Oak Ridge National Laboratory

CO_2 vs. Fluorocarbons: Thermodynamic Comparison of Subcritical and Transcritical Heat Pump Water Heater (HPWH) Efficiency

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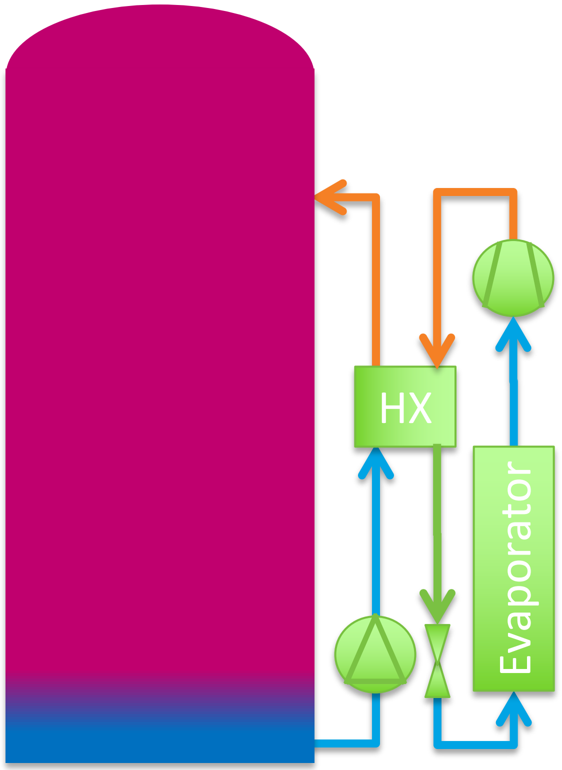
U.S. DEPARTMENT OF ENERGY

Acknowledgments

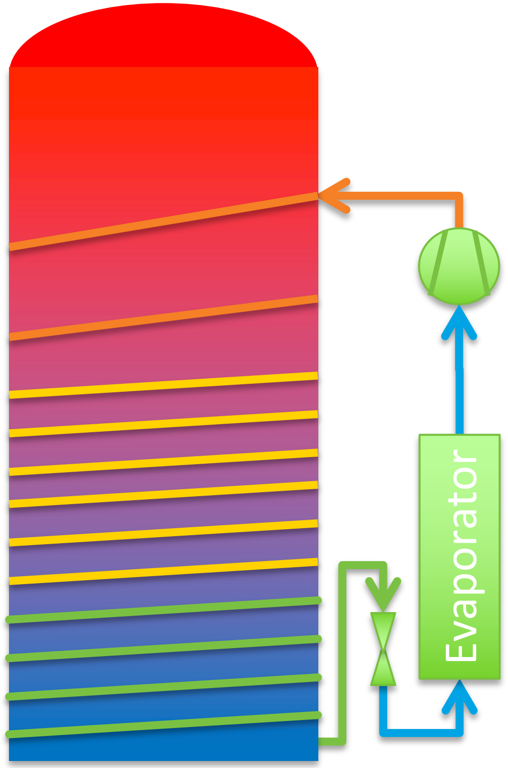
- Department of Energy (Contract DE-EE0006718.00)
- Antonio Bouza, DOE Building Technology Office

Classification of HPWHs

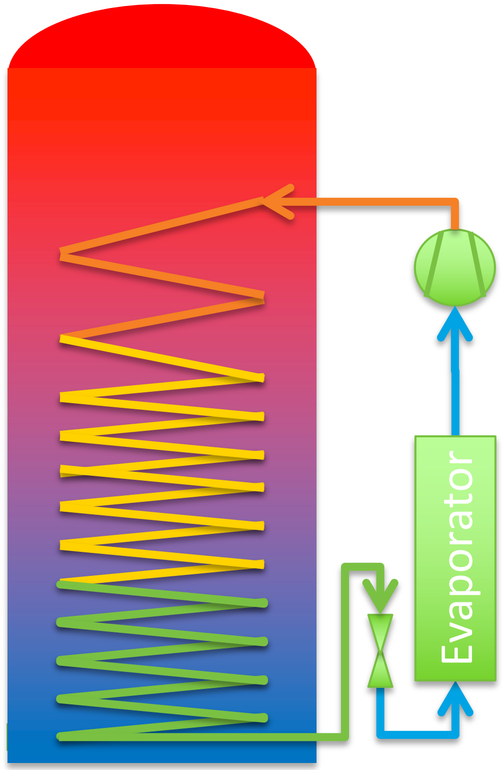
Pumped (or external):



Wrap-around:



Immersed coil:



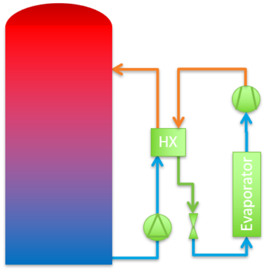
Classification of Stratification Types (Stratification During Heating)

	Table 1. Tank Stratification Categories				
Category	Heat exchanger (HX) used to transfer refrigerant heat to water	Locations of tank water taps, OR coil vertical span	High pressure refrigerant glide	Water or refrigerant flow type	Stratifying potential
1	Water pumped to HX	Bottom and top	Any	Single pass (low water flow)	Very strong
2	Water pumped to HX	Bottom; bottom	Any	Multi-pass (high water flow)	None
3	Wrapped around tank[3]	Spans tank height	Low-glide[1]	Top-down refrigerant flow	Moderate
4	Wrapped around tank[3]	Spans tank height	High-glide[2]	Top-down refrigerant flow	Strong
5	Wrapped around tank[3]	Spans tank height	Any	Bottom-up refrigerant flow	None
6	Immersed coil – tall[3]	Spans tank height	Low-glide[1]	Top-down refrigerant flow	Moderate
7	Immersed coil – tall[3]	Spans tank height	High-glide[2]	Top-down refrigerant flow	Strong
8	Immersed coil – tall[3]	Spans tank height	Any	Bottom-up refrigerant flow	None
9	Immersed coil – short[3]	Bottom region	Any	Any refr. flow direction	None

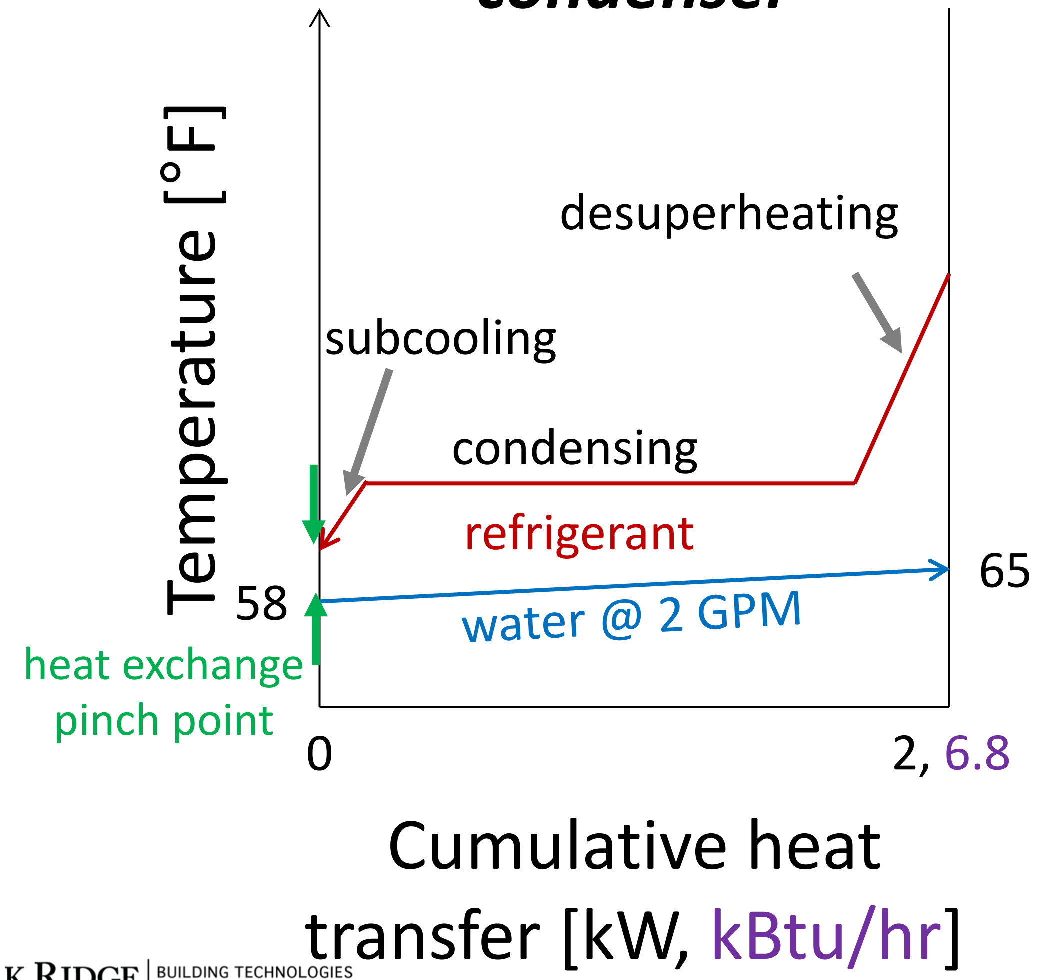
[1]for example, a subcritical HFC or HFO (condensing) cycle.
[2]for example, a transcritical CO_2 cycle.
[3]it is assumed a wrapped tank refrigerant coil will extend for most of the tank height, whereas an immersed coil may have a shorter vertical span.

Table from: Gluesenkamp, Kyle R., John Bush (2016). "Impact on Water Heater Performance of Heating Methods that Promote Tank Temperature Stratification", *ASHRAE Annual Meeting 2016*, Conference Paper Session 19, June 29, 2016, St. Louis, MO.

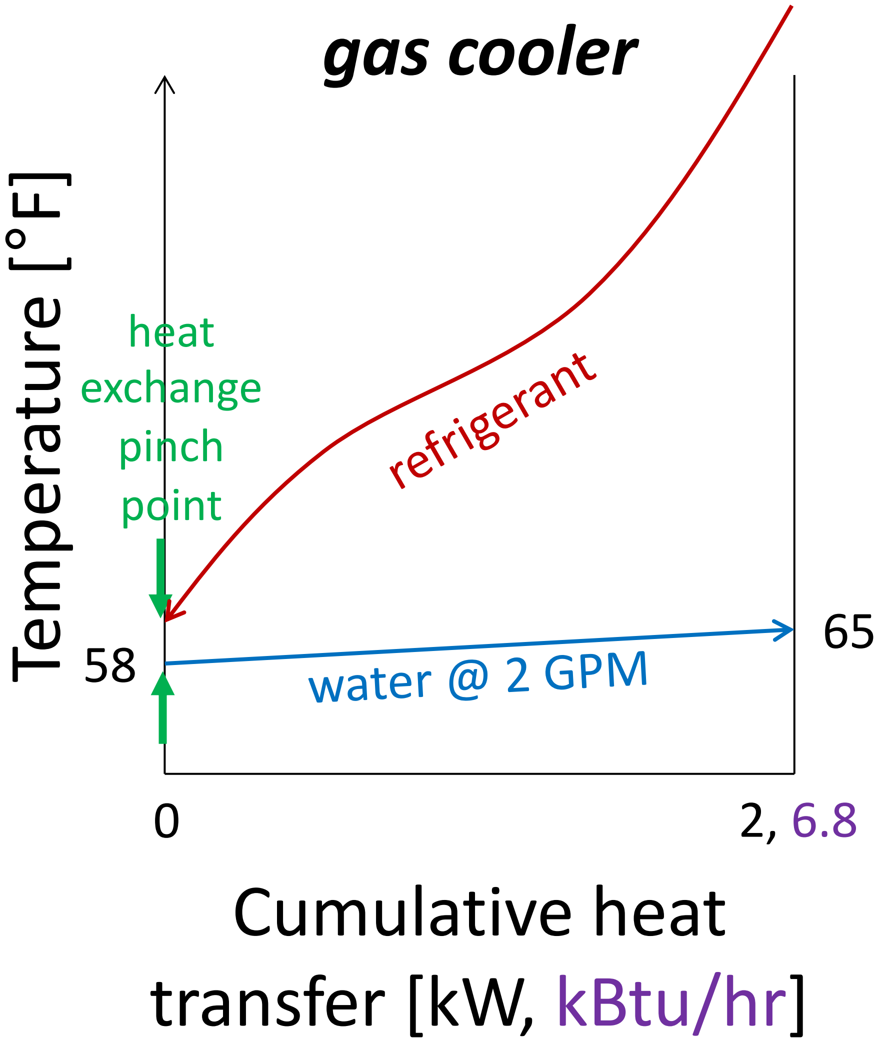
Condenser and Gas Cooler



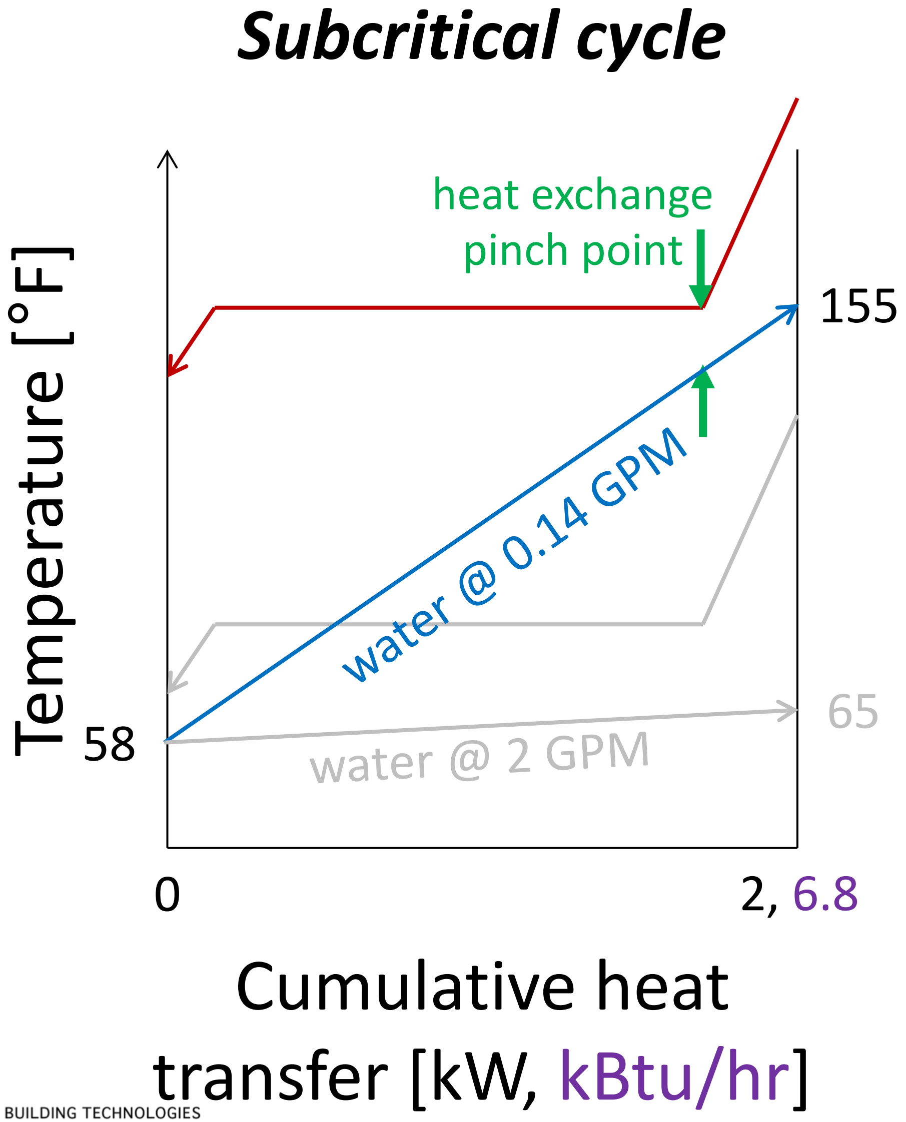
Subcritical cycle condenser

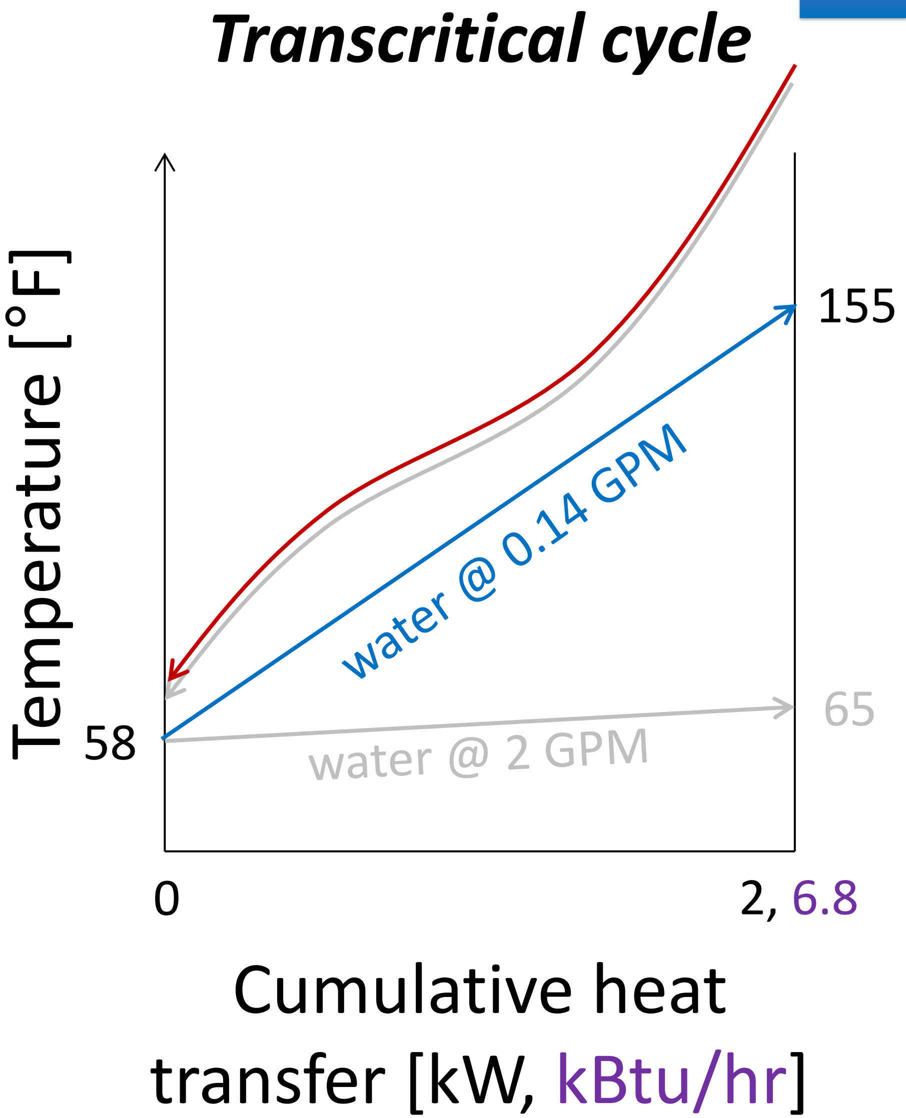


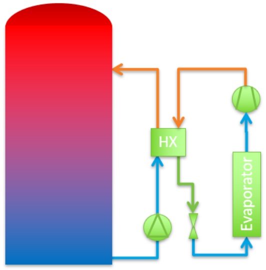
Transcritical cycle gas cooler



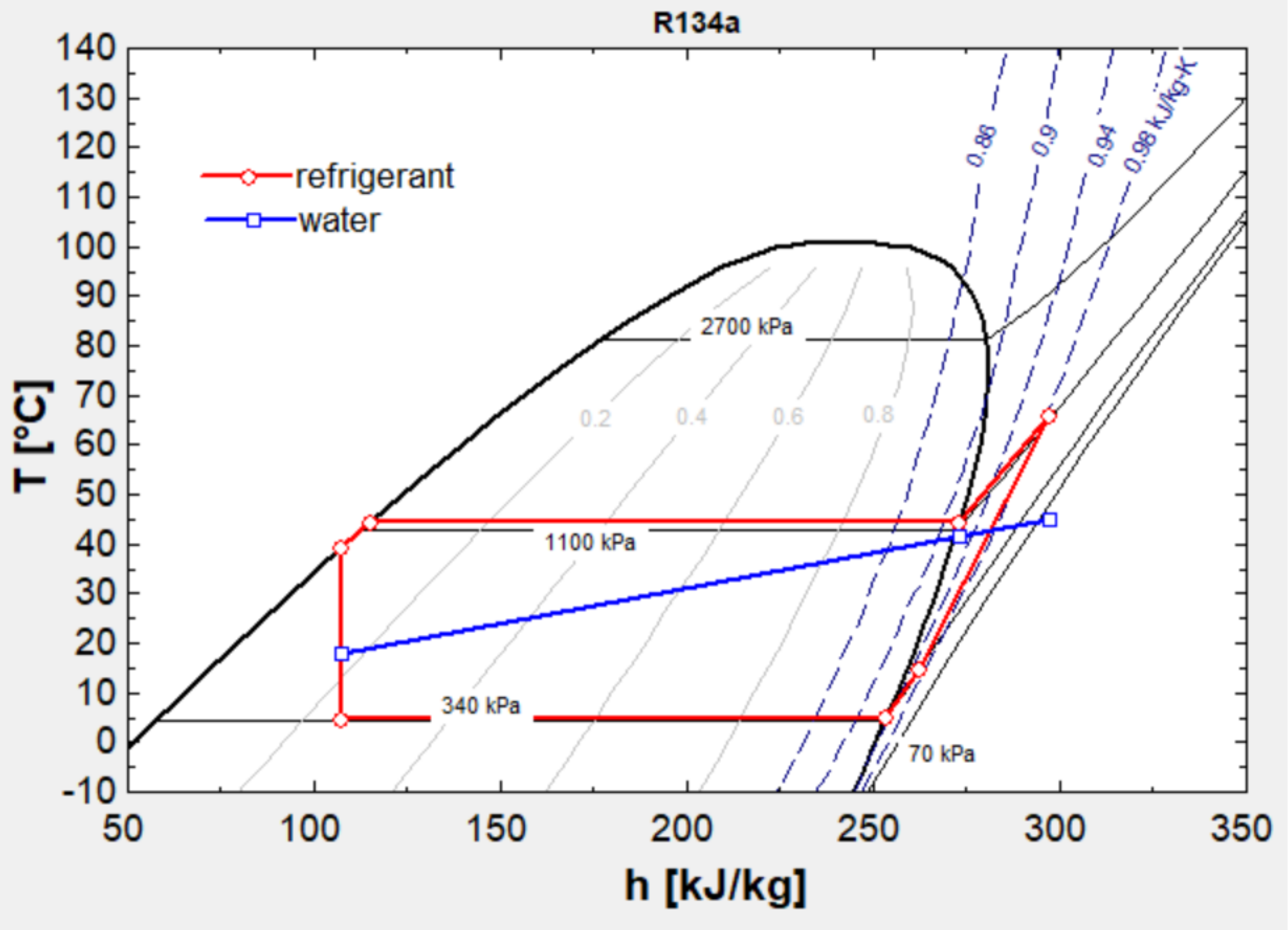
Condenser and Gas Cooler



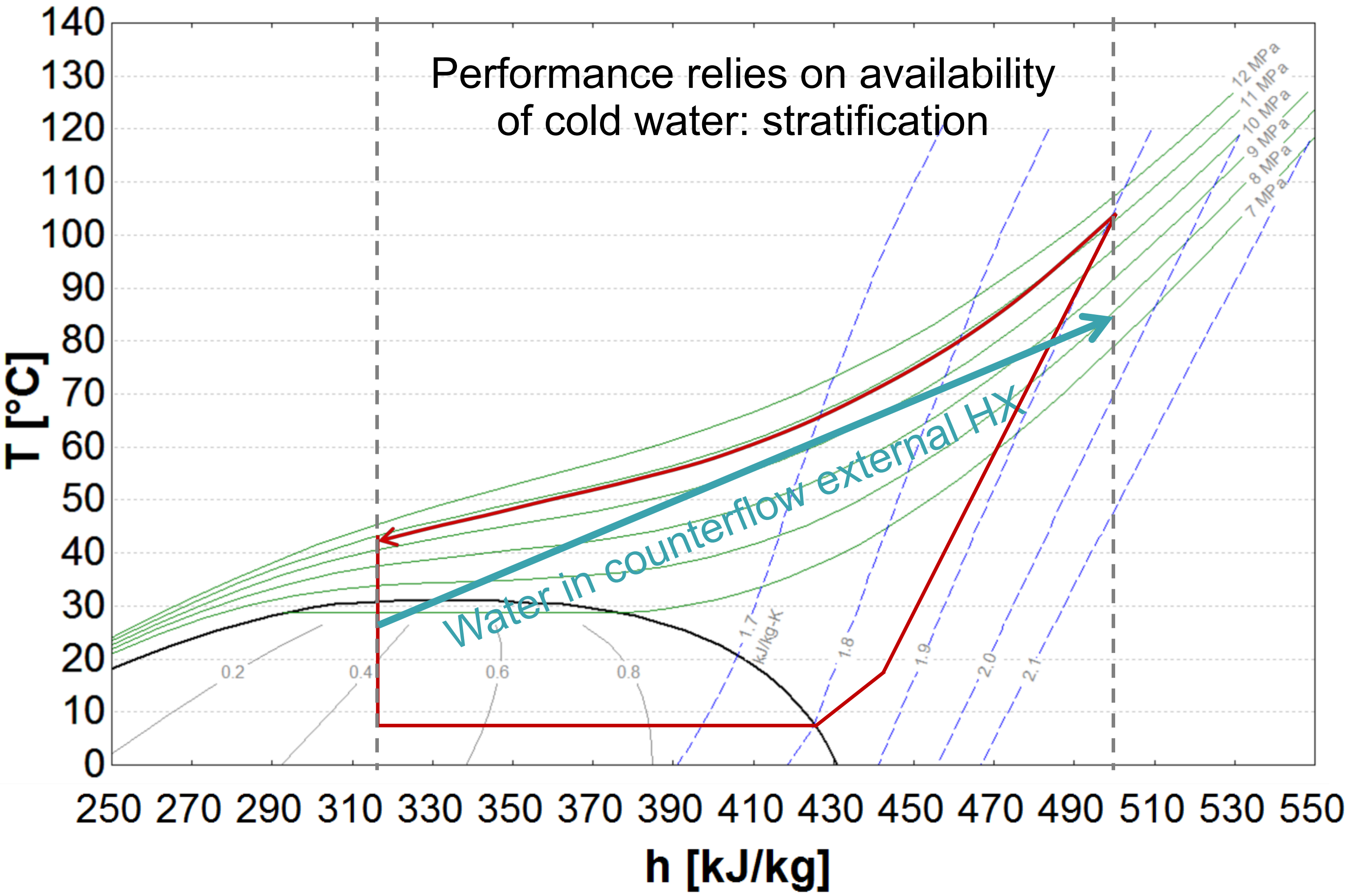




Subcritical Cycle



Transcritical Cycle

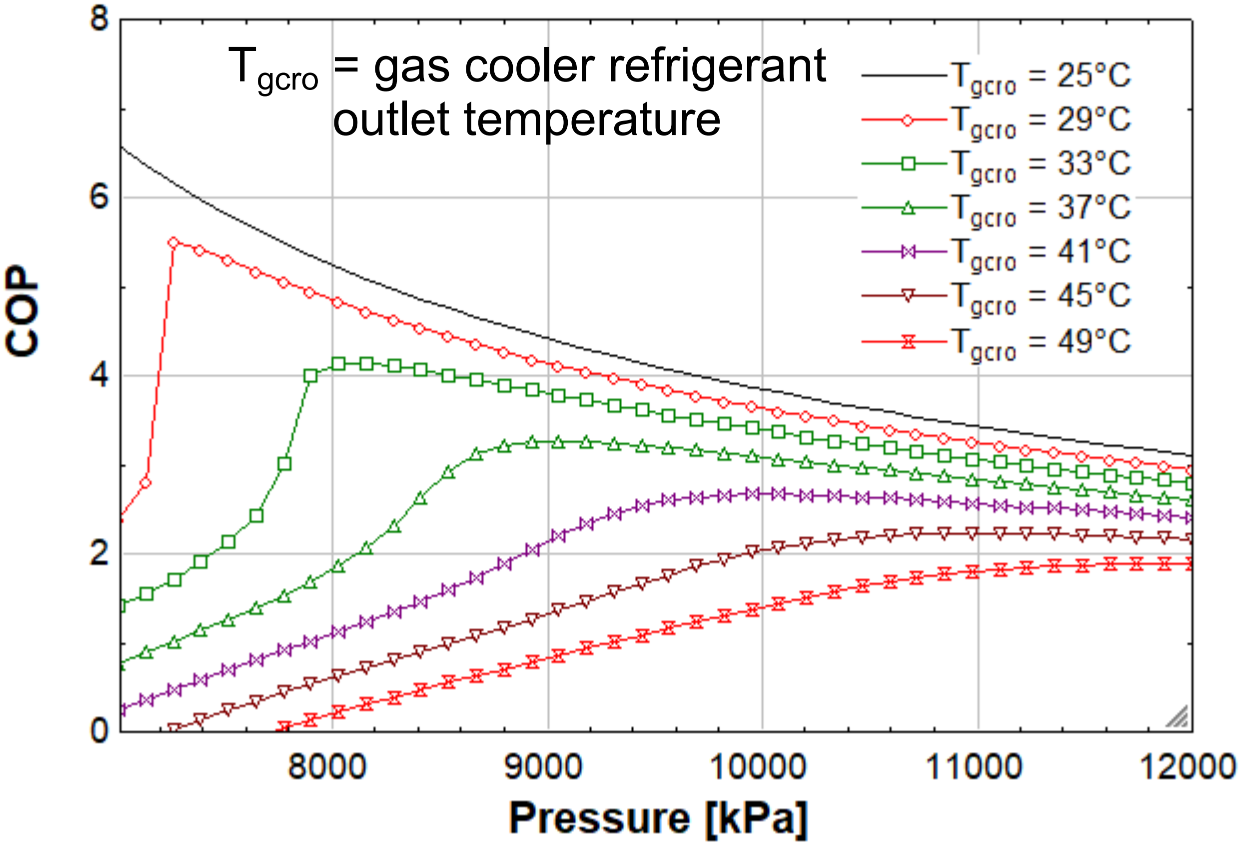


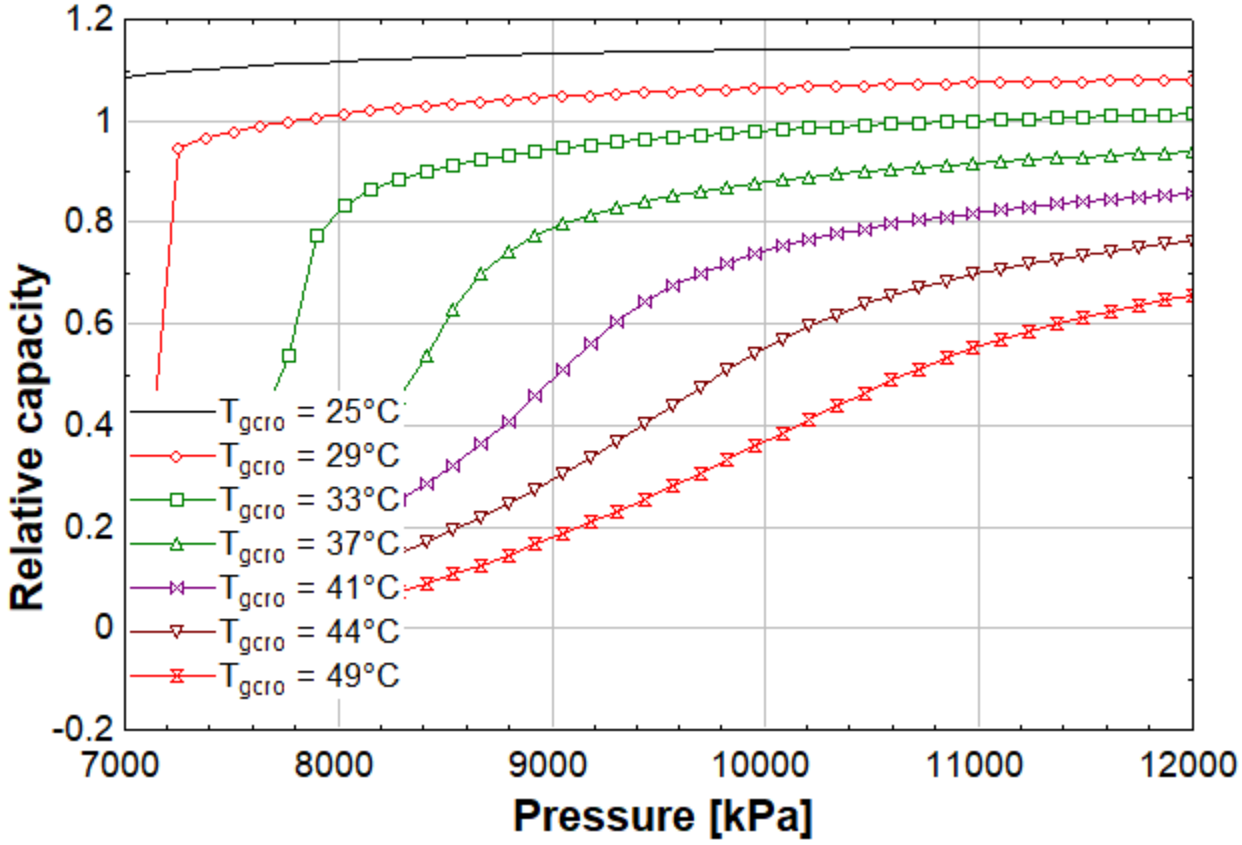
Modeling assumptions

- Across all models:
  - 10 K (18°F) evaporator superheat
  - 3 K (5°F) closest approach at the pinch
  - 0 fan and pump work
  - 95% motor efficiency
  - η_{isen} = 0.90 – 0.0467*PR
  - η_{vol} = 1.00 – 0.04*PR
  - 100 kPa condenser pressure drop
  - 50 kPa evaporator pressure drop
- CO2-specific:
  - High side pressure optimized for COP
- HFC-specific:
  - 5 K condenser subcooling

High side pressure optimization

- In transcritical cycles, the high side pressure is a free variable
- Proper modeling requires optimization of this pressure





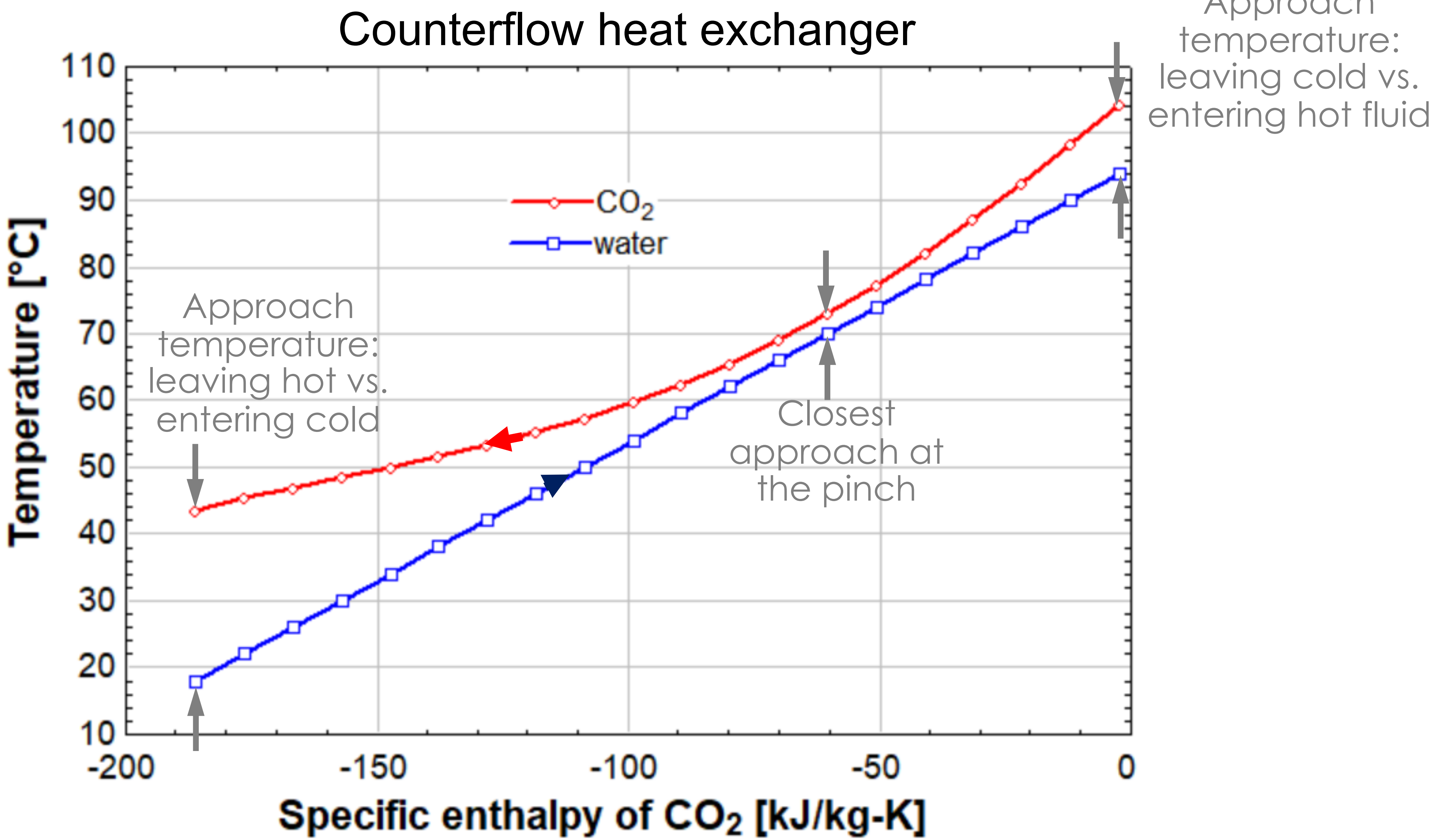
Shown for Teri = 15°C

Polynomial curve fit for optimum high side pressure

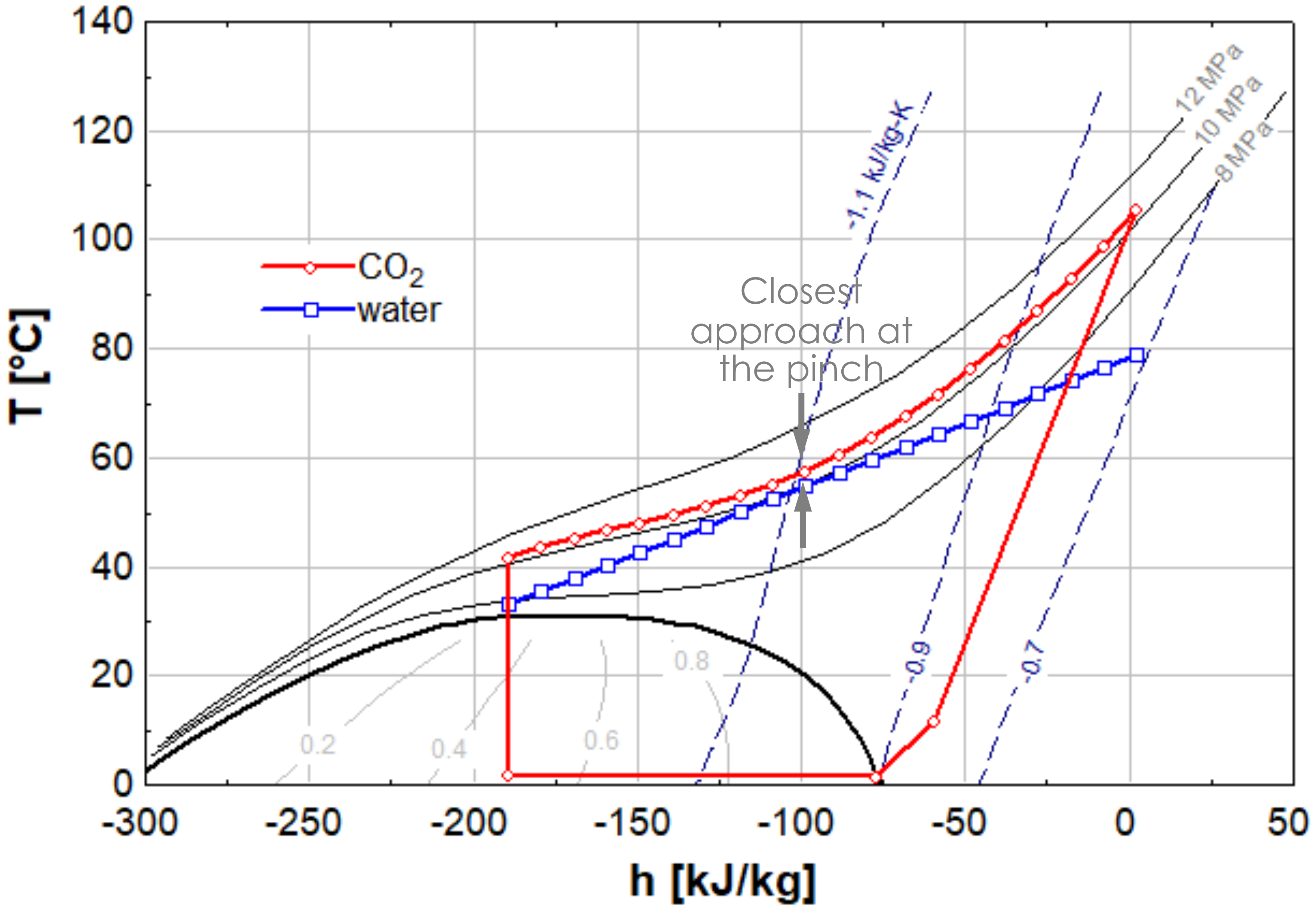
- For this work, capacity was ignored and pressure was chosen to maximize COP
  - In practice, this represents a small (~10%) sacrifice of capacity
- Optimum pressure as function of T_{eri} and T_{gcro}:
- $P_{optimum}$ [kPa] $= a + bT_{eri} + cT_{eri}^2 + dT_{gcro} + eT_{gcro}^2 + fT_{eri}T_{gcro}$
  - Where Ts are in °C
- Relative error <0.8% of optimum pressure
- Valid range:
  - 33 < Tgcro < 45°C
  - -3 < Teri < 17°C

Coefficient	Value
a	-107.476661
b	30.9365
c	-0.410714286
d	246.74575
e	0.165625
f	-1.0285

Computing closest approach at the pinch



Computing closest approach at the pinch



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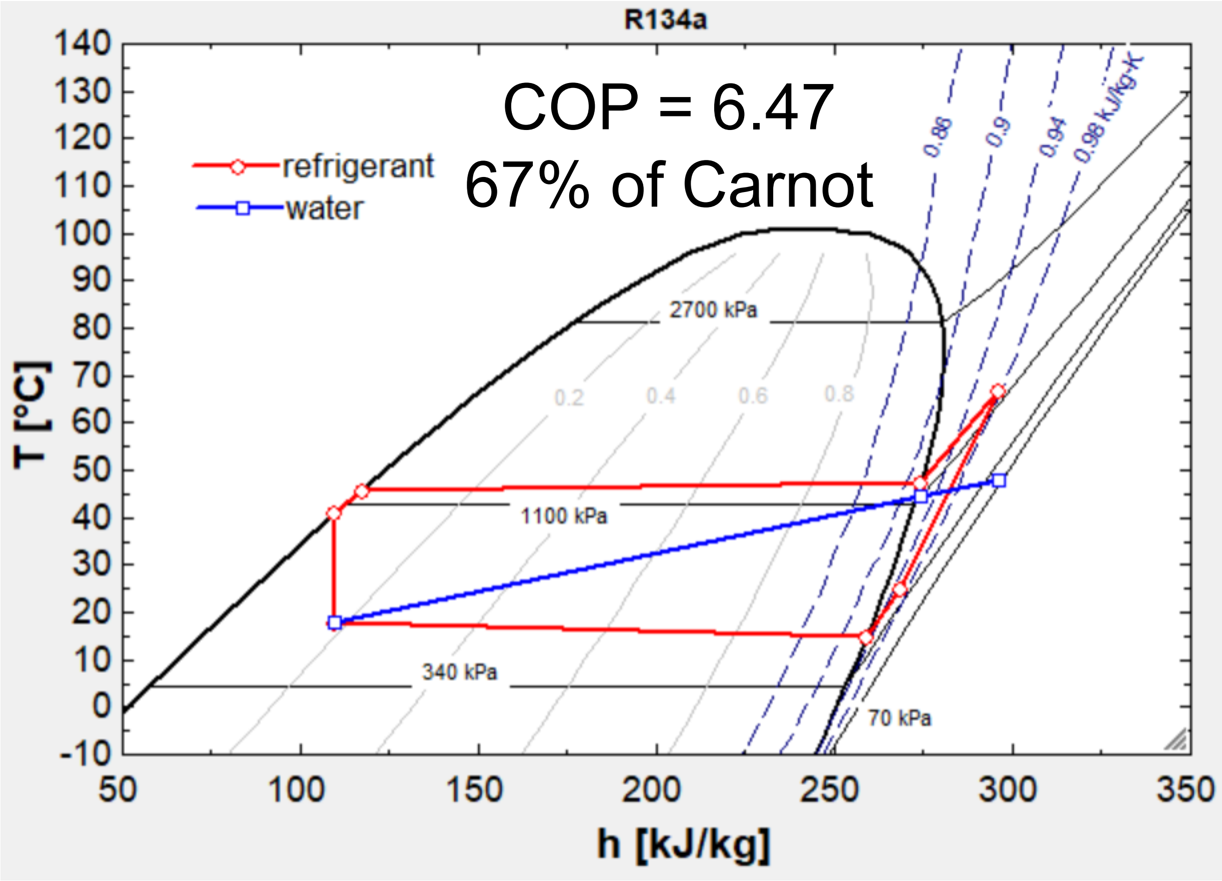
Results: transcritical cycle performance

(animations – see slides 23-47)

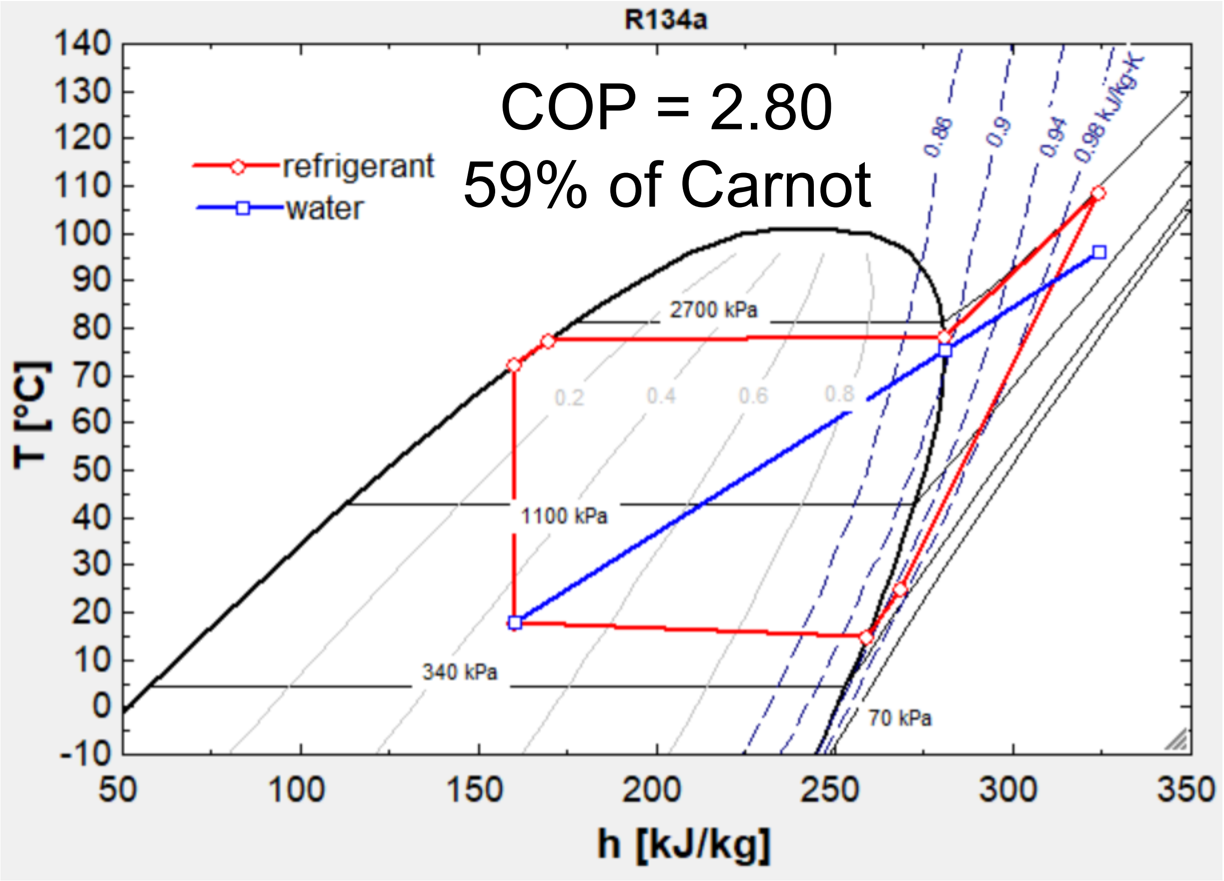
Results: subcritical cycle performance (R134a)

Ambient air temperature = 15°C
Water entering heat pump = 18 °C

T_{supply} = 48°C



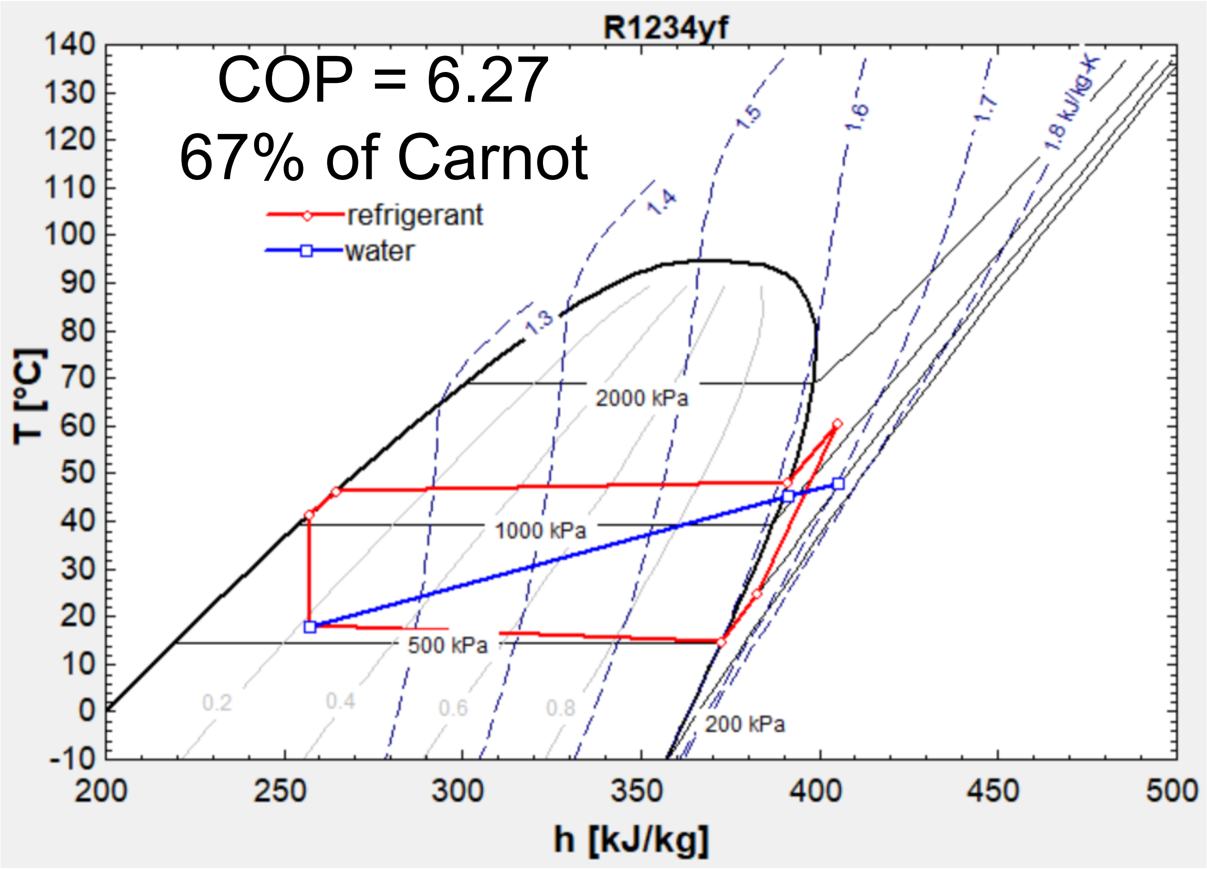
T_{supply} = 96°C



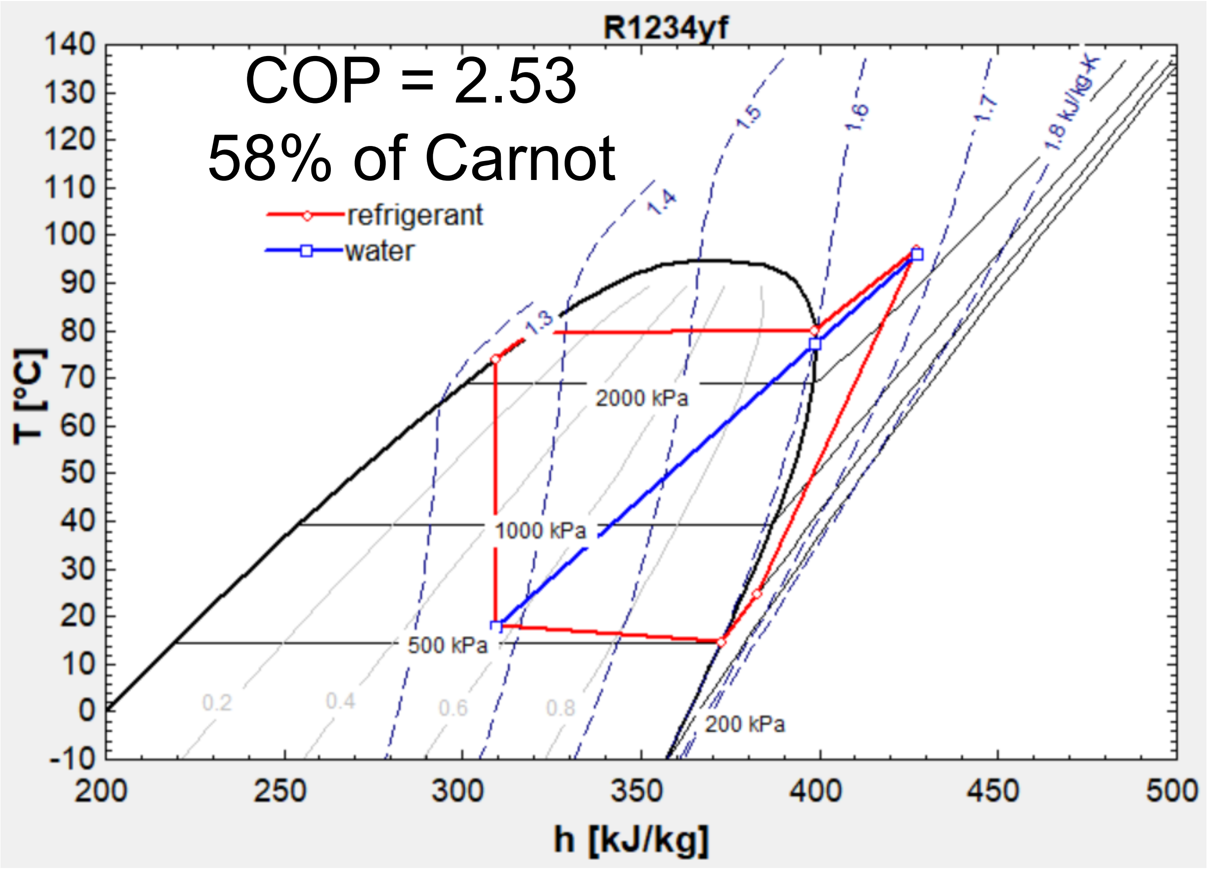
Results: subcritical cycle performance (R1234yf)

Ambient air temperature = 15°C
Water entering heat pump = 18 °C

T_{supply} = 48°C

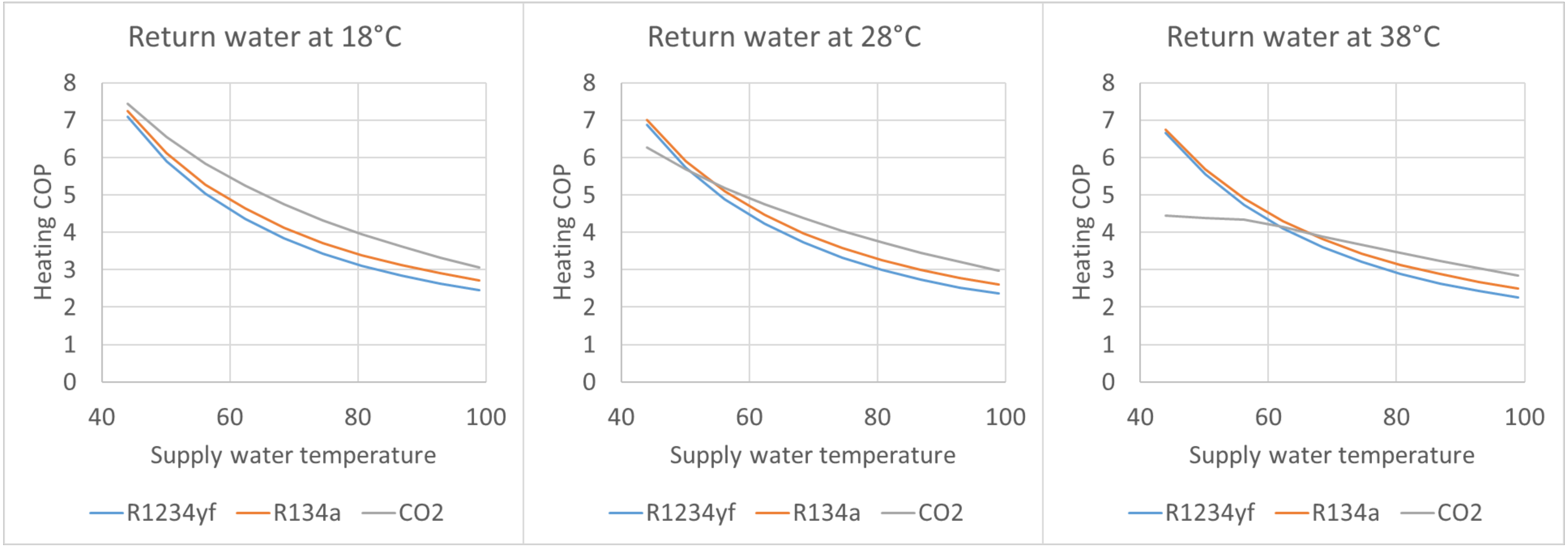


T_{supply} = 96°C



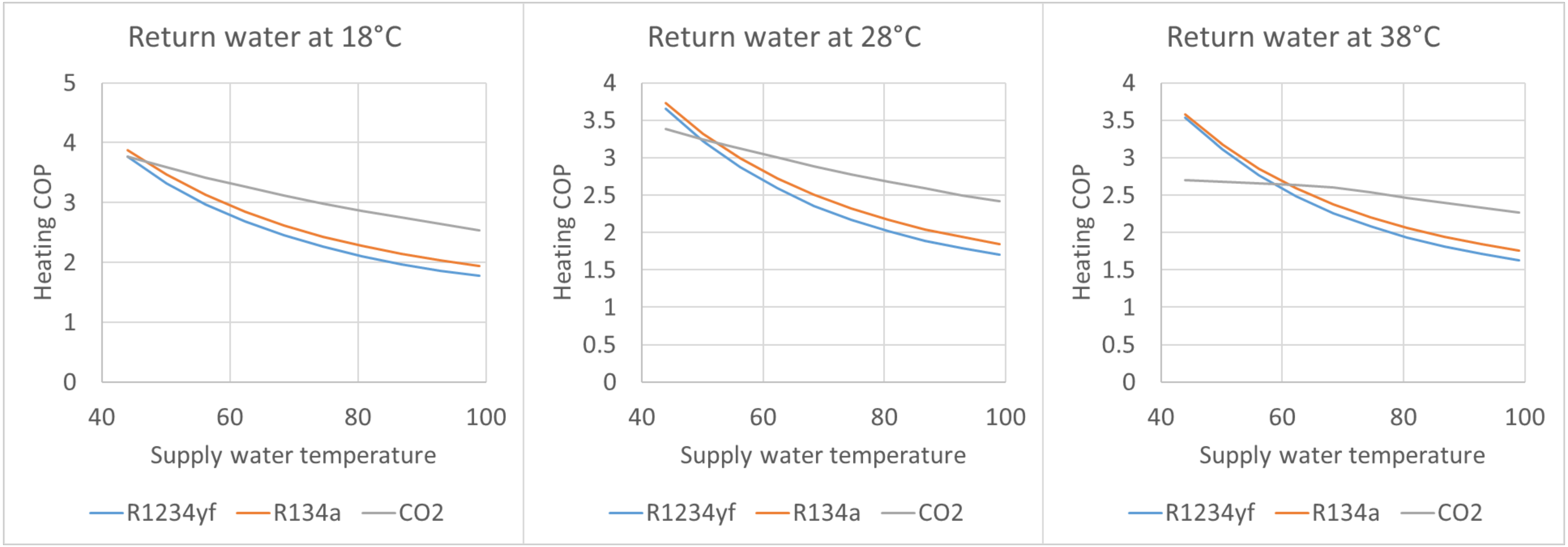
Results

Ambient air temperature = 15°C



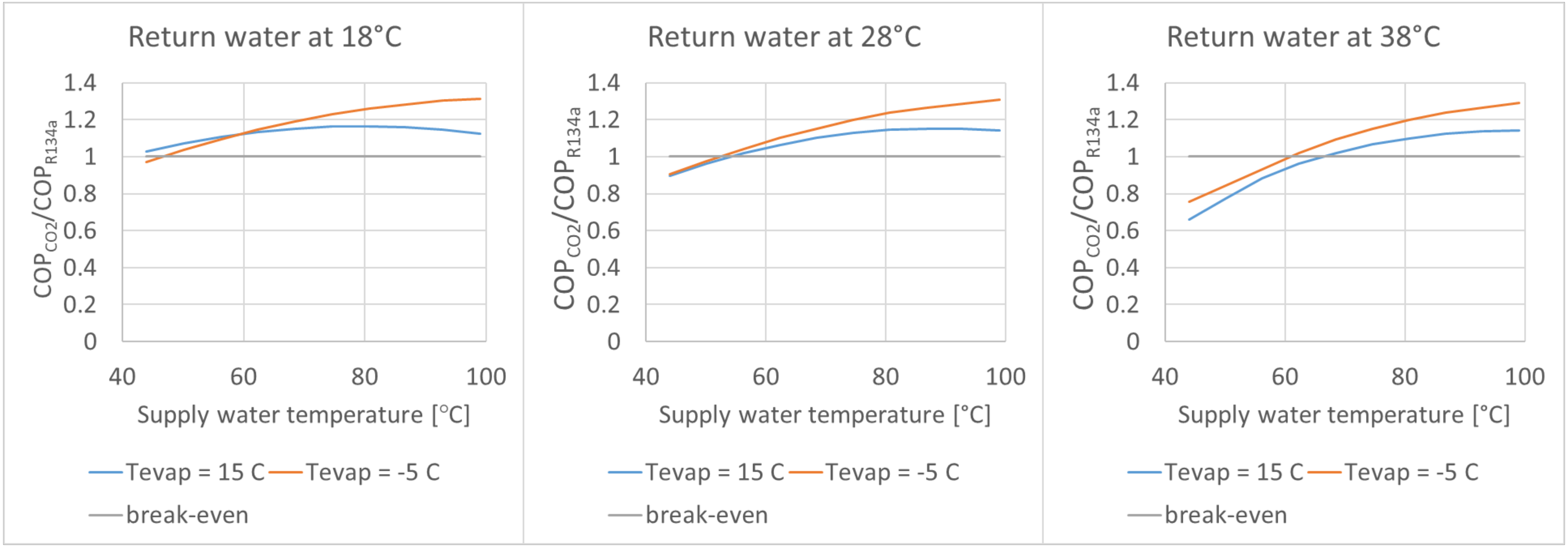
Results

Ambient air temperature = –5°C



Results: crossover temperature

CO_2 COP advantage over R134a



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Conclusions

The “crossover temperature”

- At 15°C Ambient, CO_2 has higher COP:
  - Above 42°C for 18°C return
  - Above 56°C for 28°C return
  - Above 67°C for 38°C return
- At -5°C Ambient, CO_2 has higher COP:
  - Above 47°C for 18°C return
  - Above 54°C for 28°C return
  - Above 62°C for 38°C return

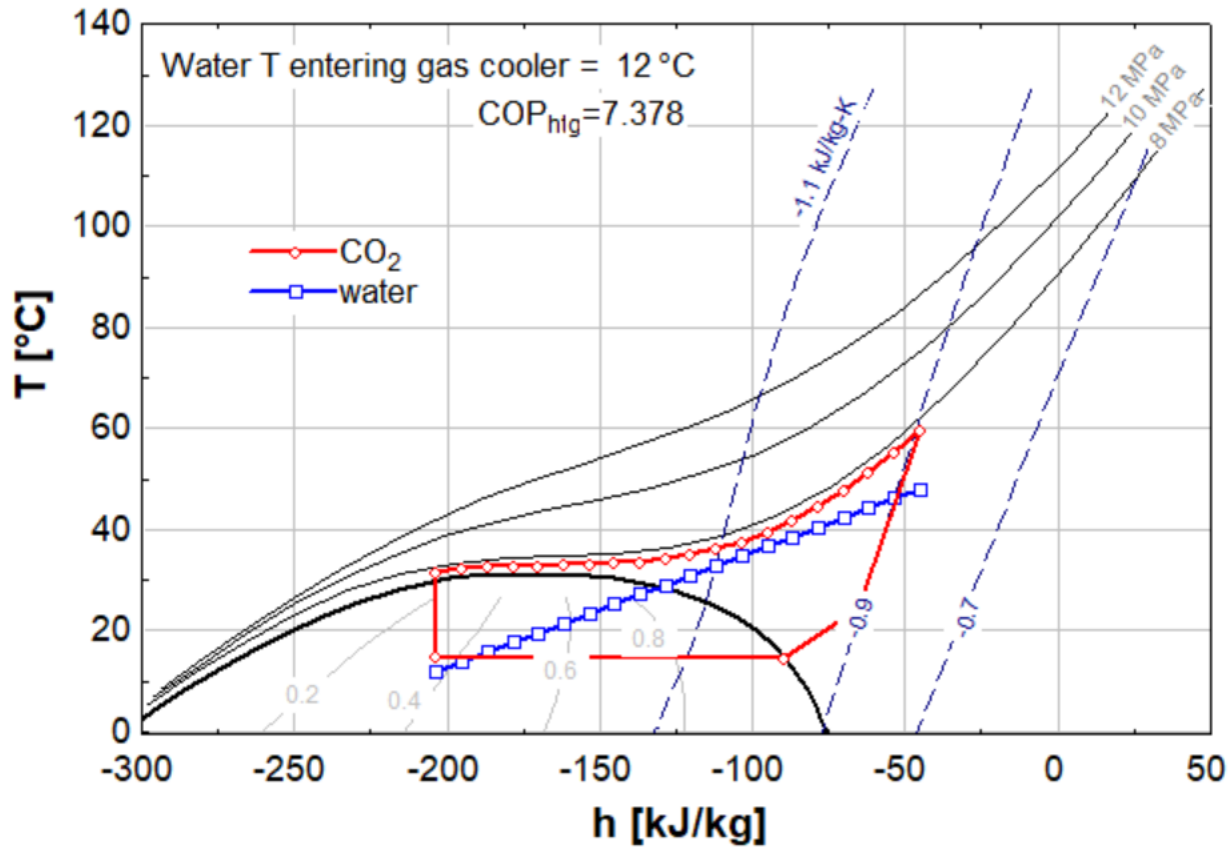
References

- Gluesenkamp, K., Abdelaziz, O., Patel, V., Mandel, B., deAlmeida, V. (May 2017). "High Efficiency Water Heating Technology Development – Final Report, Part II: CO2 and Absorption-Based Residential Heat Pump Water Heater Development" ORNL publication TM-2016/291. Available at http://info.ornl.gov/sites/publications/Files/Pub68329.pdf
- Kashif Nawaz, Bo Shen, Ahmed Elatar, Van Baxter. "Hydroflouroolefins (HFOs) as Low GWP Refrigerants for Residential Heat Pump Water Heaters", ACEEE HWF 2017.
- Gluesenkamp, K., Bush, J. (2016). "Impact on Water Heater Performance of Heating Methods that Promote Tank Temperature Stratification", *ASHRAE Annual Meeting 2016*, Conference Paper Session 19, June 29, 2016, St. Louis, MO.
- B. Shen, K. Nawaz, A. Elatar, V. Baxter, "Development and Validation of Quasi-Steady-State Heat Pump Water Heater Model Having Stratified Water Tank and Wrapped-Tank Condenser" *International Journal of Refrigeration*, 2018, 87,78-90.
- K. Nawaz, B. Shen, A. Elatar, V. Baxter, O. Abdelaziz, "Performance Optimization of CO2 HPWH System", *International Journal of Refrigeration*, 2017, 85, 213-218.

Thank You

Animation

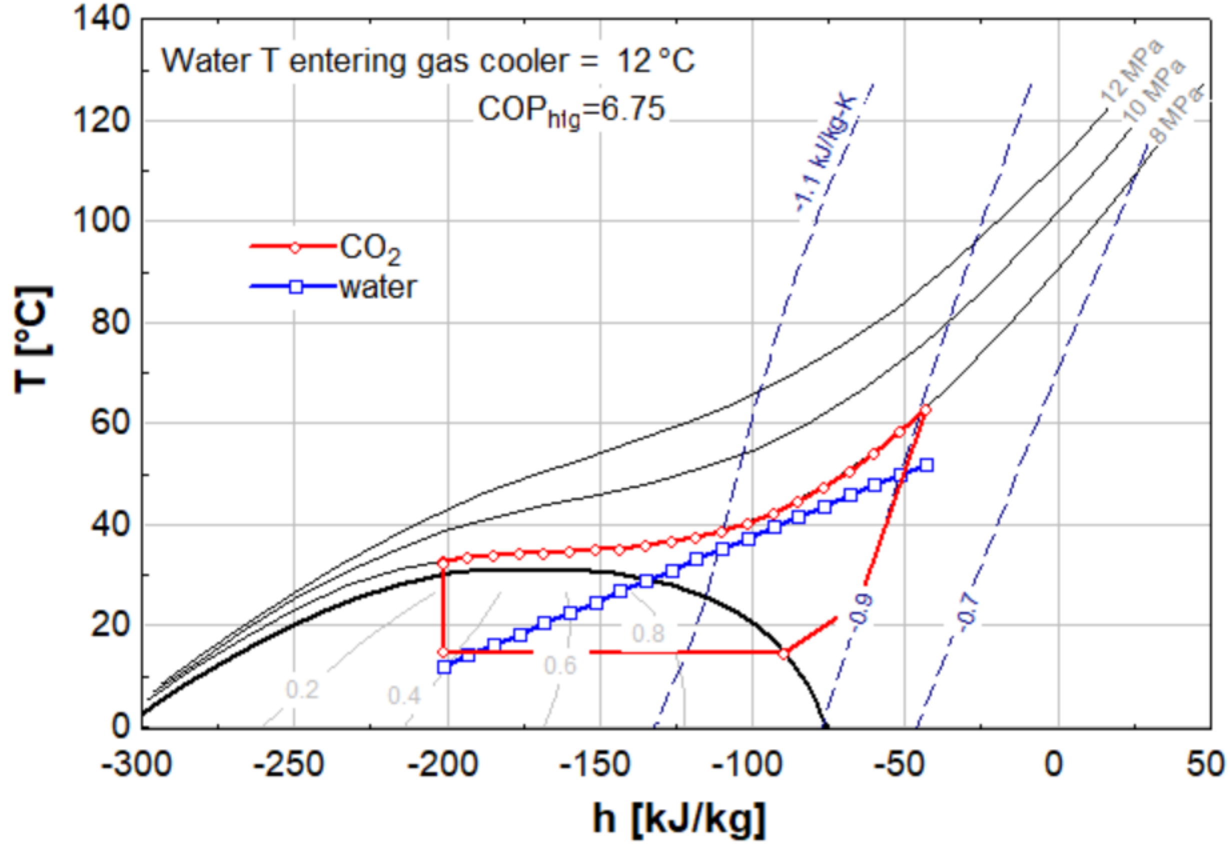
Ambient air temperature = 15°C



Supply water temperature = 46°C

Animation

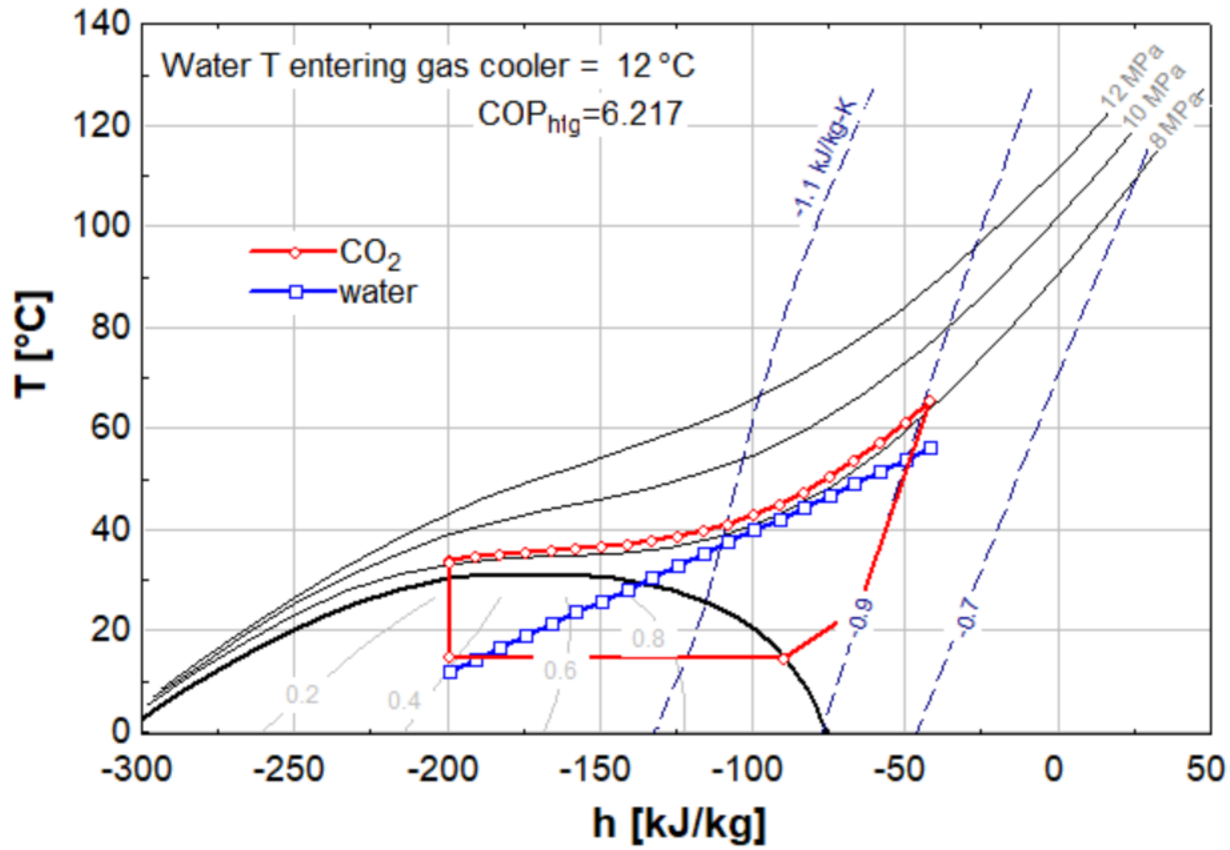
Ambient air temperature = 15°C



Supply water temperature = 50°C

Animation

Ambient air temperature = 15°C



Supply water temperature = 54°C

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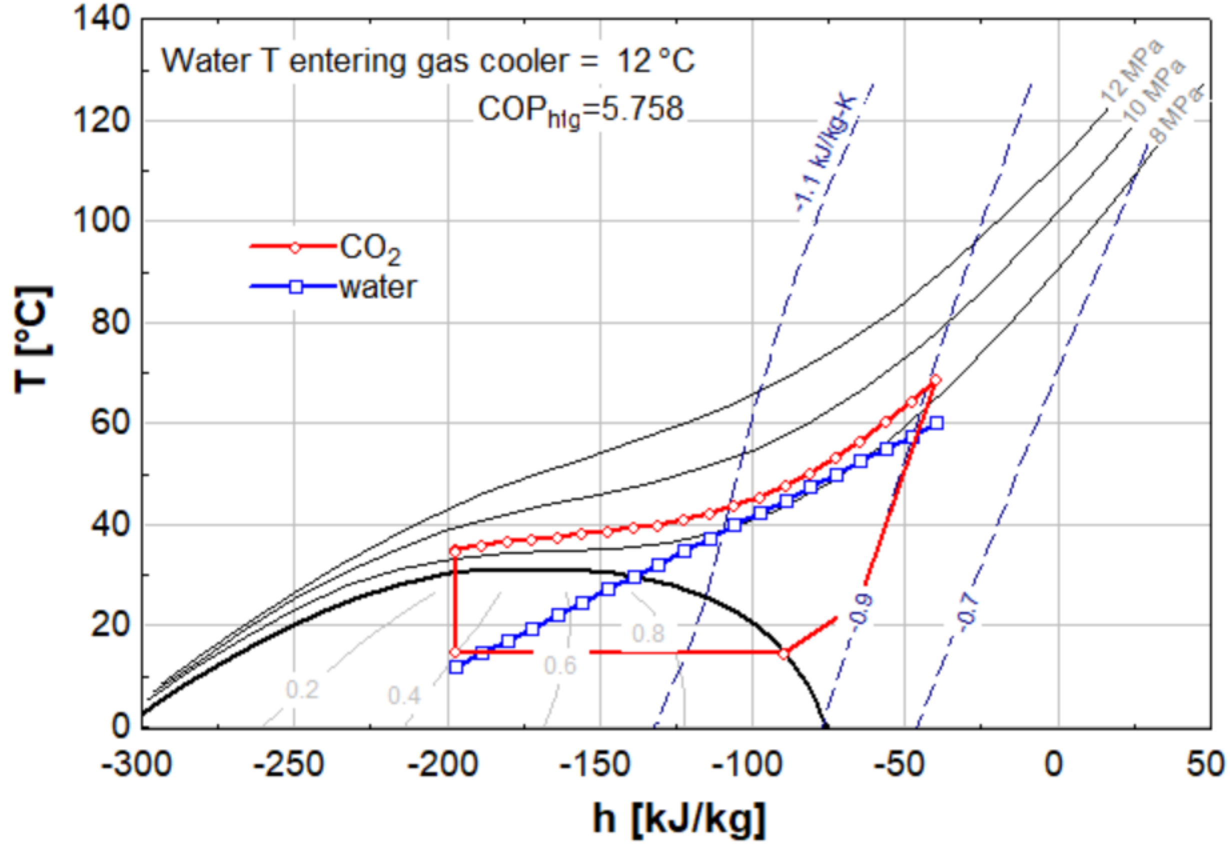
Animation

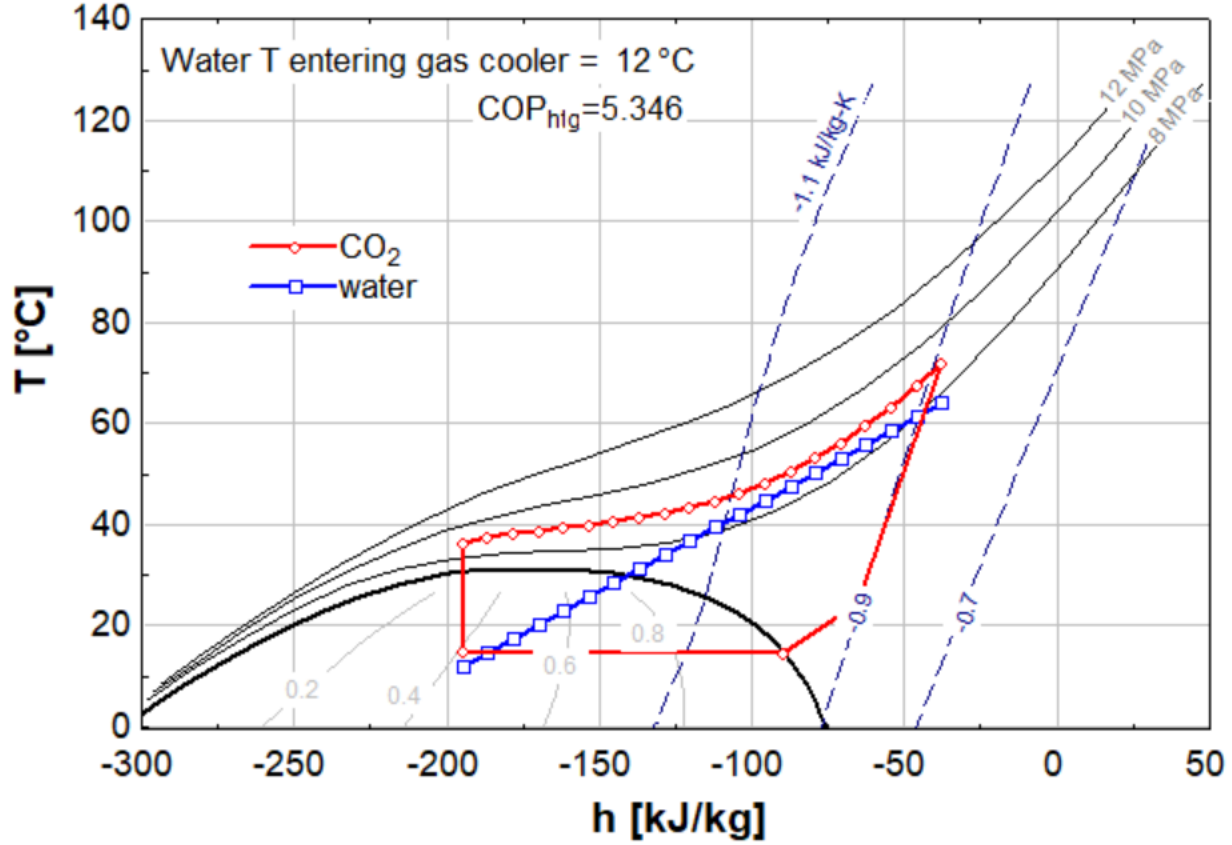
Ambient air temperature = 15°C



Supply water temperature = 58°C

Animation

Ambient air temperature = 15°C



Supply water temperature = 64°C

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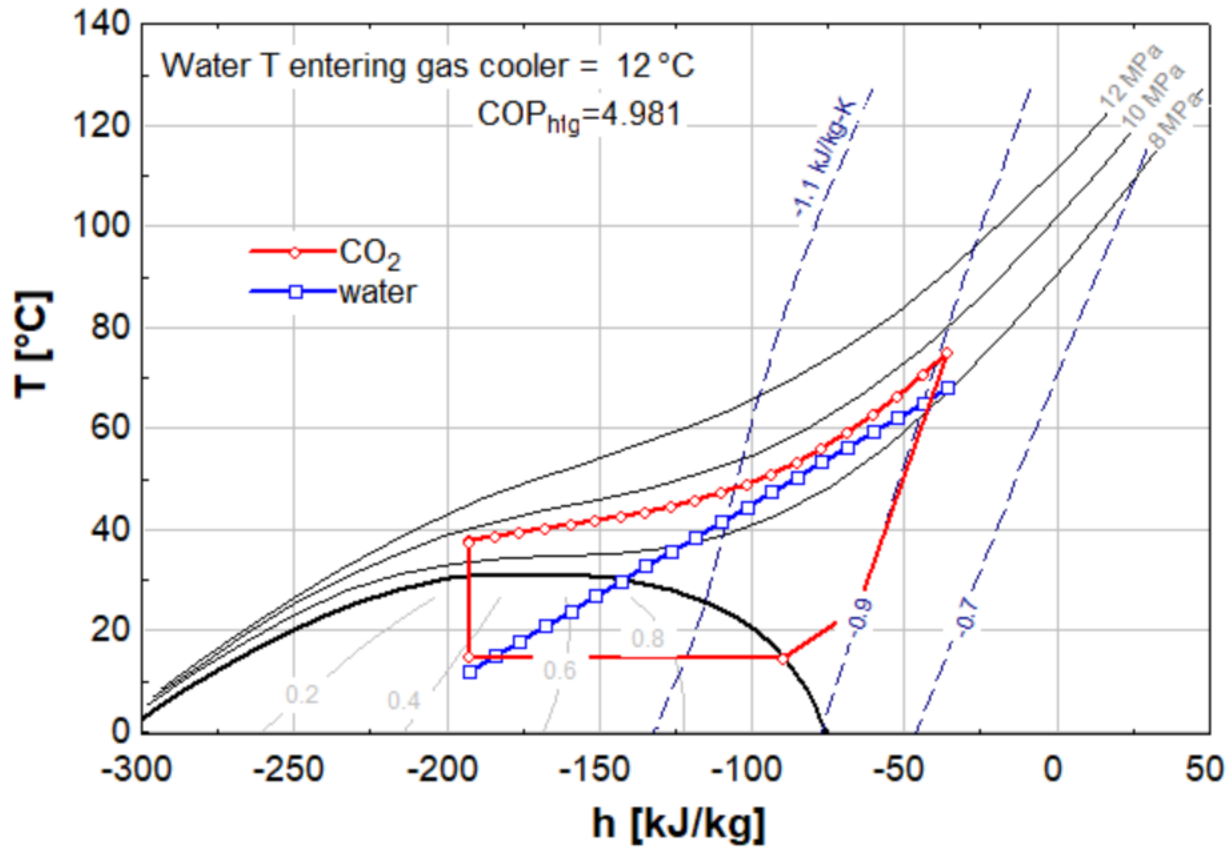
Animation

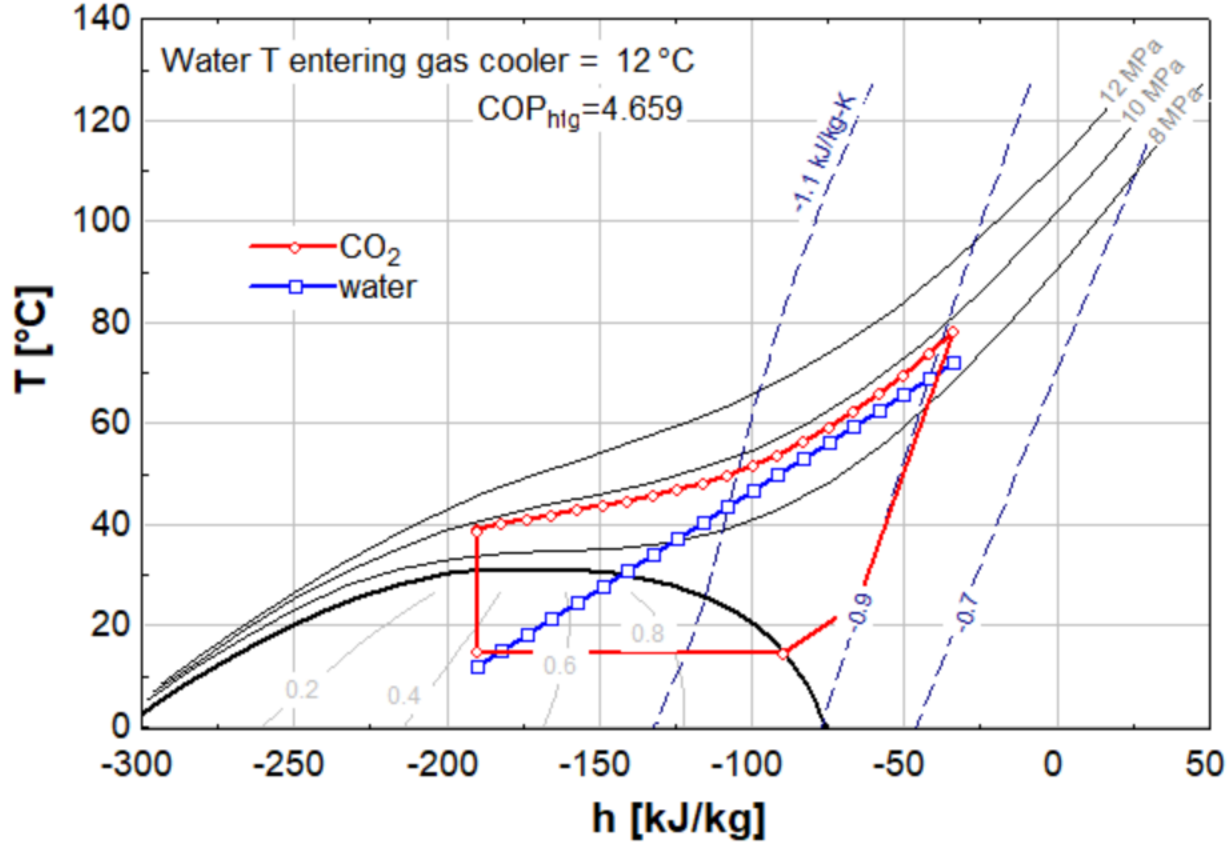
Ambient air temperature = 15°C



Supply water temperature = 68°C

Animation

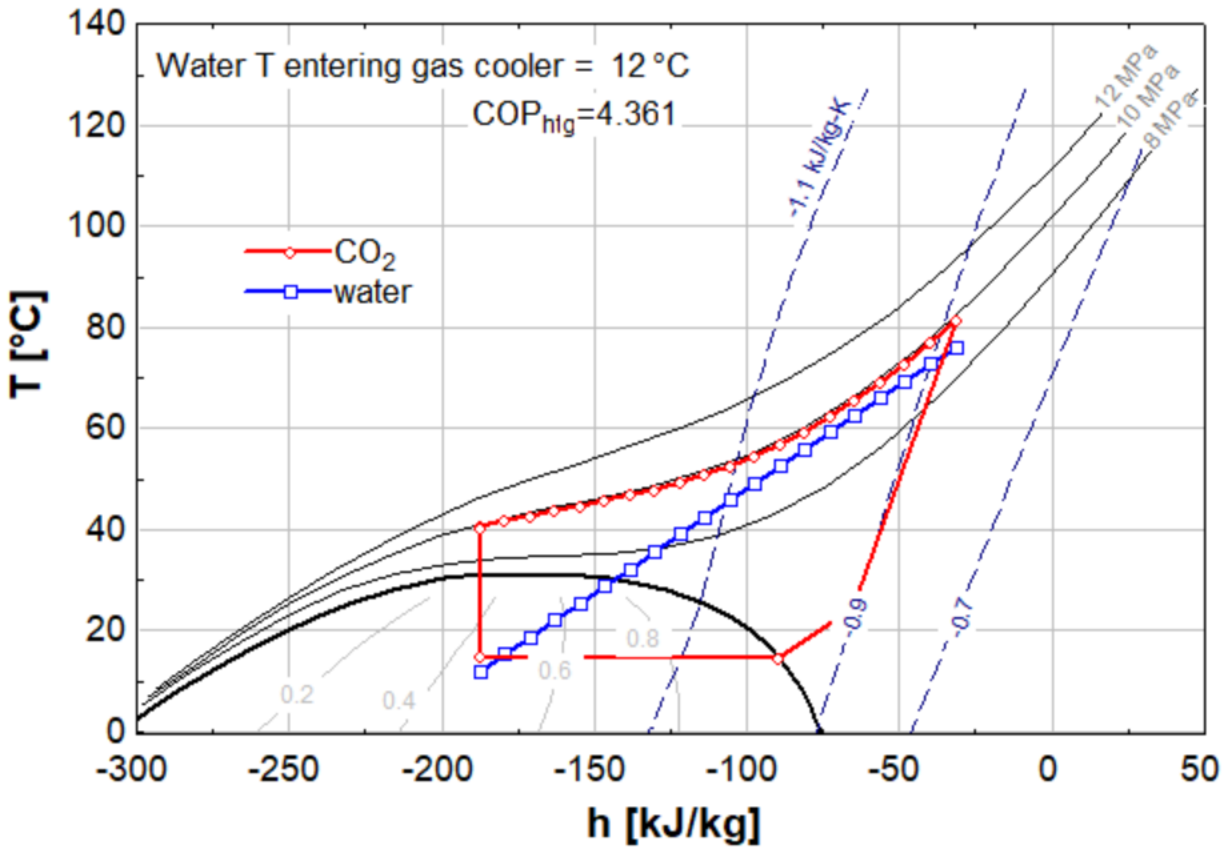
Ambient air temperature = 15°C



Supply water temperature = 72°C

Animation

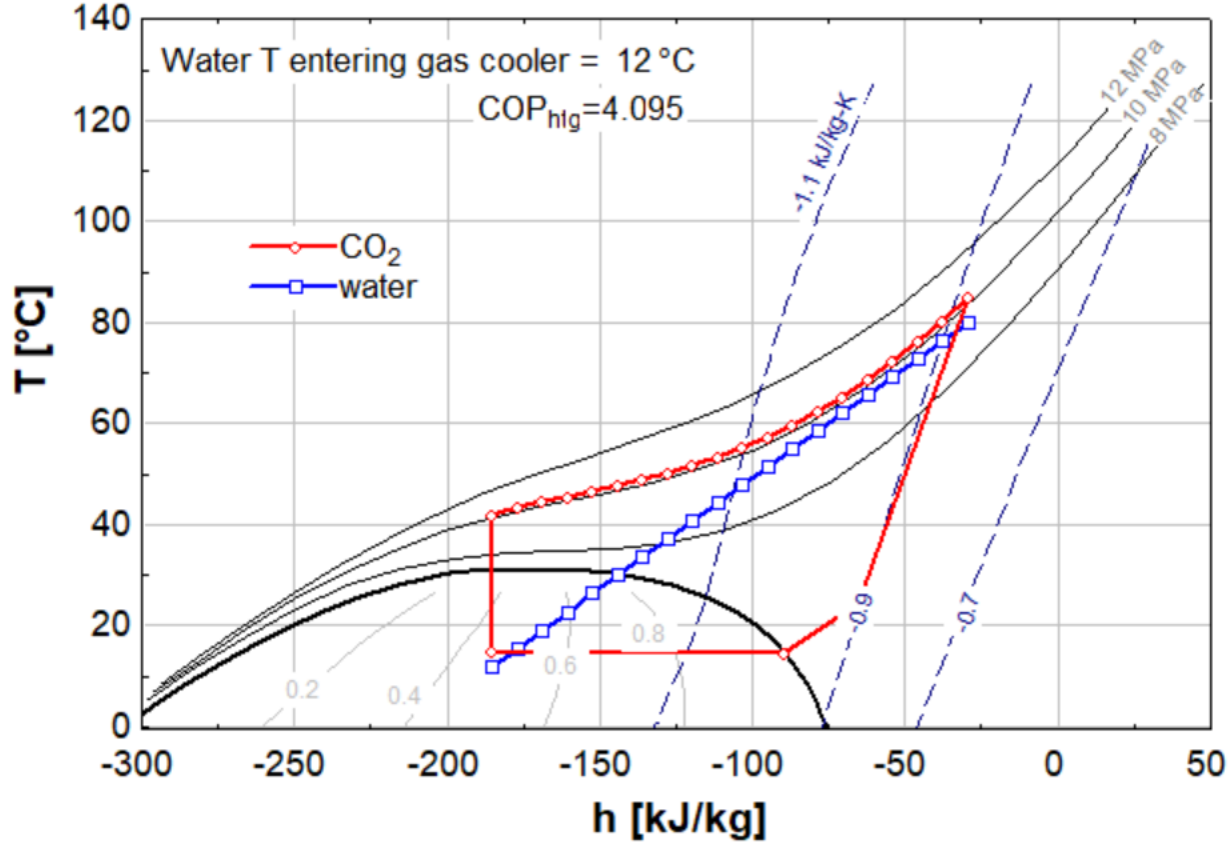
Ambient air temperature = 15°C



Supply water temperature = 76°C

Animation

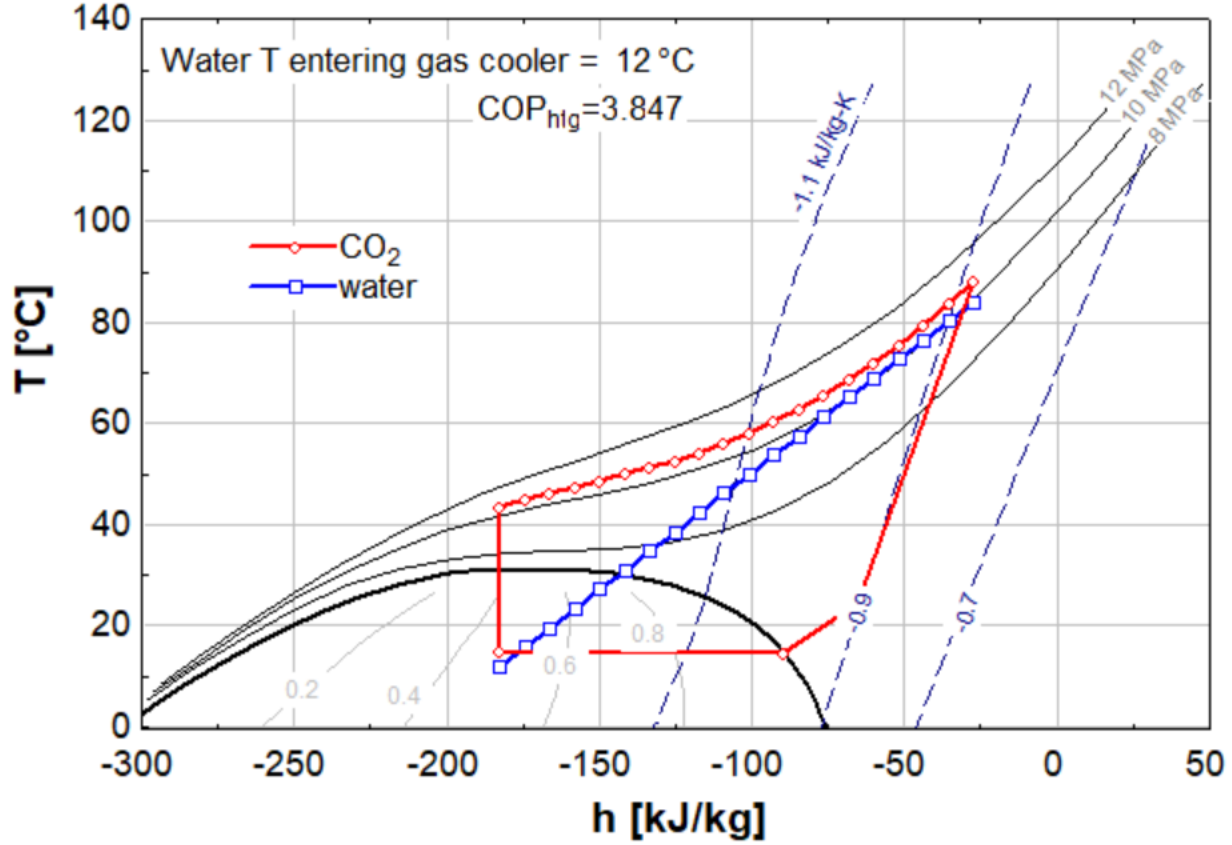
Ambient air temperature = 15°C



Supply water temperature = 80°C

Animation

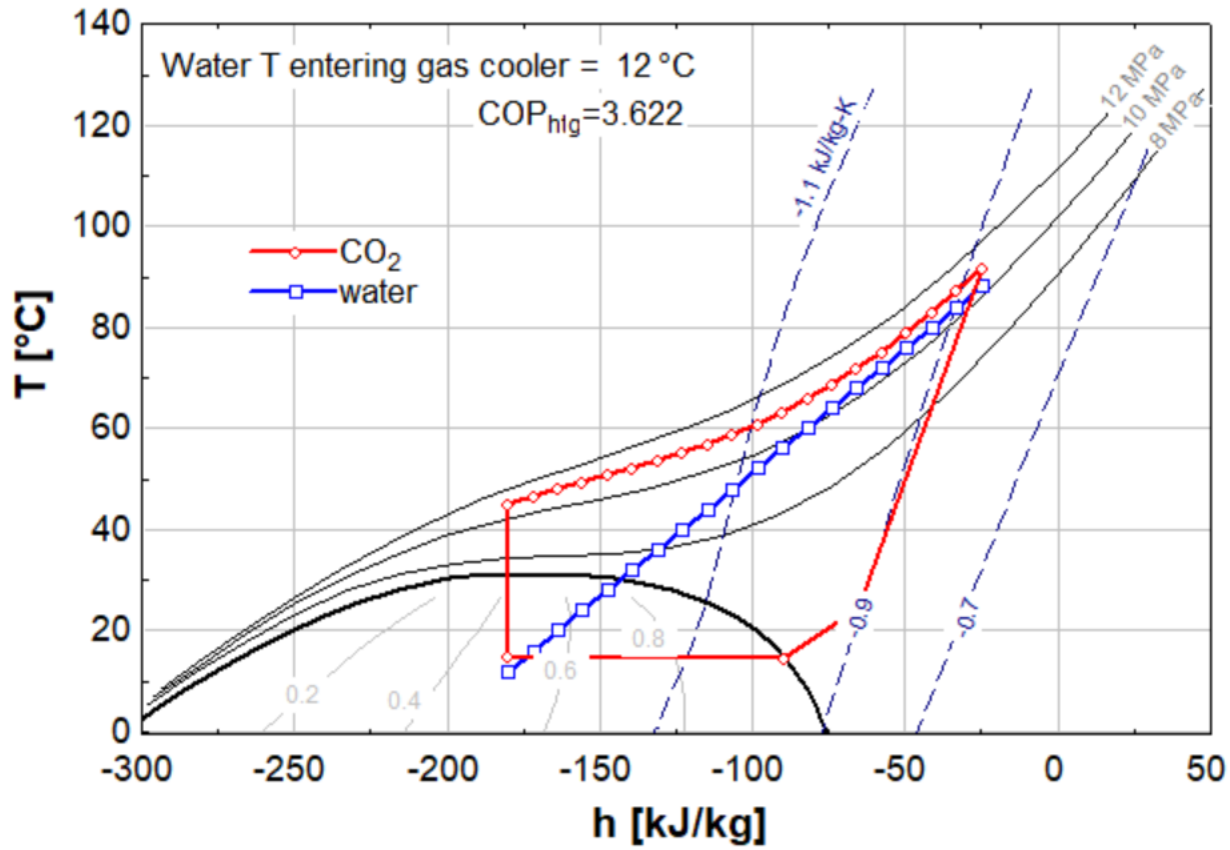
Ambient air temperature = 15°C



Supply water temperature = 84°C

Animation

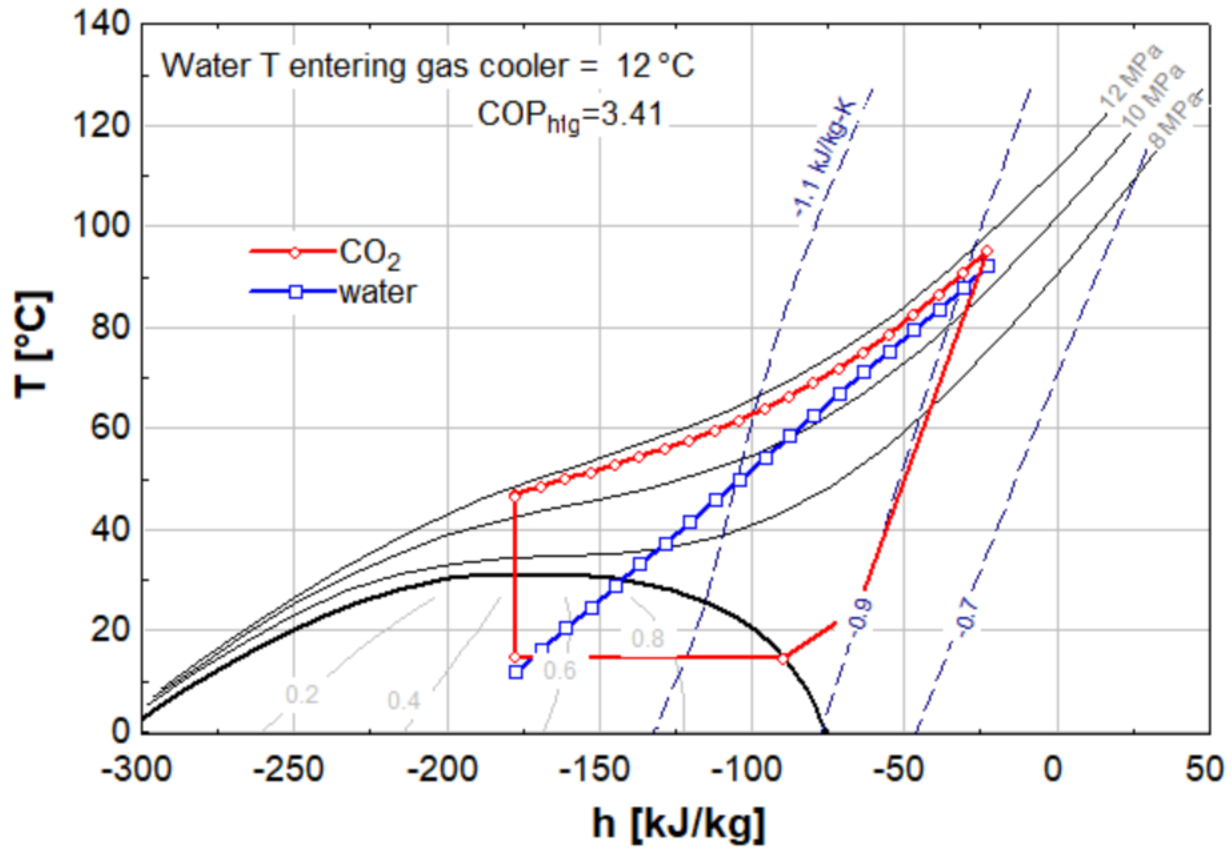
Ambient air temperature = 15°C



Supply water temperature = 88°C

Animation

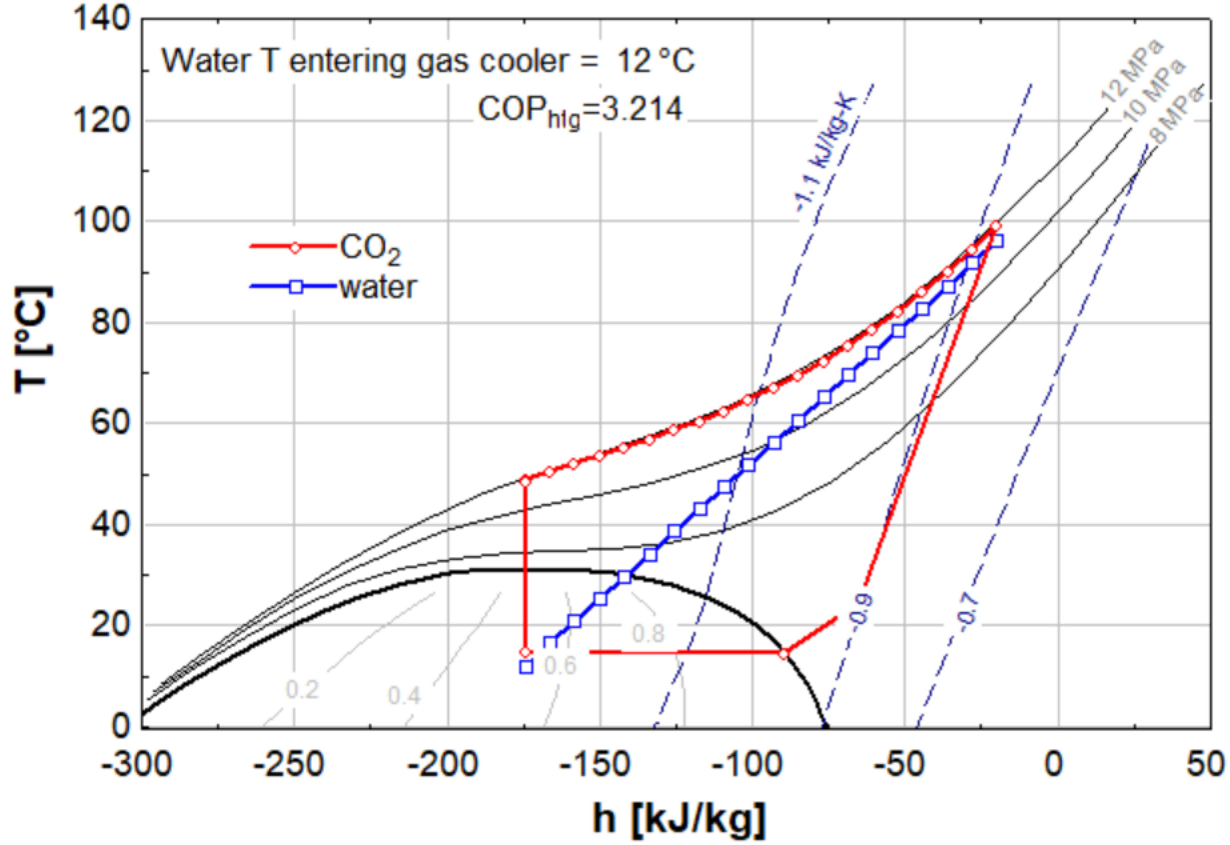
Ambient air temperature = 15°C



Supply water temperature = 92°C

Animation

Ambient air temperature = 15°C



Supply water temperature = 96°C

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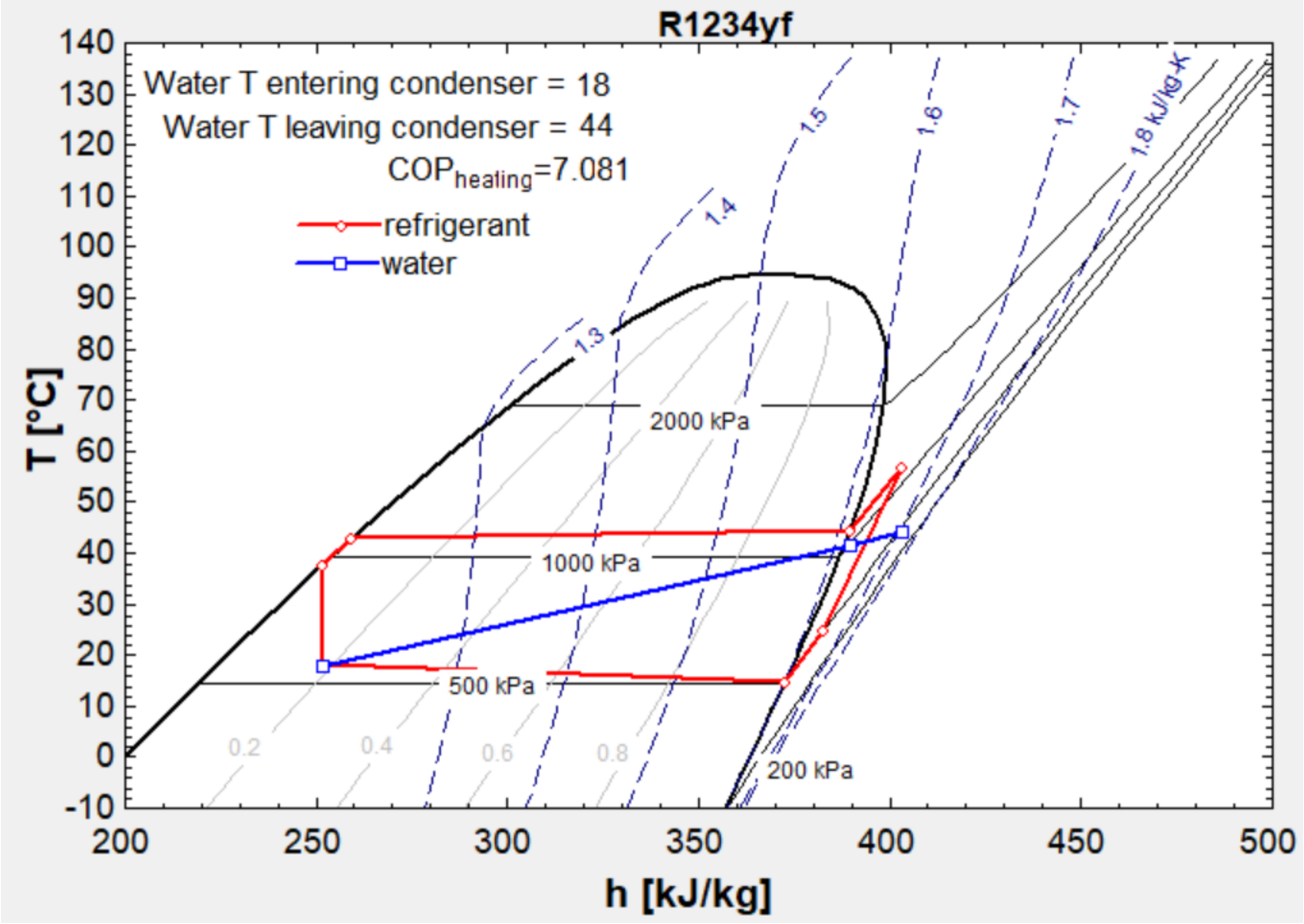
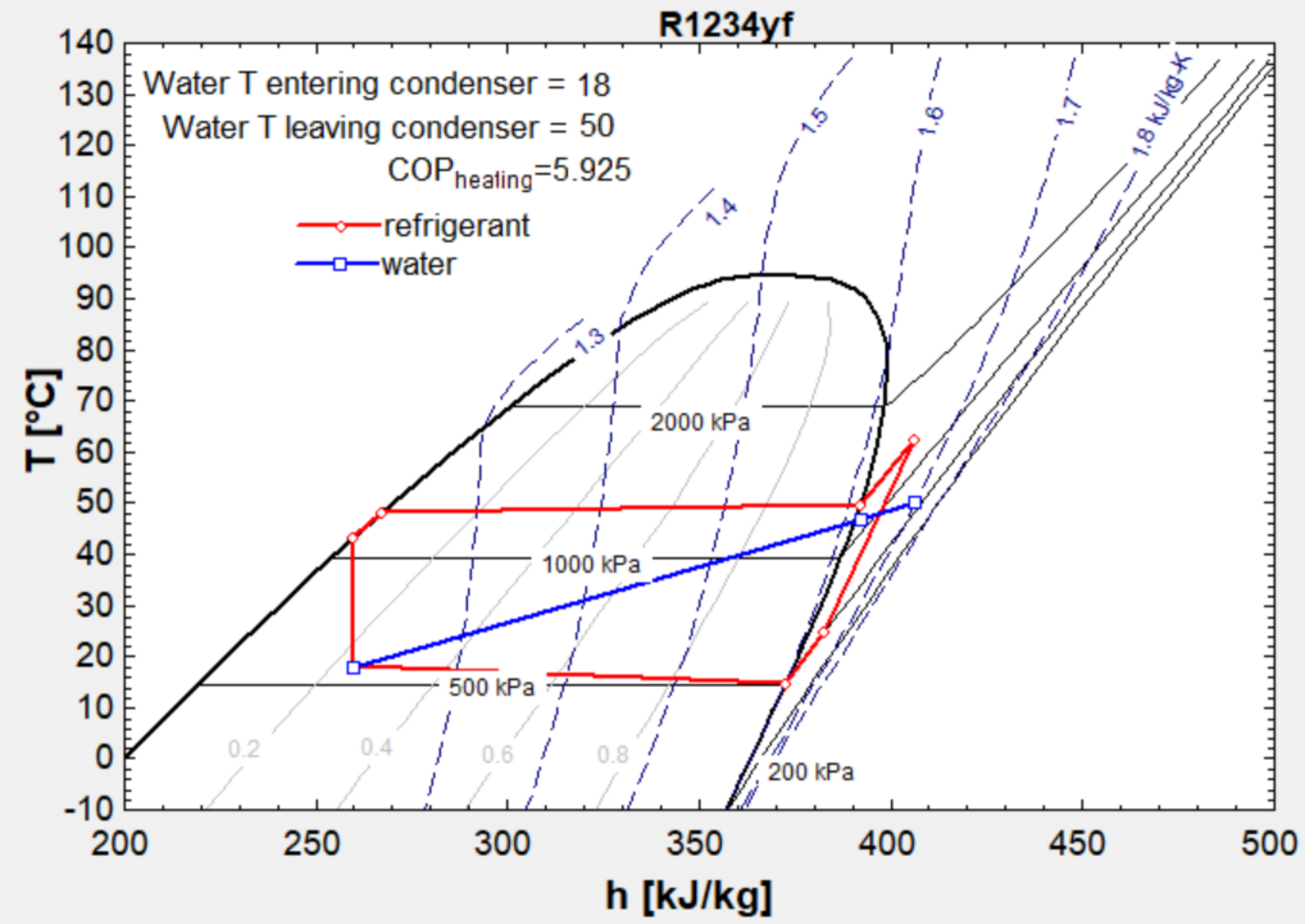
Animation

Evaporation temperature = 15°C



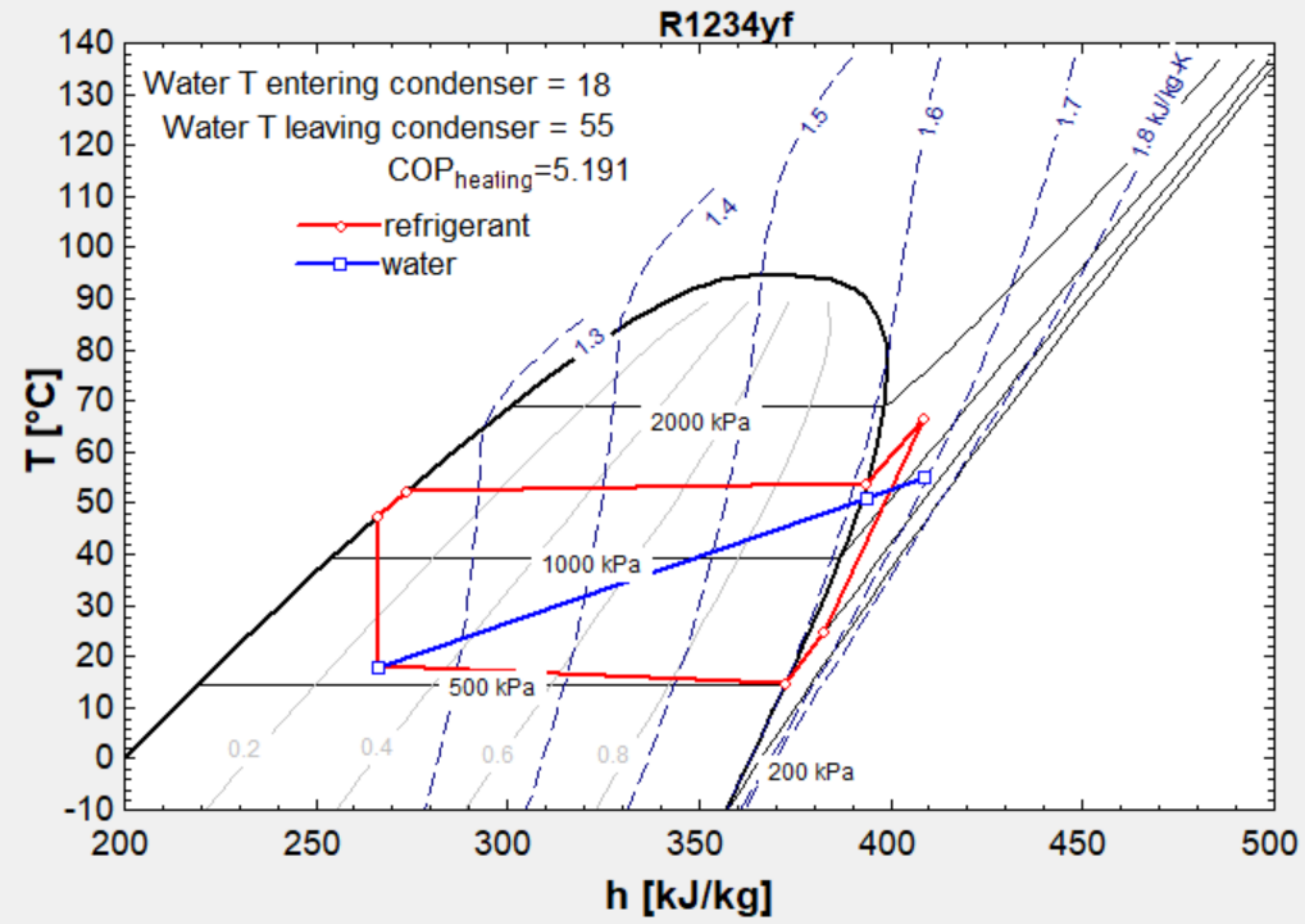
Animation

Evaporation temperature = 15°C



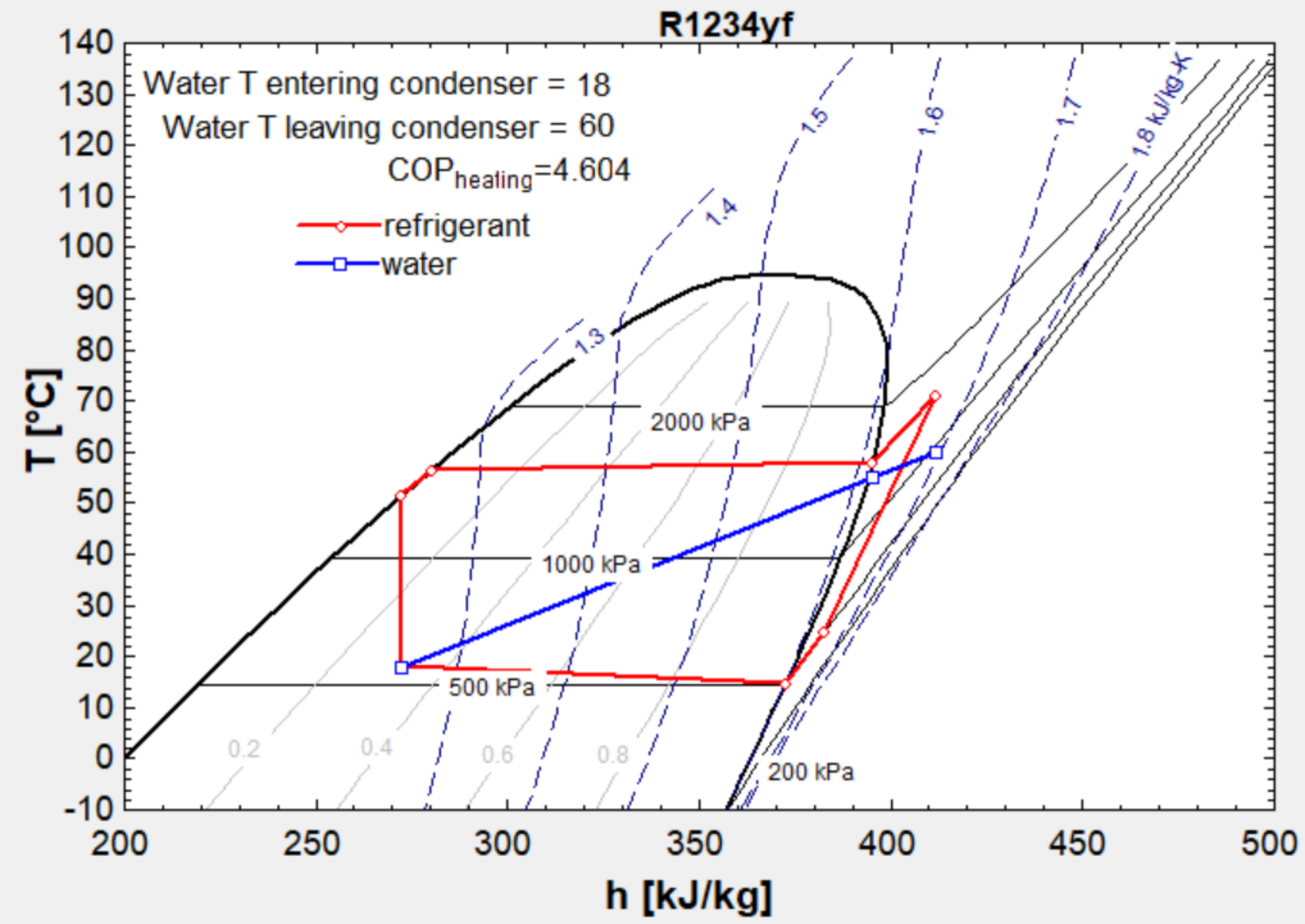
Animation

Evaporation temperature = 15°C



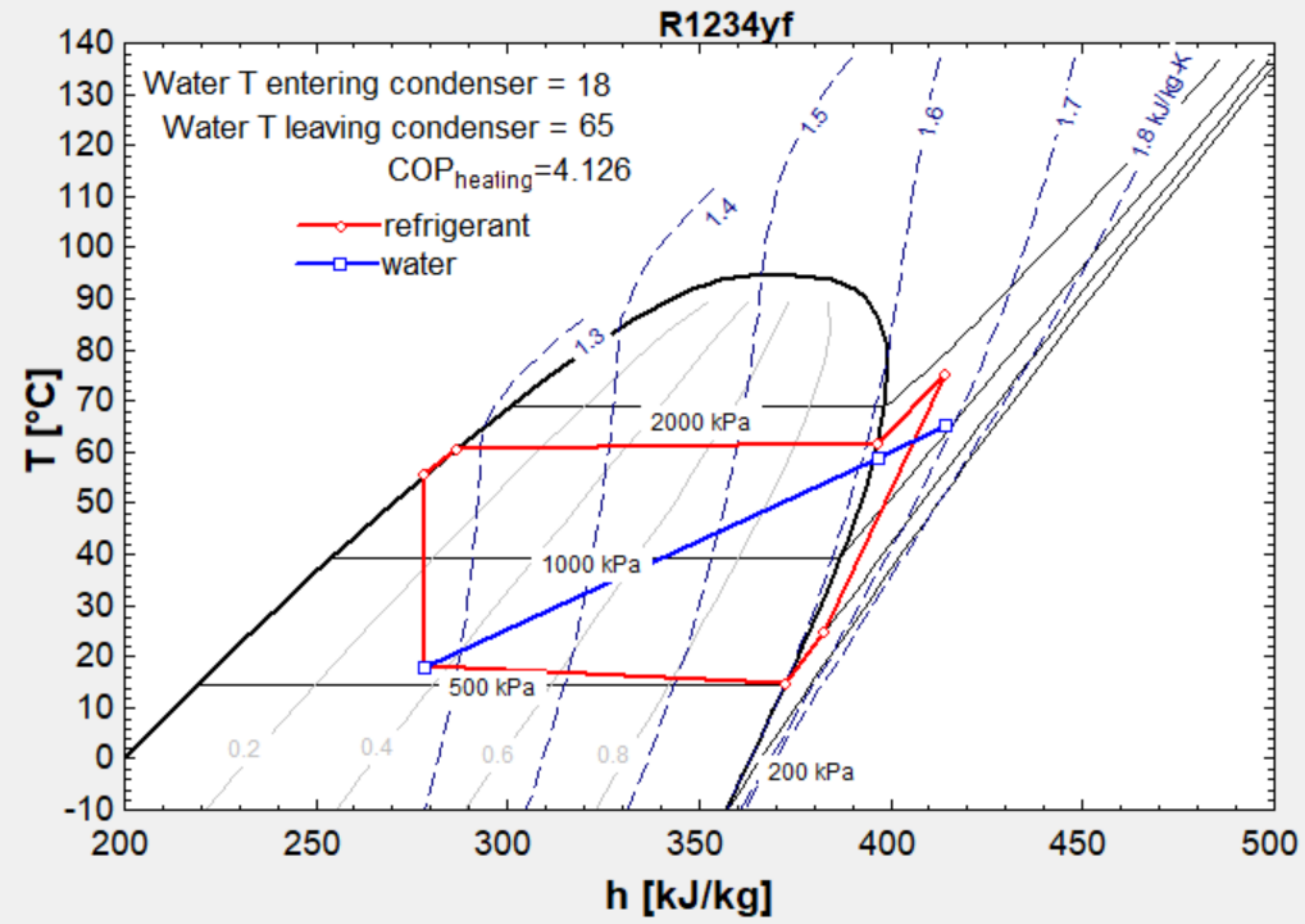
Animation

Evaporation temperature = 15°C



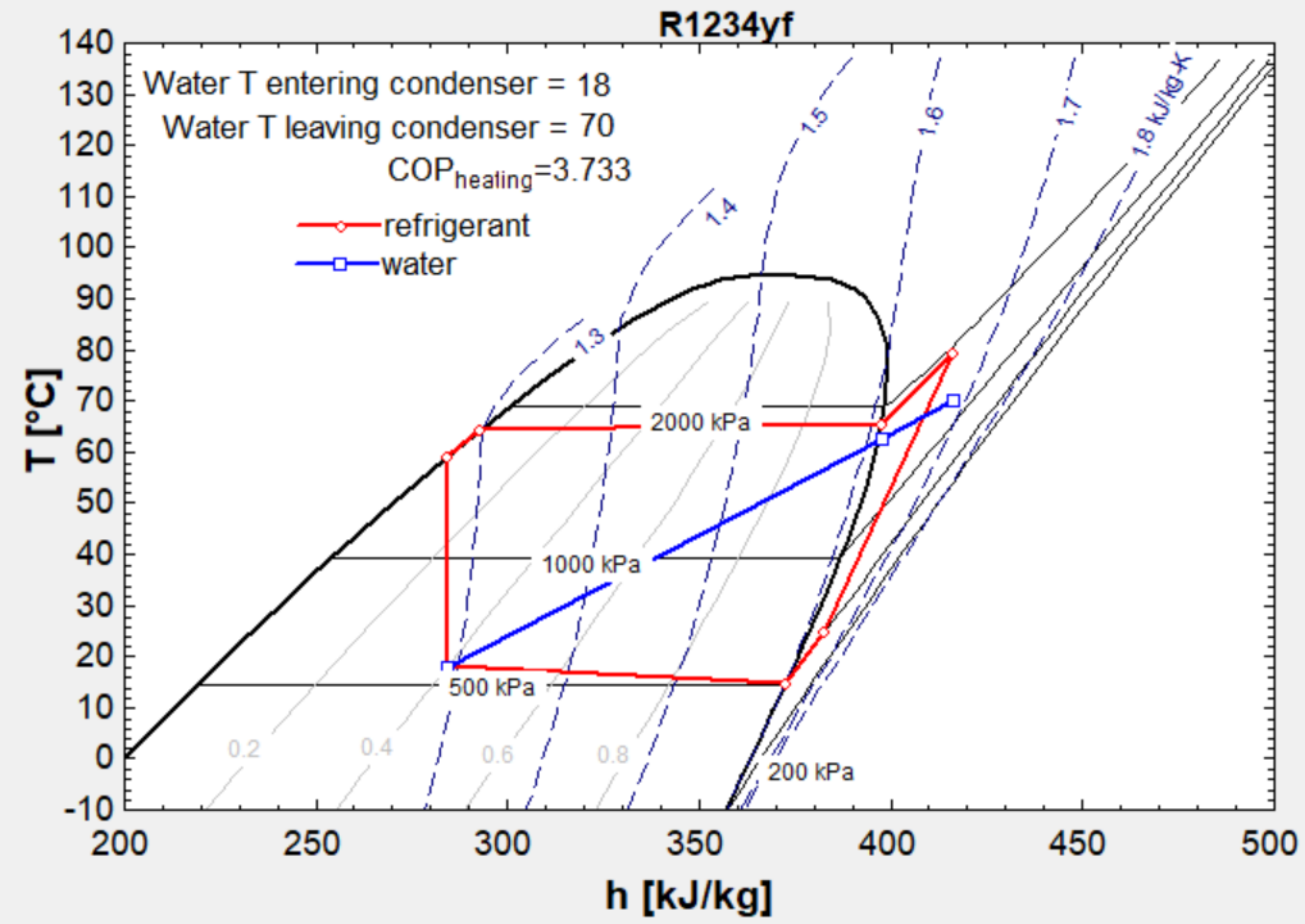
Animation

Evaporation temperature = 15°C



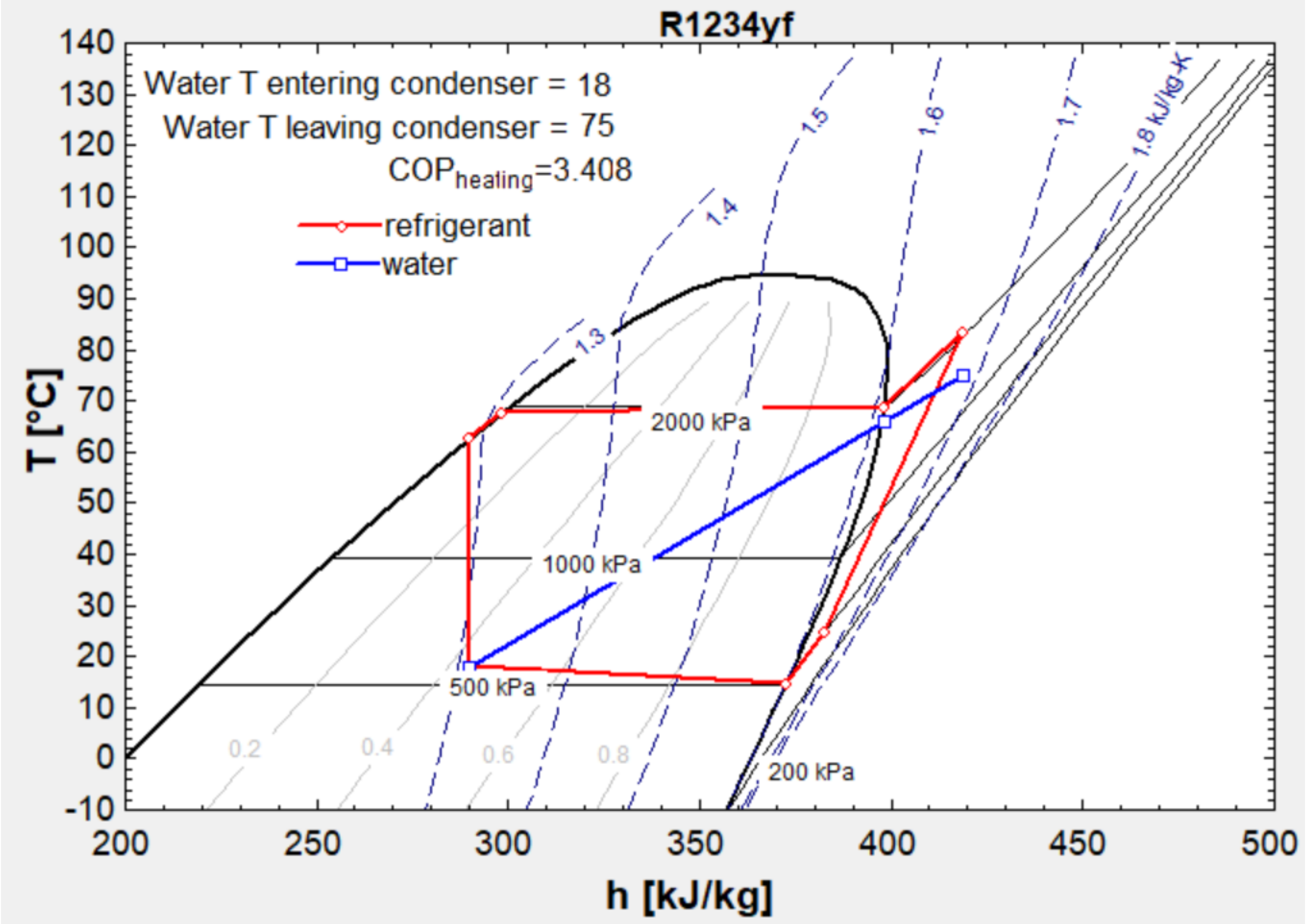
Animation

Evaporation temperature = 15°C



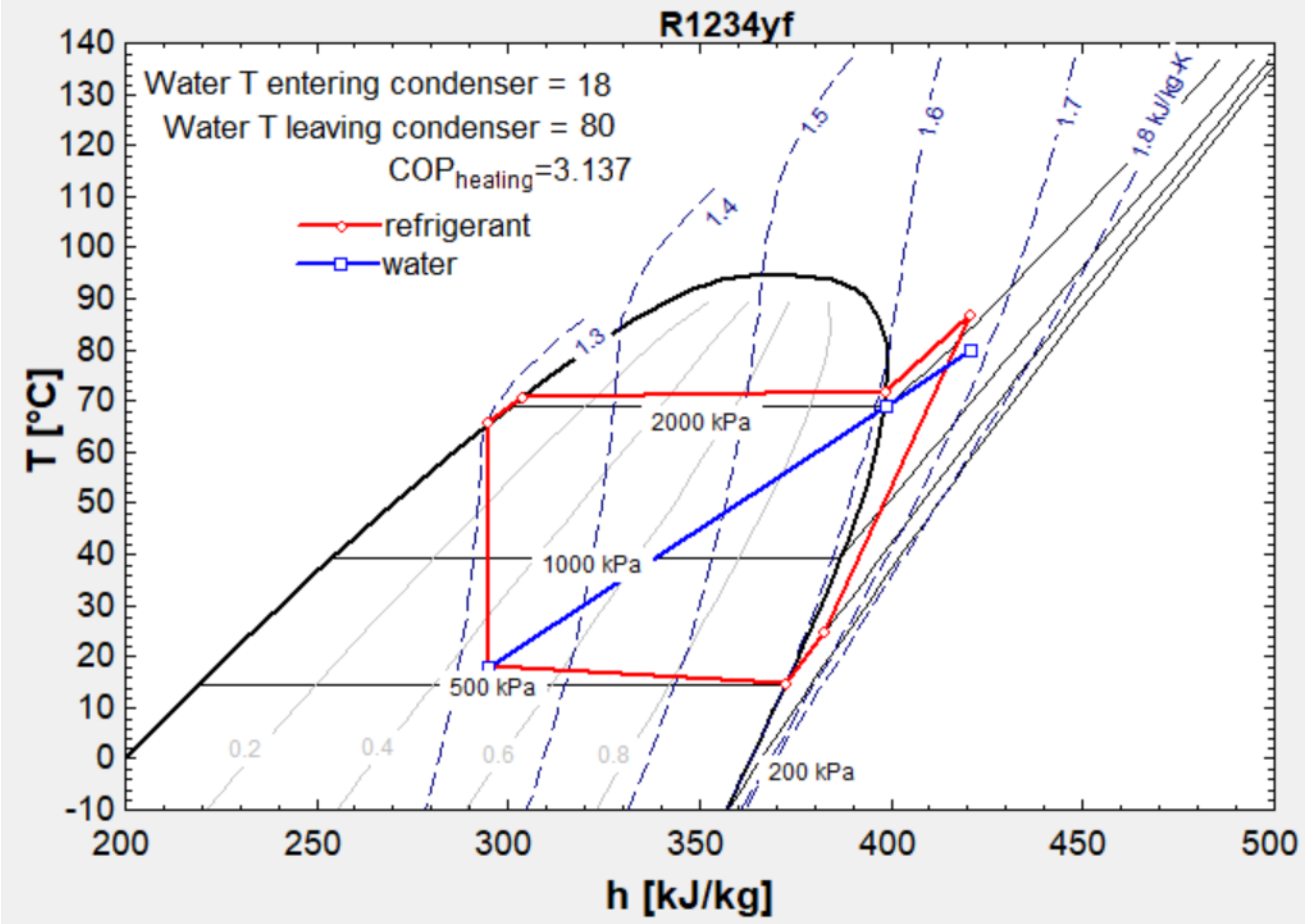
Animation

Evaporation temperature = 15°C



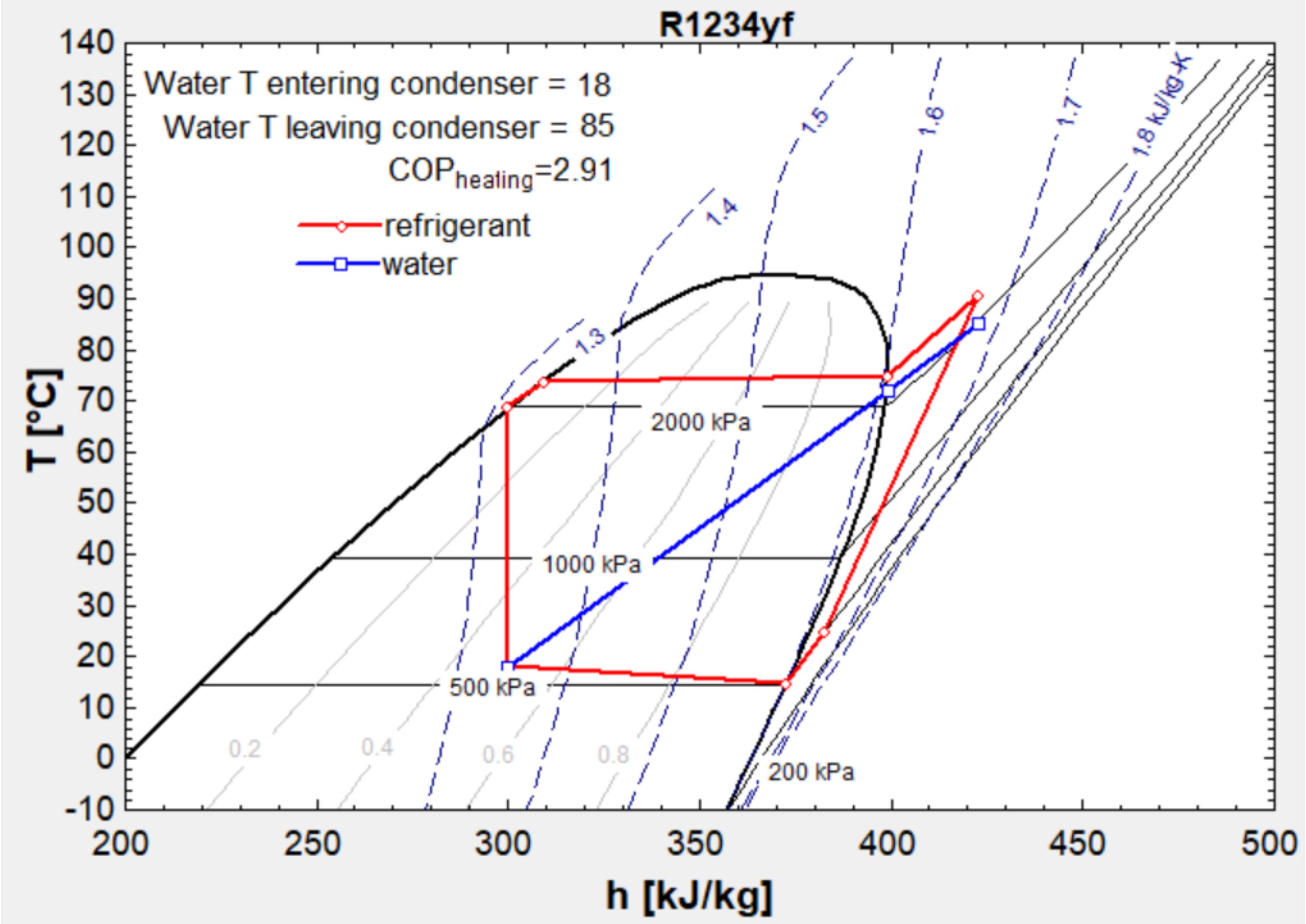
Animation

Evaporation temperature = 15°C



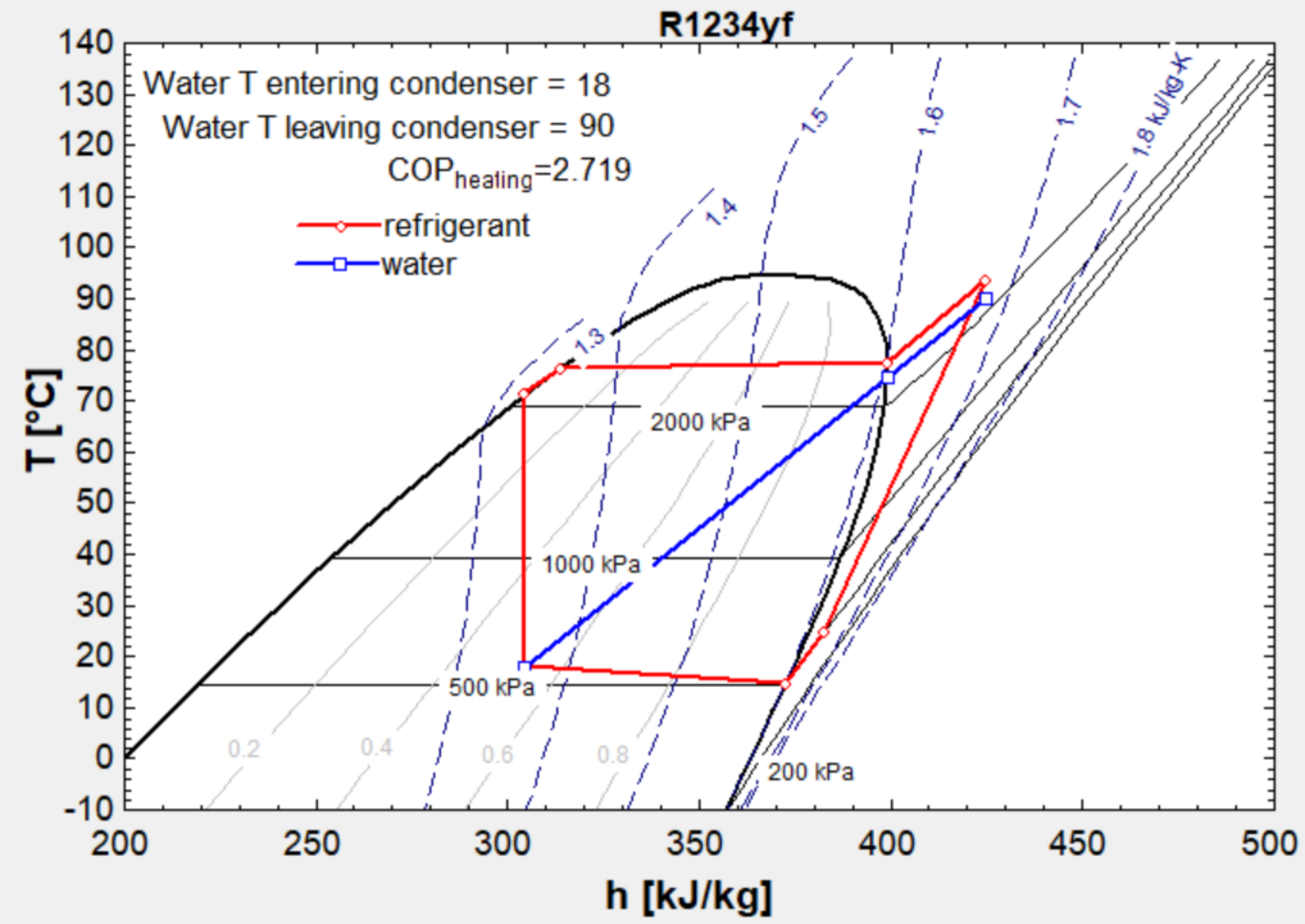
Animation

Evaporation temperature = 15°C



Animation

Evaporation temperature = 15°C



Animation

Evaporation temperature = 15°C