Chiller Control

Friday Seminar 2022-03-04

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Chiller control

Cooperation with Carrier

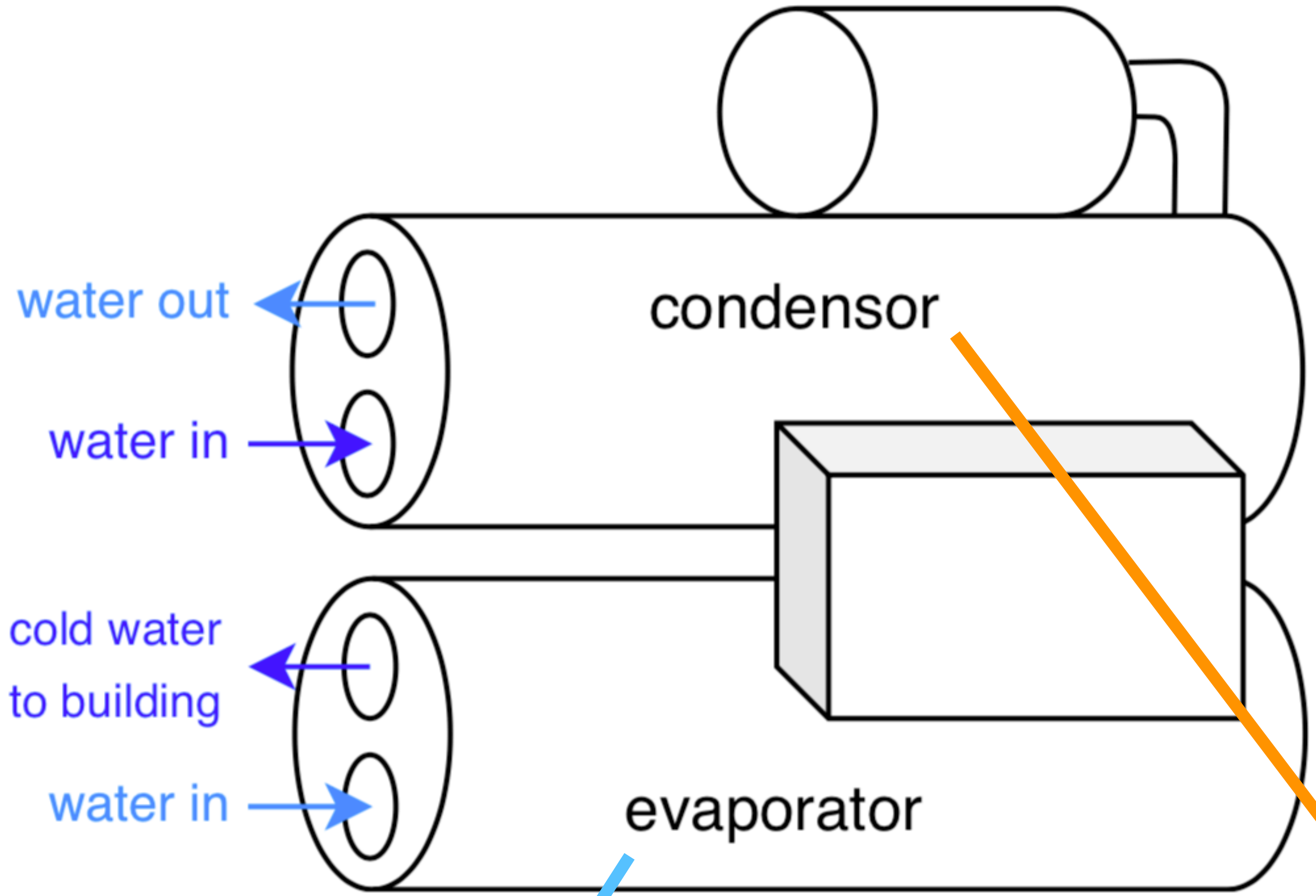
Willis Carrier (1876–1950)

Invented modern air conditioning in 1902.

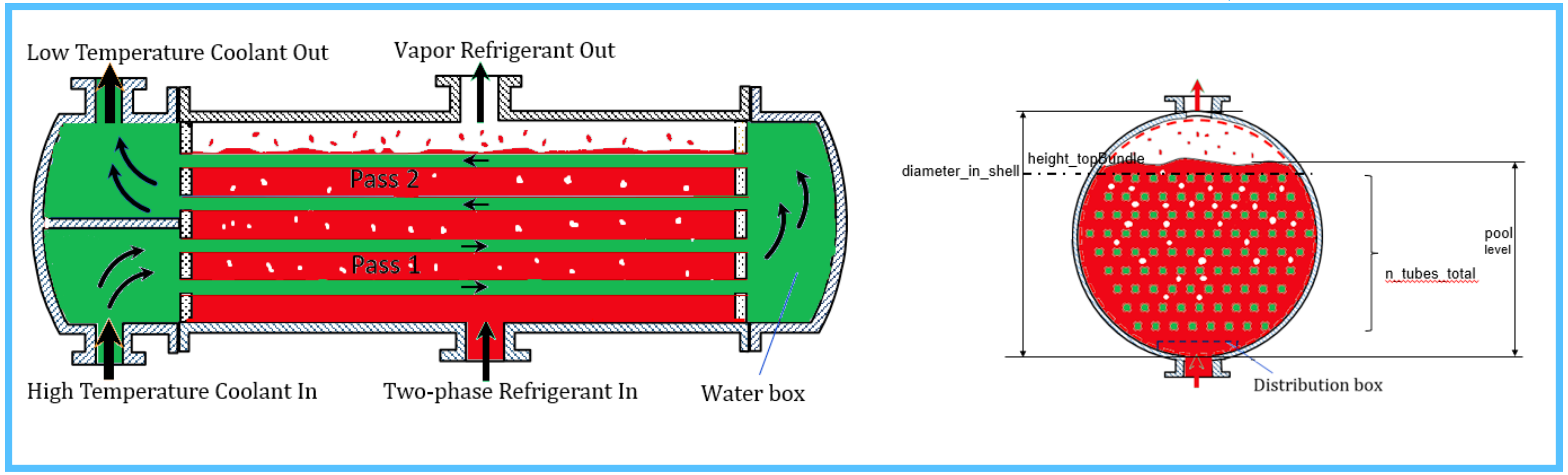
Founded the company in 1915, with six other engineers.

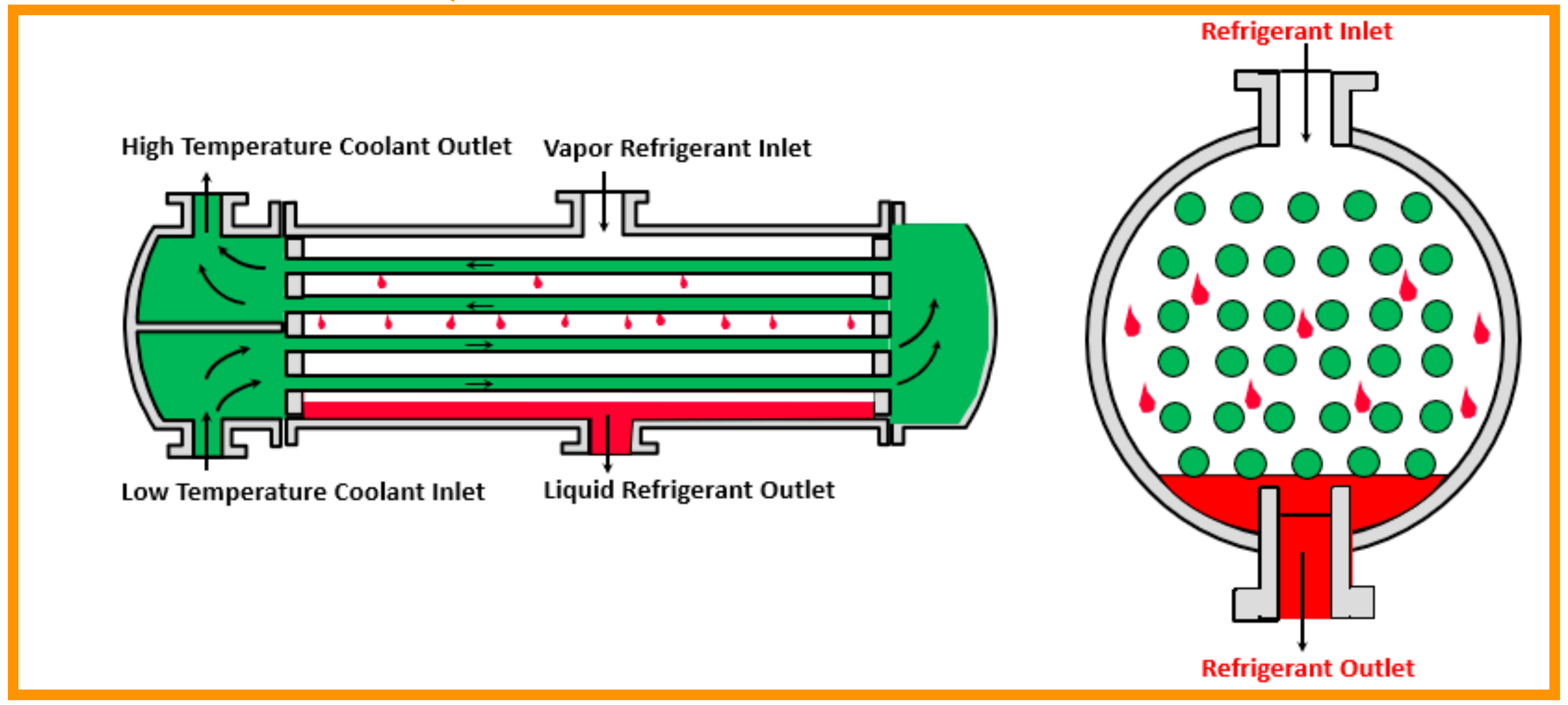
Thanks to
Bryan Eisenhower, Magda Atlevi and Clas Jacobson @ Carrier

What is a chiller?



Goal: Cool down water to be used for cooling of buildings etc.





Energy consumption

”**Energy consumption for space cooling has more than tripled since 1990**, with significant implications for electricity grids, especially during peak demand periods and extreme heat events.”
— *International Energy Agency, IEA*

Space cooling consumes about 1885 TWh per year, which is **about 8% of the world’s total electricity consumption.** [1,2]

Question: Can we improve the efficiency by using machine learning methods?

[1] https://www.iea.org/reports/cooling
[2] https://www.statista.com/statistics/280704/world-power-consumption/

Some thermodynamics

Definition: **Enthalpy**

= thermodynamical potential

$H = U + pV$

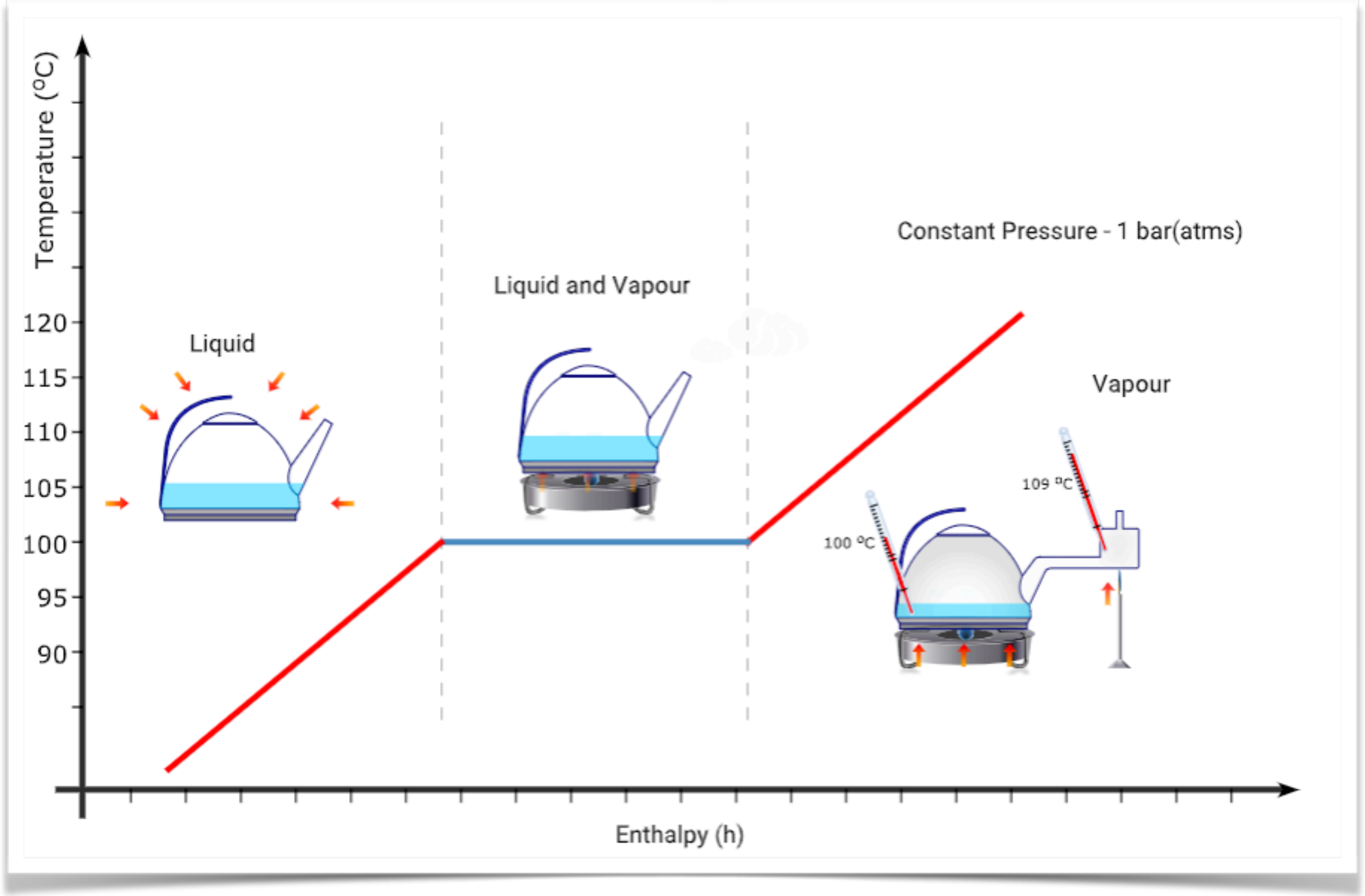
- U: inner energy
- p: pressure
- V: volume

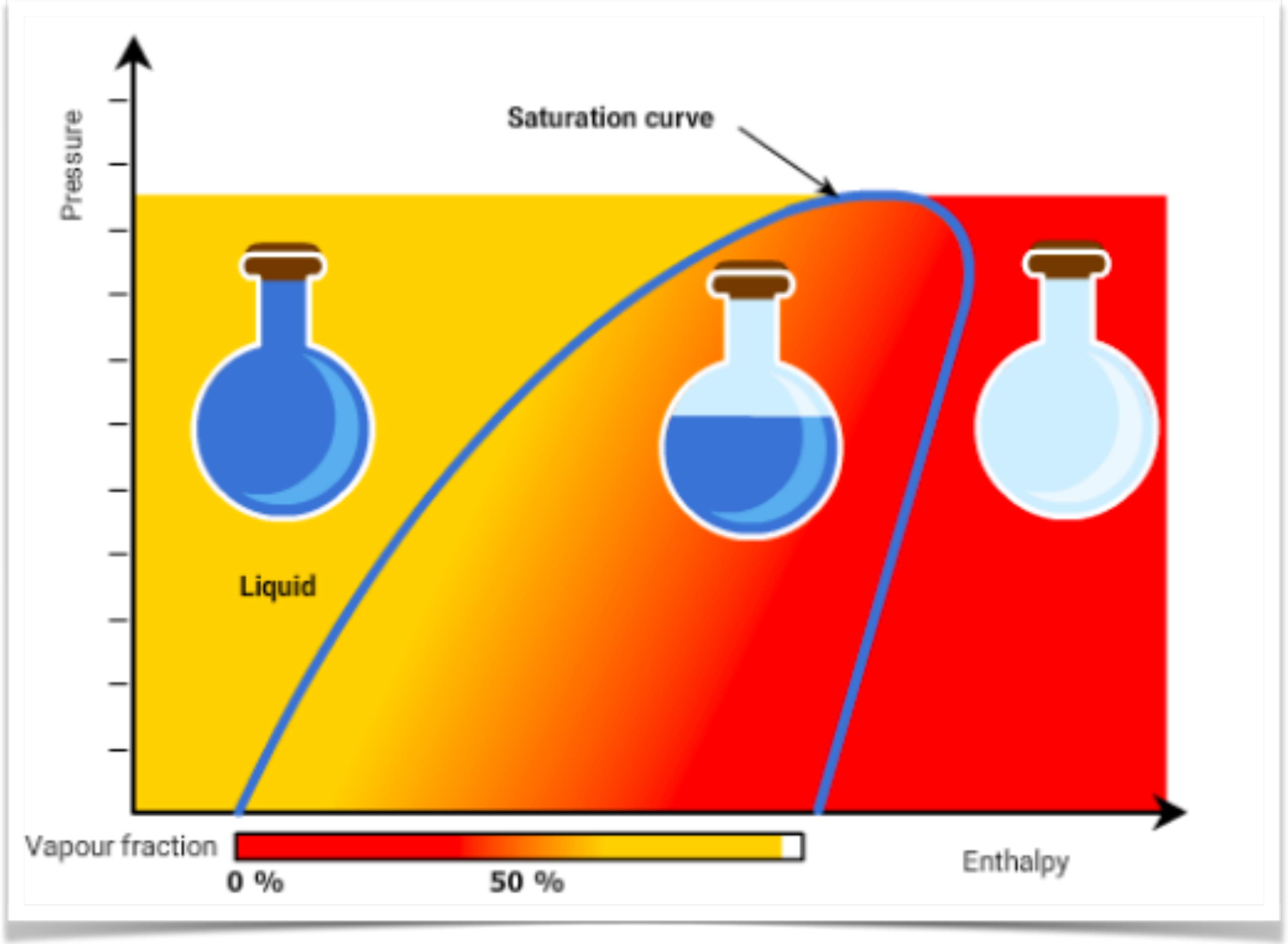
At constant pressure:

$$dH = dq \overset{*}{=} C_p dT$$

- dq: heat
- C_p: constant
- T: temperature

* if there is no phase change





p-h diagram

Refrigerant cycle

Definition: **Enthalpy**

= thermodynamical potential

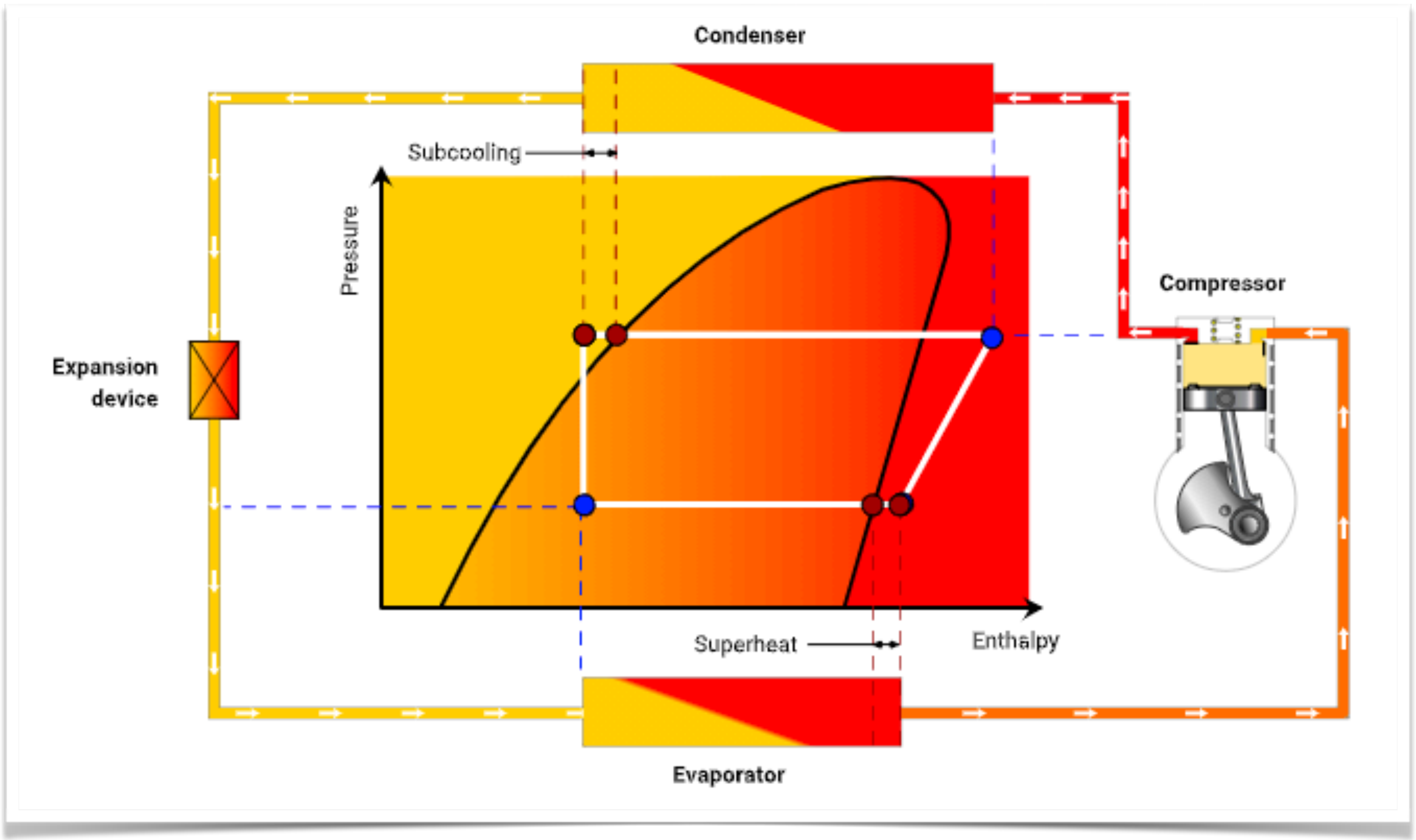
$H = U + pV$ — inner energy (U), pressure (p), volume (V)

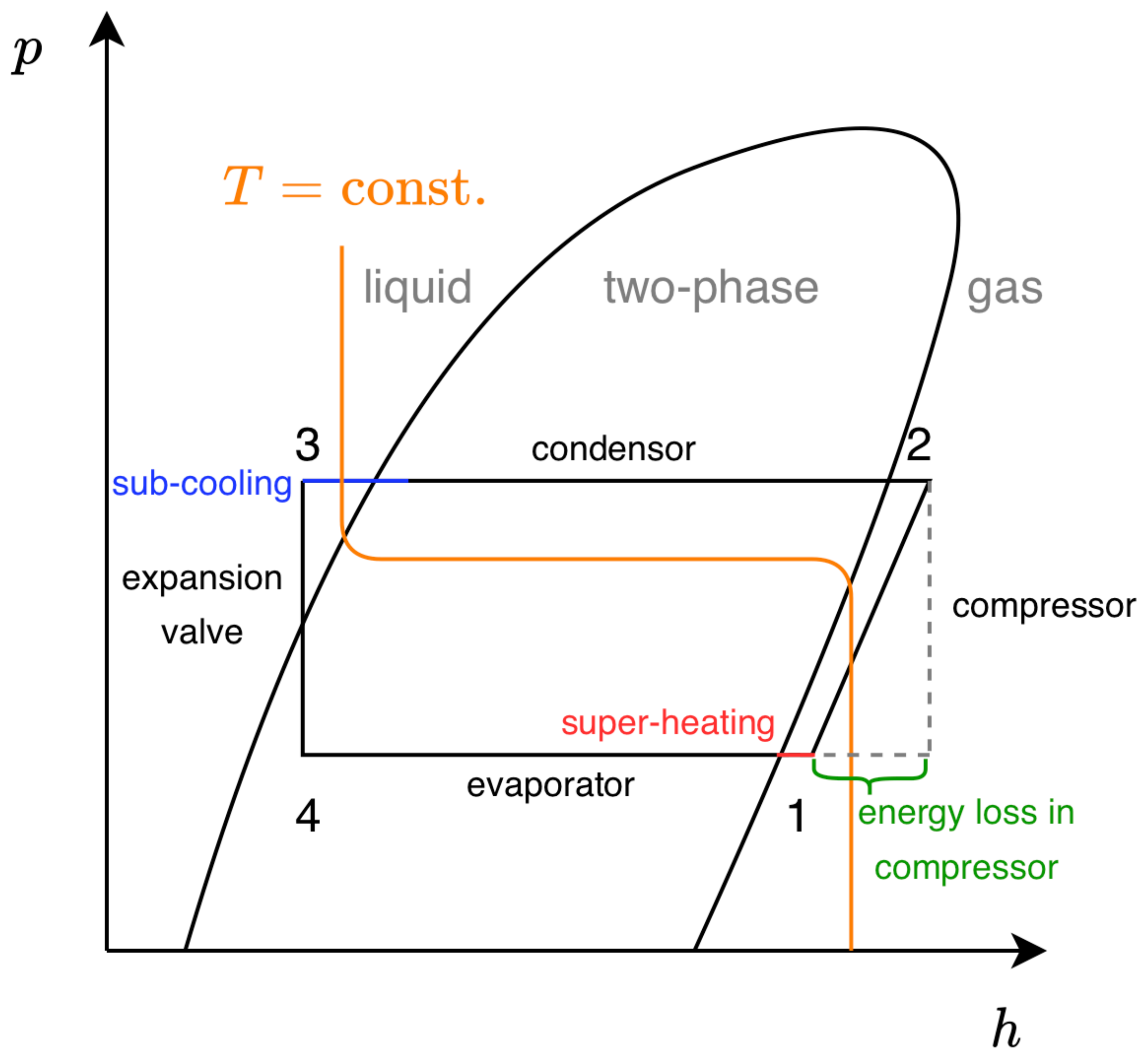
At constant pressure:

$$dH = dq \overset{*}{=} C_p dT$$

heat (q), constant (C_p), temperature (T)

* if there is no phase change

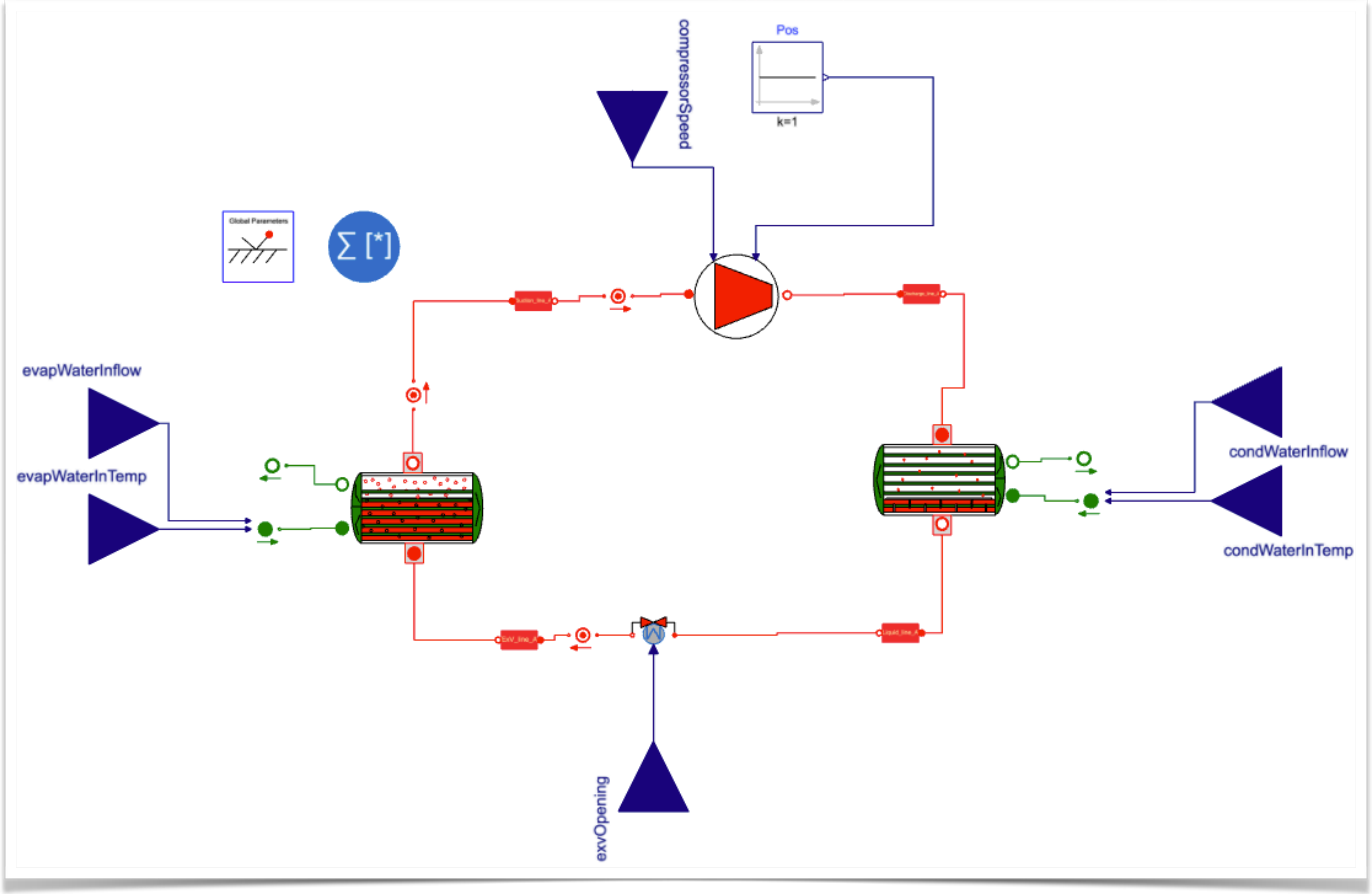




Simulation model

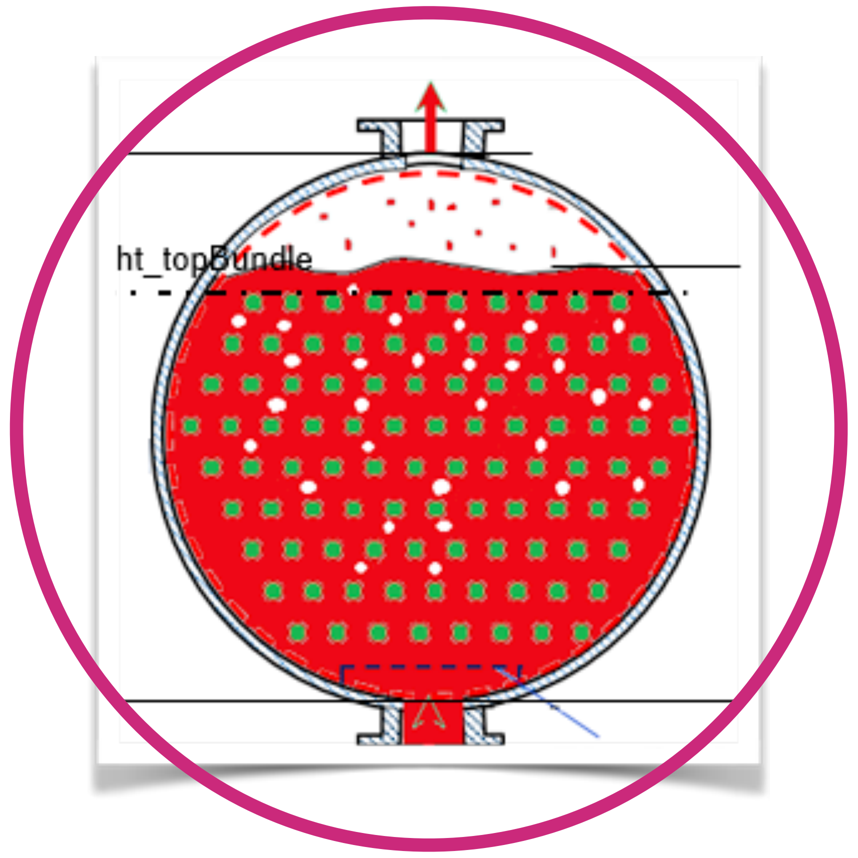
Complex nonlinear model, with 161 states.

Simulations can be done in Modelon Impact or in Python with an FMU.

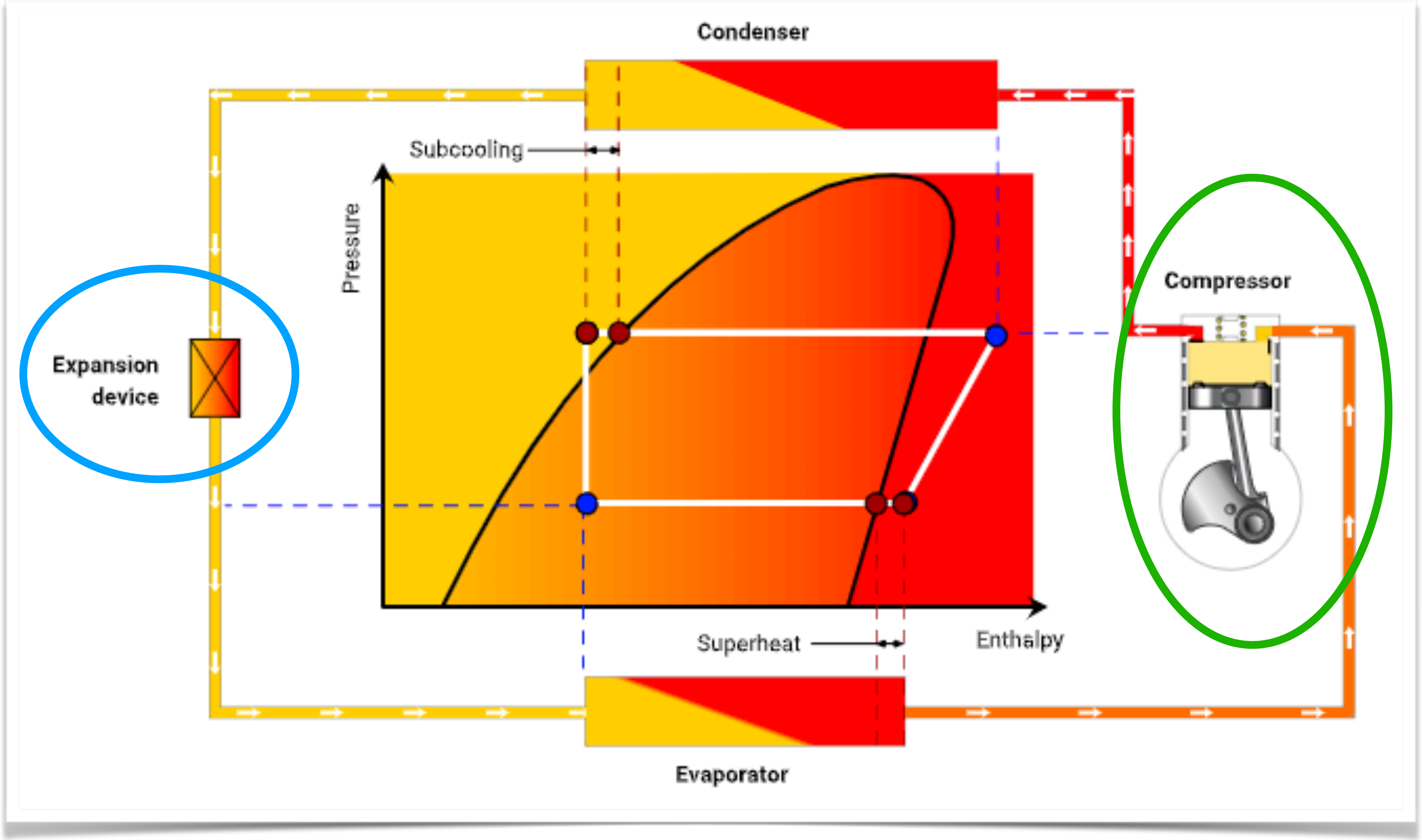


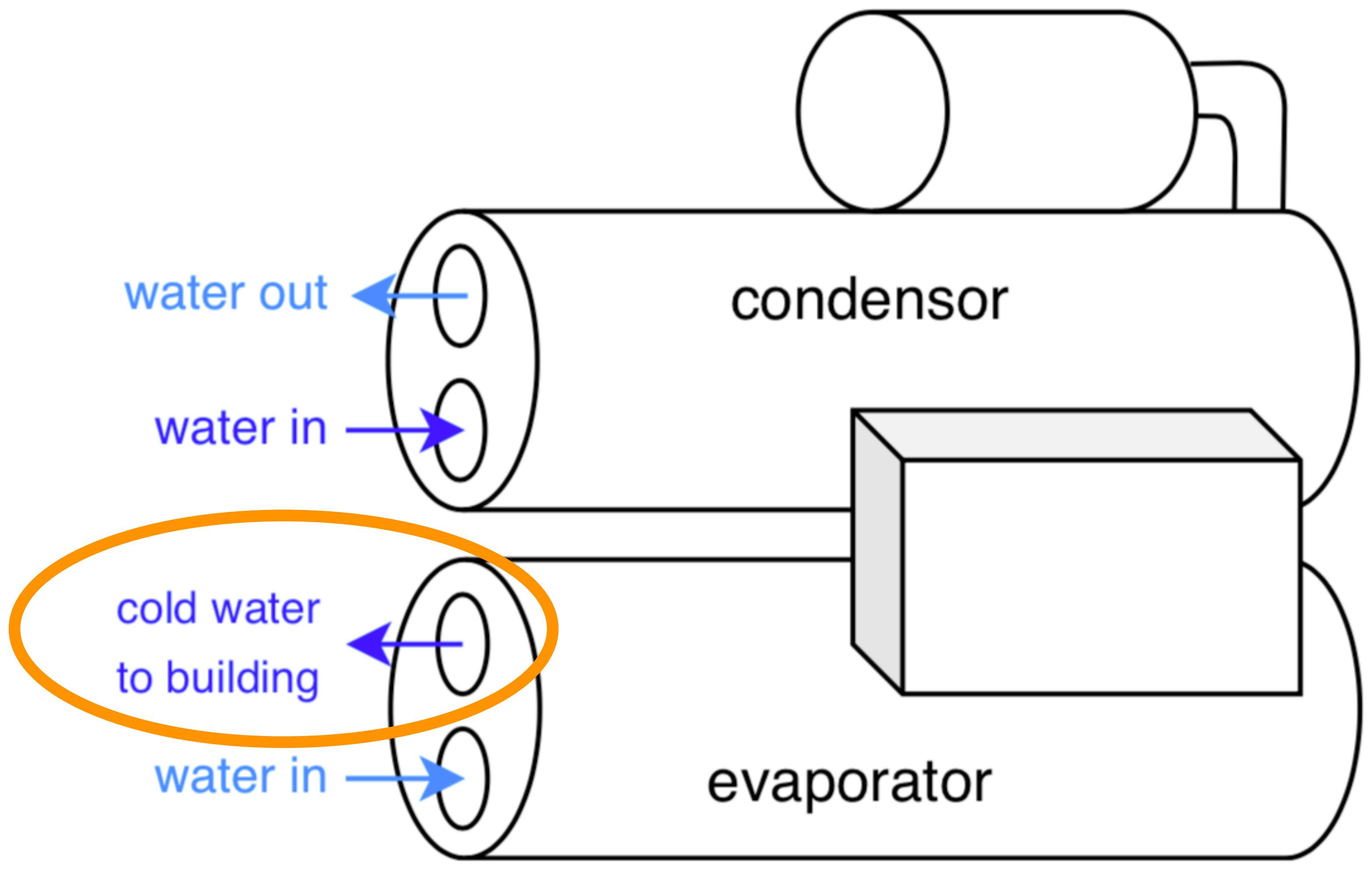
Control problem

Actuators:
- Compressor speed
- Expansion valve opening



Objectives and constraints:
- **Achieve requested out-water temp**
- **Maximize efficiency** (COP)
  - Correlated to refrigerant level in evaporator
- Satisfy constraints such as
  - Pressure limits in compressor
  - Actuator limitations





Controller

System inputs:
- Compressor speed
- Expansion valve opening

System outputs:
- Evaporator LWT
- Evaporator level

Controller structure:

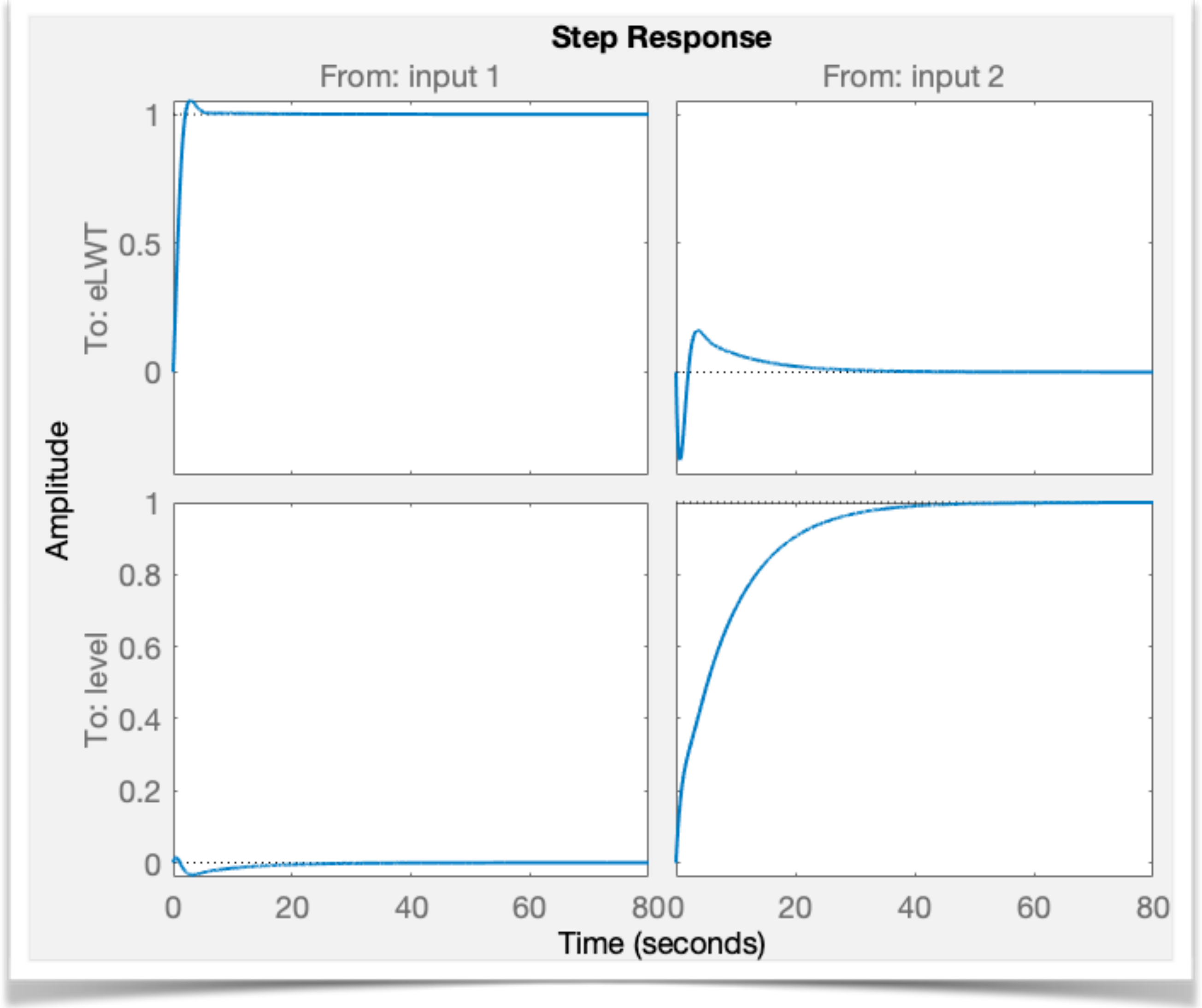
$$C(s) = G^{-1}(0)\begin{bmatrix} C_1(s) & 0 \\ 0 & C_2(s) \end{bmatrix}$$

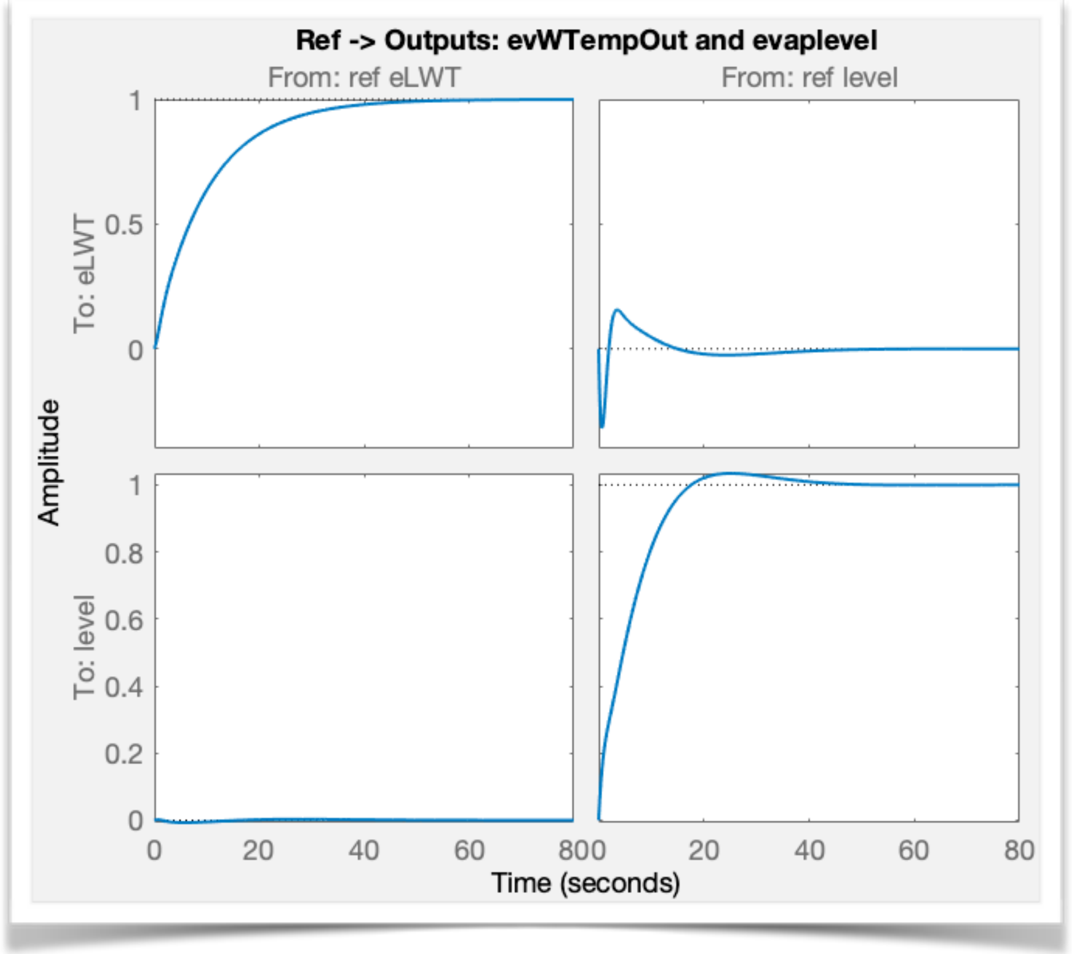
with PI-controllers $C_1(s)$ and $C_2(s)$,
where $G(s)$ is a linearization of the system

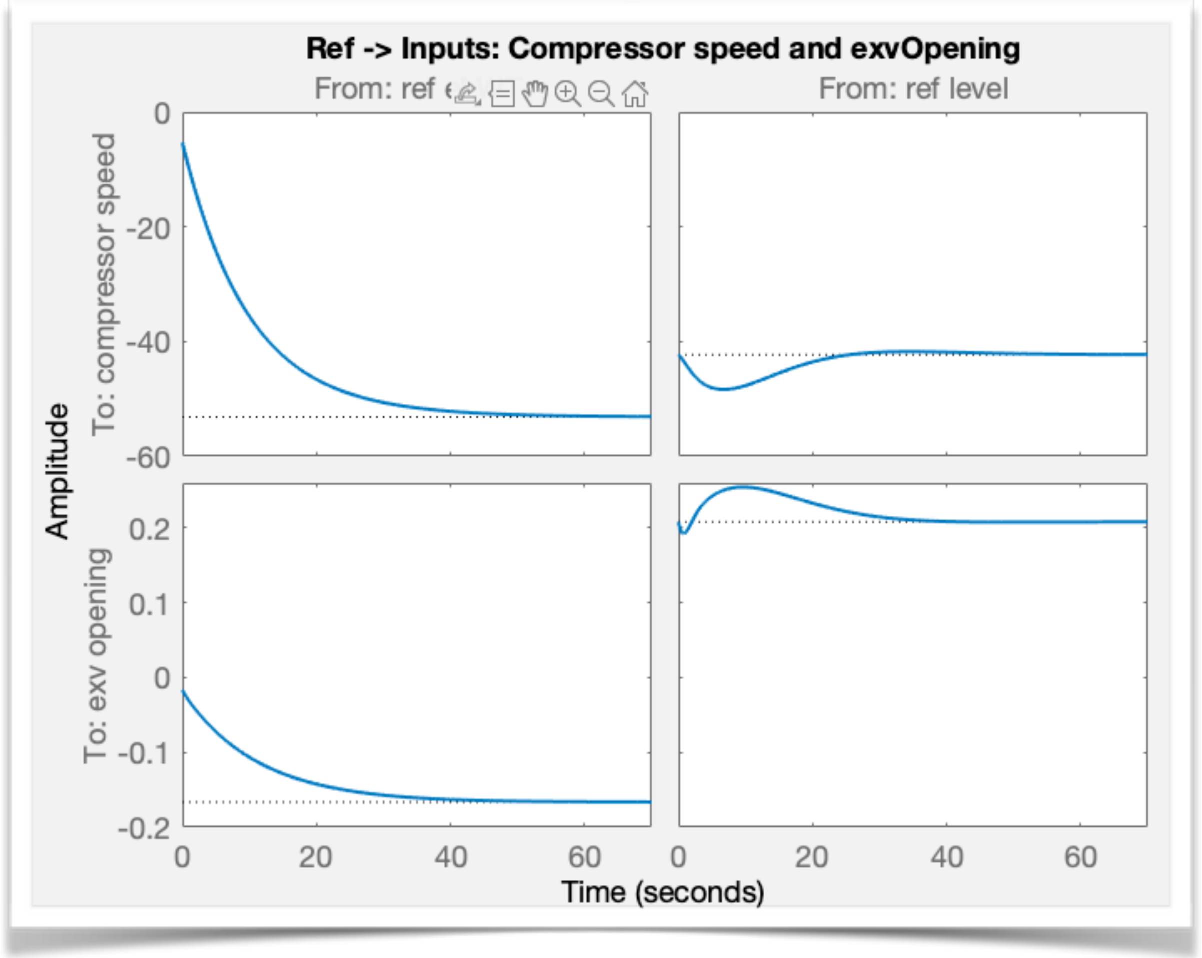
Chosen PI-controllers:

$$C_1(s) = 0.1\left(1 + \frac{1}{s}\right), \quad C_2(s) = 1\left(1 + \frac{1}{5s}\right)$$

Decoupled system $G(s)G^{-1}(0)$







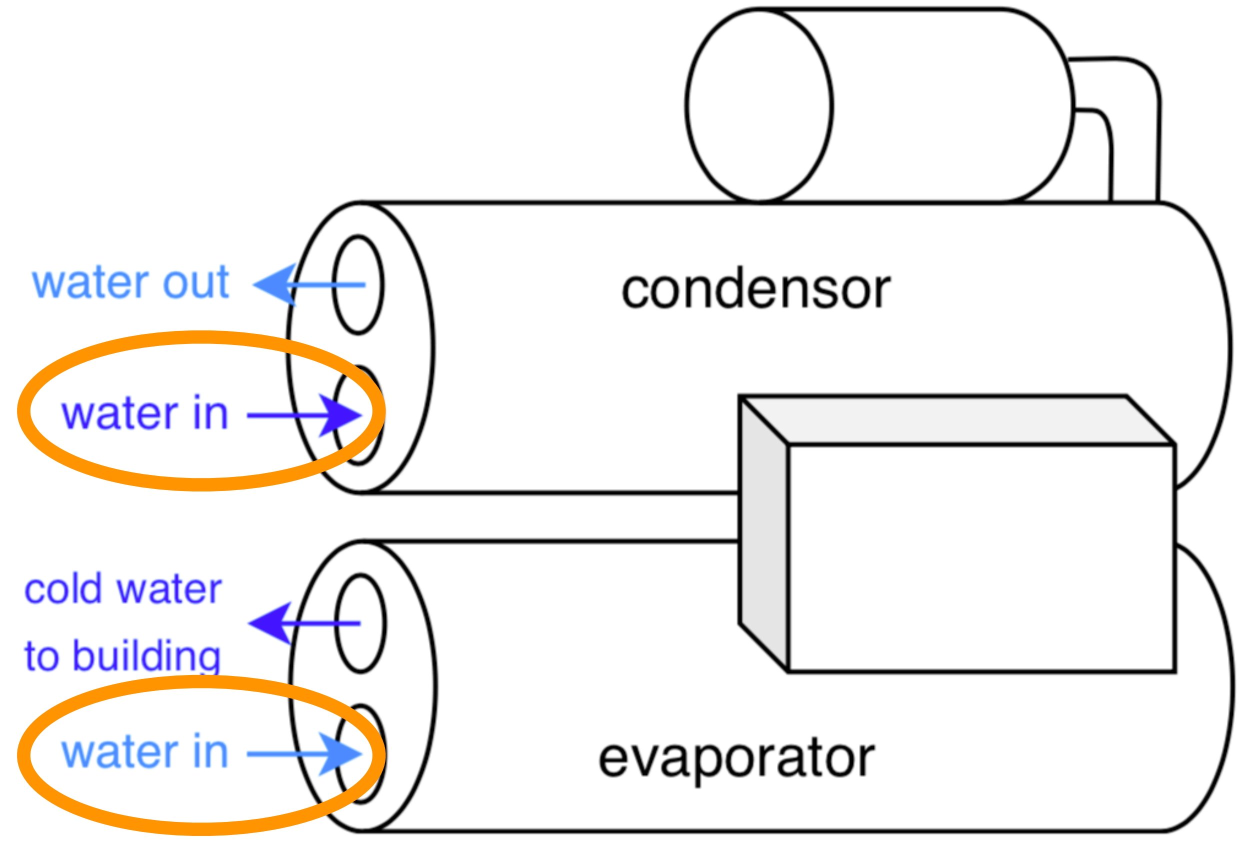
Controller tests

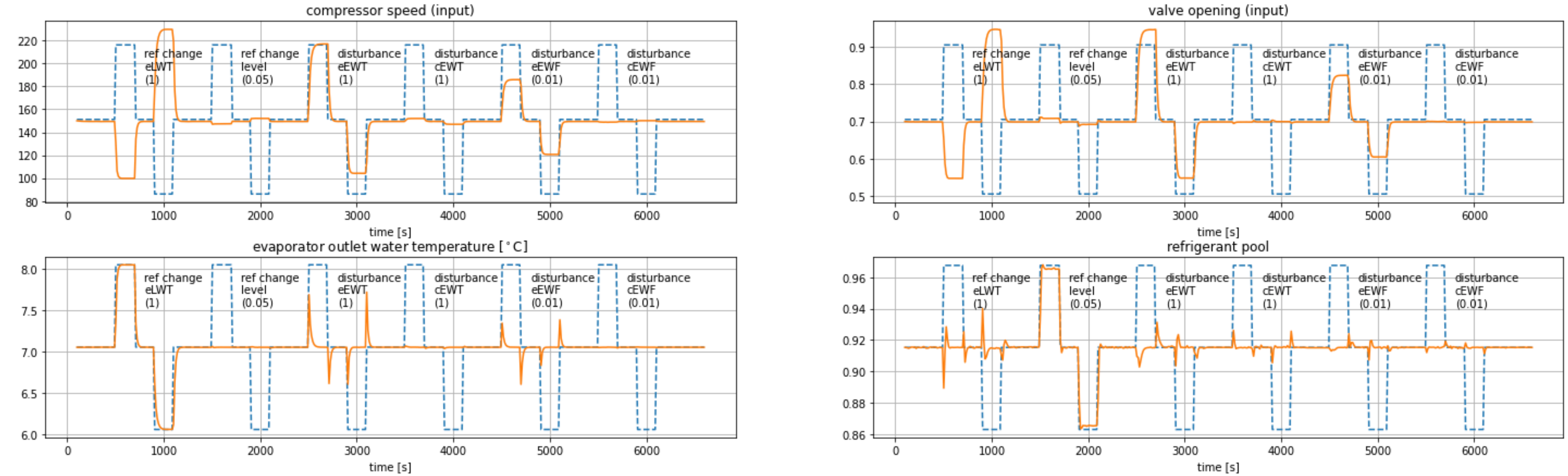
Controller performance for reference changes (eLWT and evap level) **and disturbances**

Disturbances:

- cond entering water flow (cEWF)
- cond entering water temp (cEWT)

- evap entering water flow (eEWF)
- evap entering water temp (eEWT)





Level measurement problem

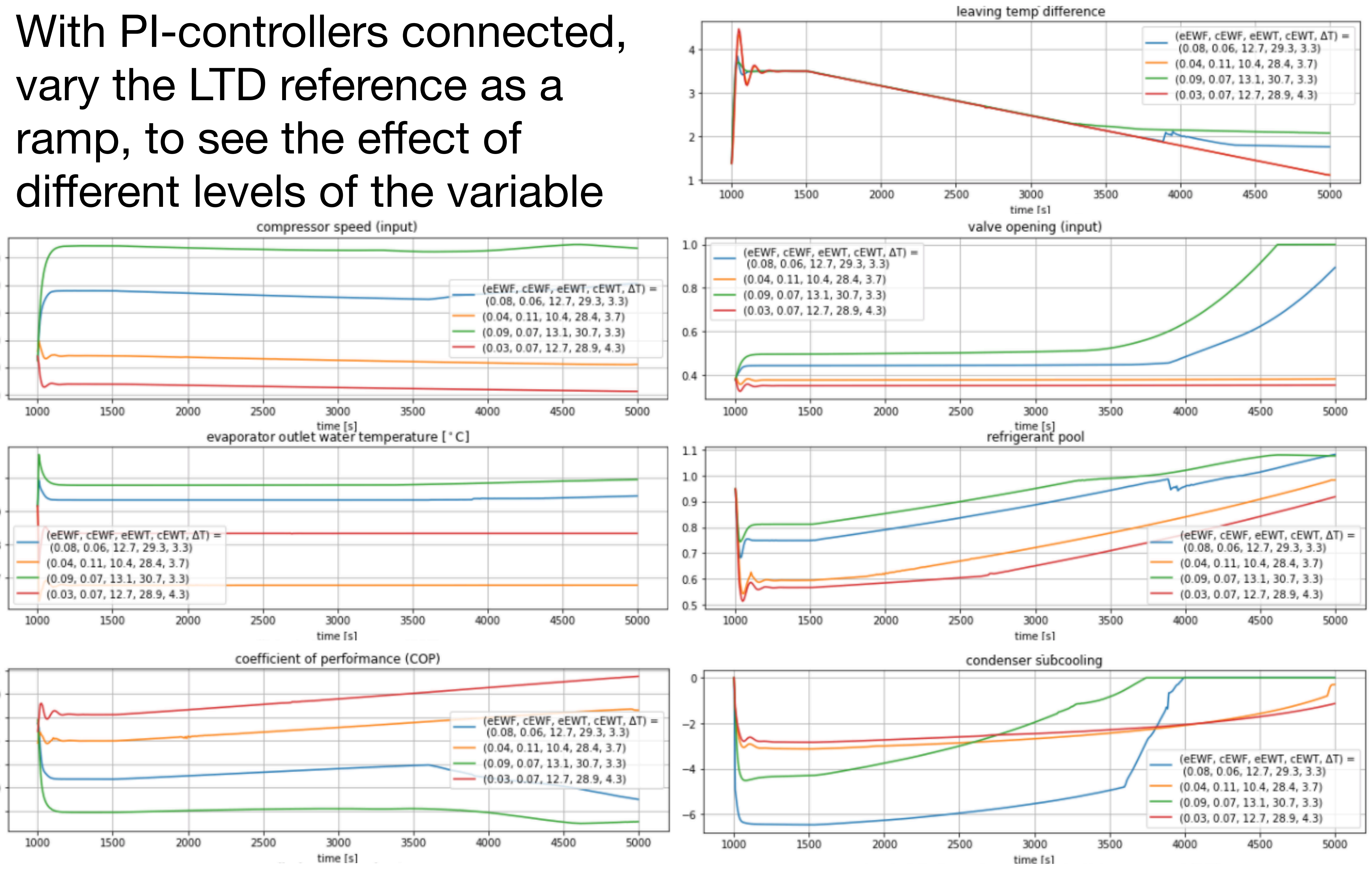
Problem: The evaporator level is not measurable

Possible solutions:
1. Add an expensive sensor
2. Use other measurement signals for feedback instead
3. Use other measurement signals to estimate the level

Alternative feedback signals:

- Leaving temperature difference (LTD) = LWT – leaving refrigerant temp
- Subcooling

With PI-controllers connected, vary the LTD reference as a ramp, to see the effect of different levels of the variable



Idea: Use learning methods to find an LTD reference level that keeps the subcooling away from zero, the evaporator level <1, and high COP, for given operating conditions.

Level measurement problem

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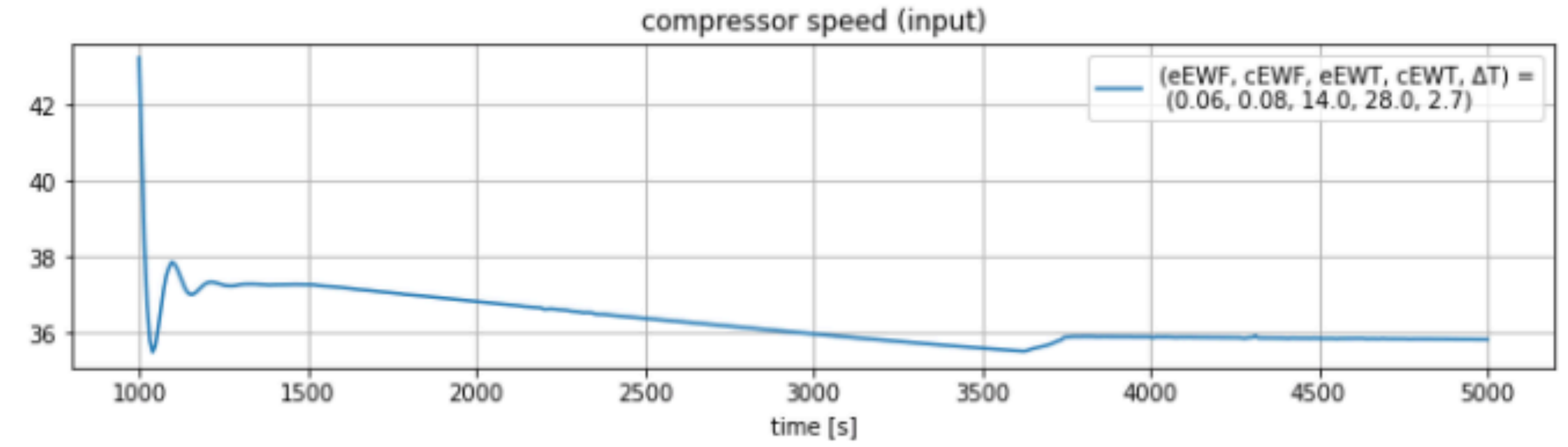
Use a controller based on the level and estimate the level from measurable variables by e.g.

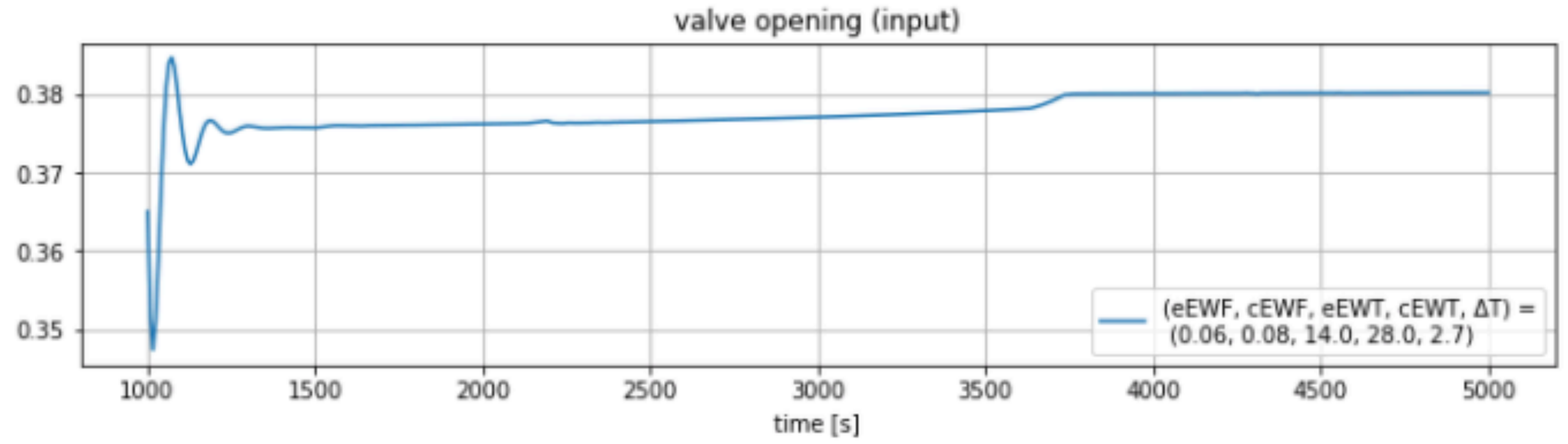
- Random Tree Regressor
- Nearest Neighbor
- Support Vector Machines
- SVM (with and without kernels)
- Gaussian Processes
- Other methods?

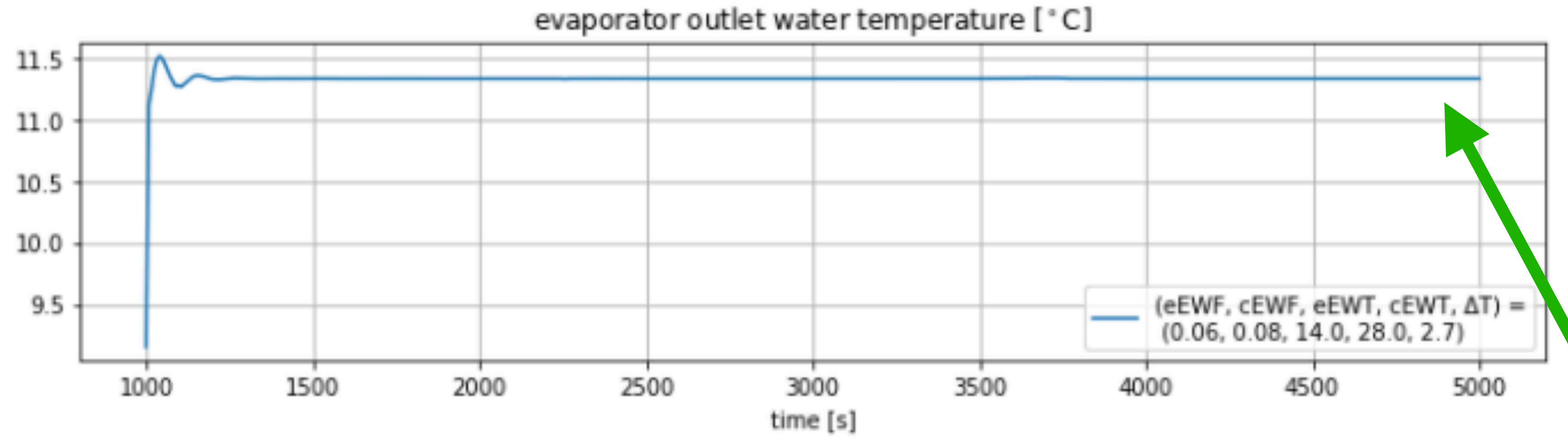
Questions

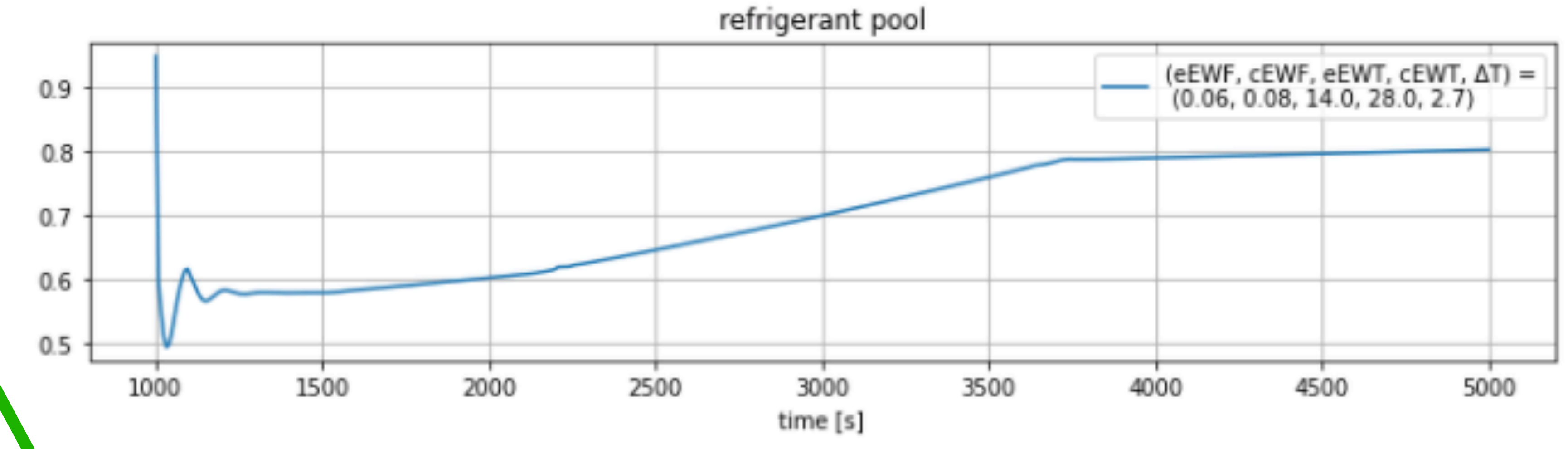
- How to best generate training data?
- Which signals are most important?

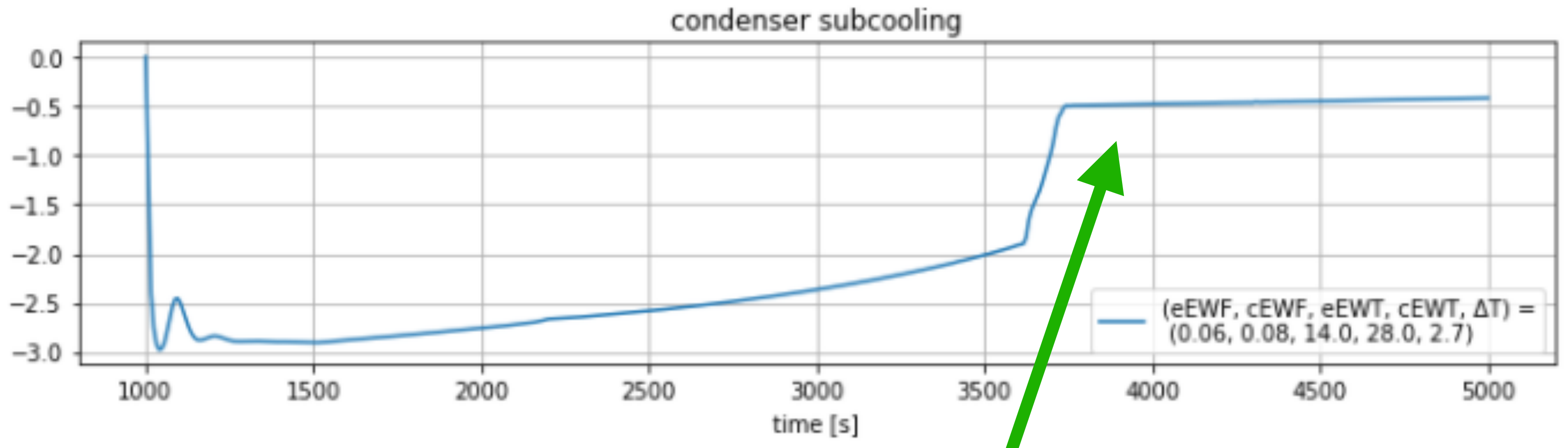
Results from control with LTD











Reaches reference temp of 11.3°C

Feedback term added to counteract subcooling exceeding -0.5

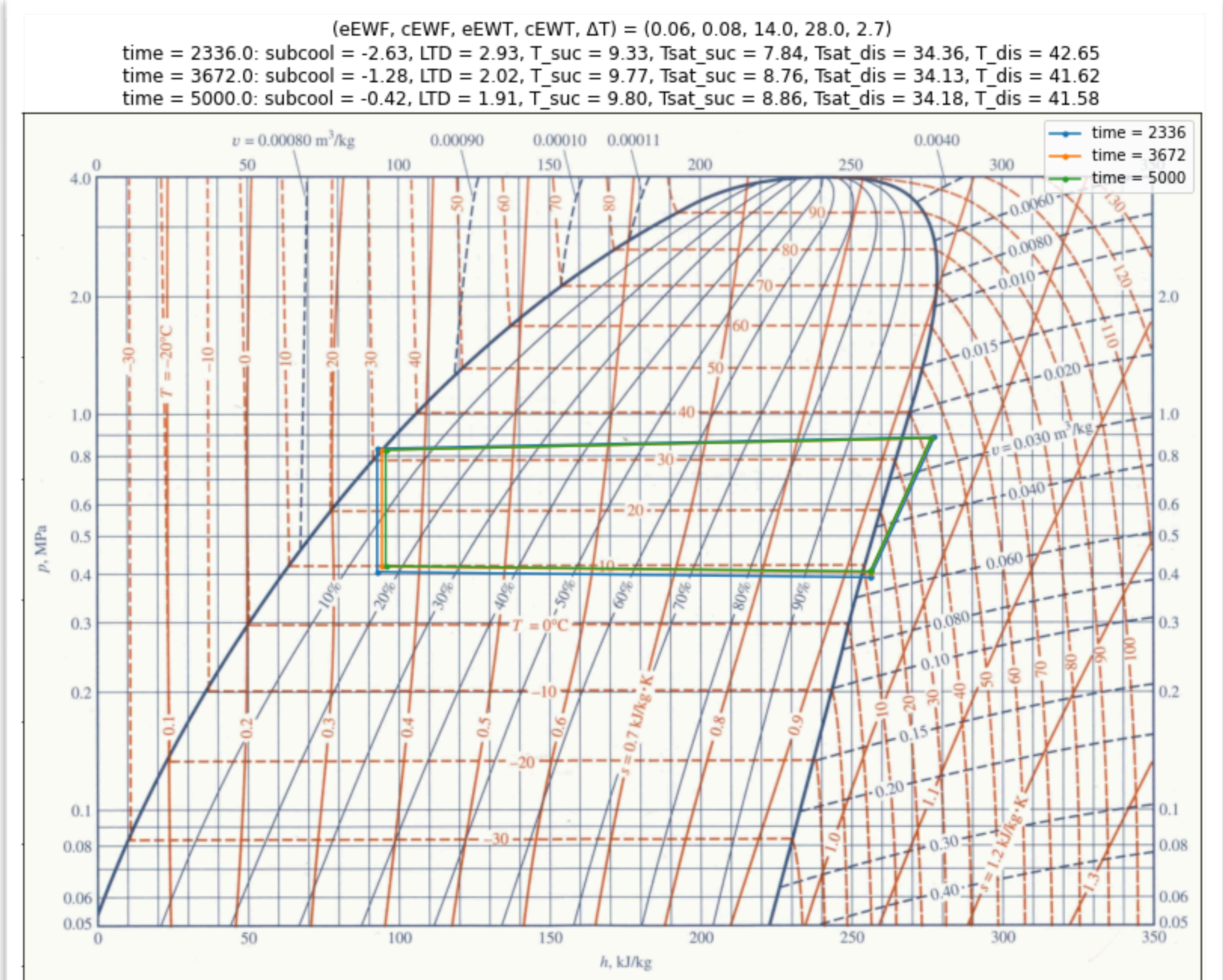


Chart A-11 R134a ph diagram. (Source: Based on Thermodynamic Properties of HFC-134a (1,1,1, 2-tetrafluoroethane). DuPont Company, Wilmington, Delaware, 1993, with permission.)

Works well in this scenario.

Future work

- How is the COP (efficiency) affected by different control settings (different feedback signals, parameter values, etc.)?
- What sensors are worth to add?
- Can we optimize the control adaptively, e.g. by some kind of dual control?

Thanks for listening!