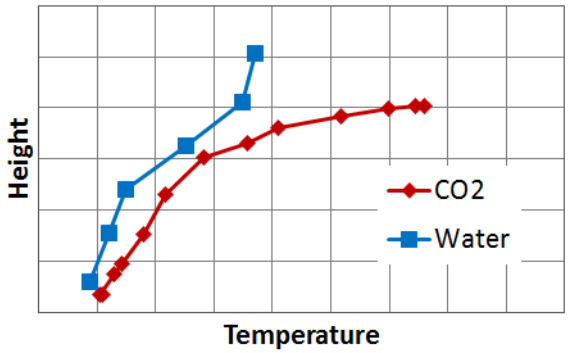
Temperature approach at the pinch: ~10 K

Improved coil construction; improved placement with insights from CFD



Temperature approach at the pinch: ~5 K

CFD-aided design



Temperature approach at the pinch: ~2.5 K

Results

- EF of 2.1 achieved (pre-2015 TP, 135°F)
- EF_{NC} of 1.9 achieved (pre-2015 TP, 135°F)
- FHR of 73 gallons (post-2015 TP, 125°F: medium use category for UEF)

Conclusion

- More affordable path demonstrated to ENERGY STAR qualified CO_2 HPWH
- EF of 2.1 achieved with
  - Single speed compressor
  - Single expansion device
  - Wrap-around gas cooler

Characteristic	Plate heat exchanger	Wrap-around heat exchanger
Cost	High	Low
Water fouling	Significant challenge	None
Water pump	Required	Not required
Additional tank water inlet/outlet ports	Required	Not required
Performance	Good	EF>2.0 demonstrated