Printed Circuit Heat Exchanger and Finned-Tube Heat Exchanger Modeling for a Supercritical CO_2 Power Cycle

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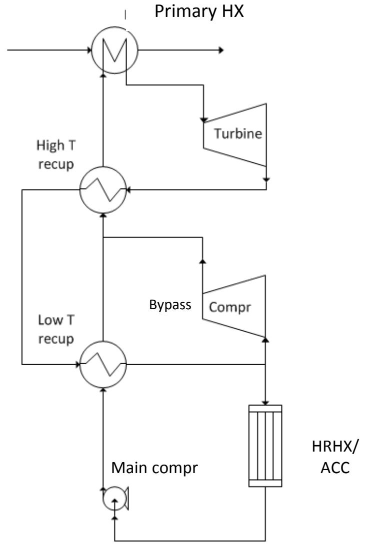
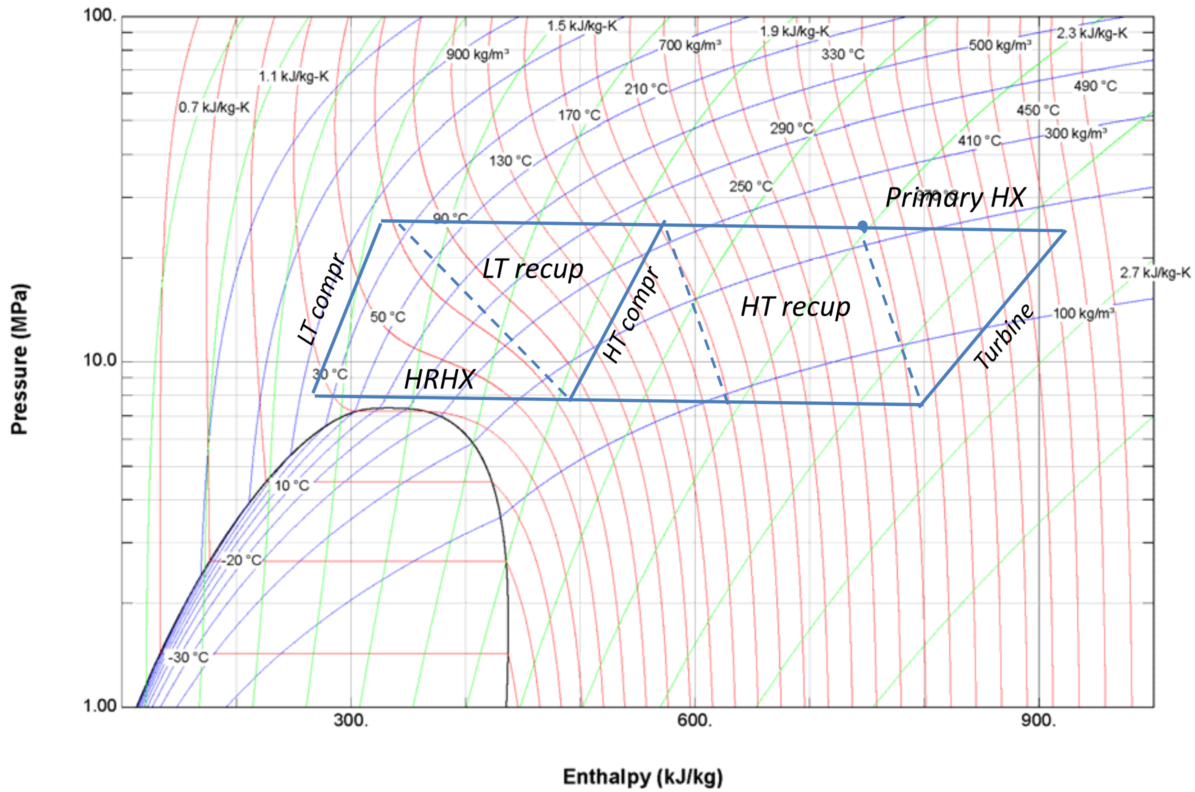
Objectives of today's discussion

1. Heat exchangers in present study
   a) Printed circuit HX (HRHX and RHX)
   b) Finned-tube HX (PHX and ACC)
2. Test system configuration
3. HX modeling in GT-SUITE
4. HX model validation
5. Results and discussion
6. Summary

sCO_2 cycles are highly dependent upon recuperation

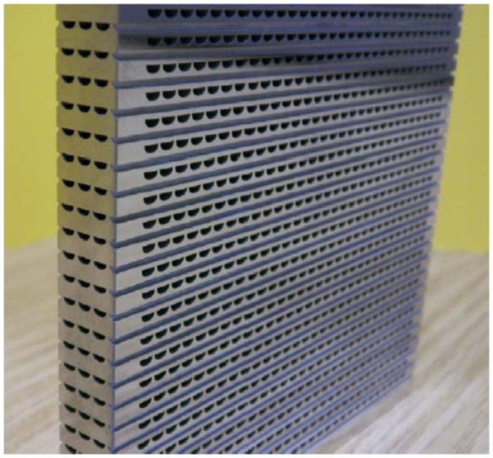


Low PR = high turbine outlet temperature, large amount of unused enthalpy



Printed Circuit Heat Exchangers (PCHE)

- Recuperators (RHX): This high degree of recuperation requires high conductance (UA) and high operating pressures demand for advanced compact HX technology.
- Used as heat rejection HX (HRHX) in sCO_2 cycles for direct water cooling option.
- Consists of layers of chemically etched metal plates in a diffusion-bonded assembly.
- RHX and HRHX models are validated for transient and steady-state performance against measured data from EPS100 testing.



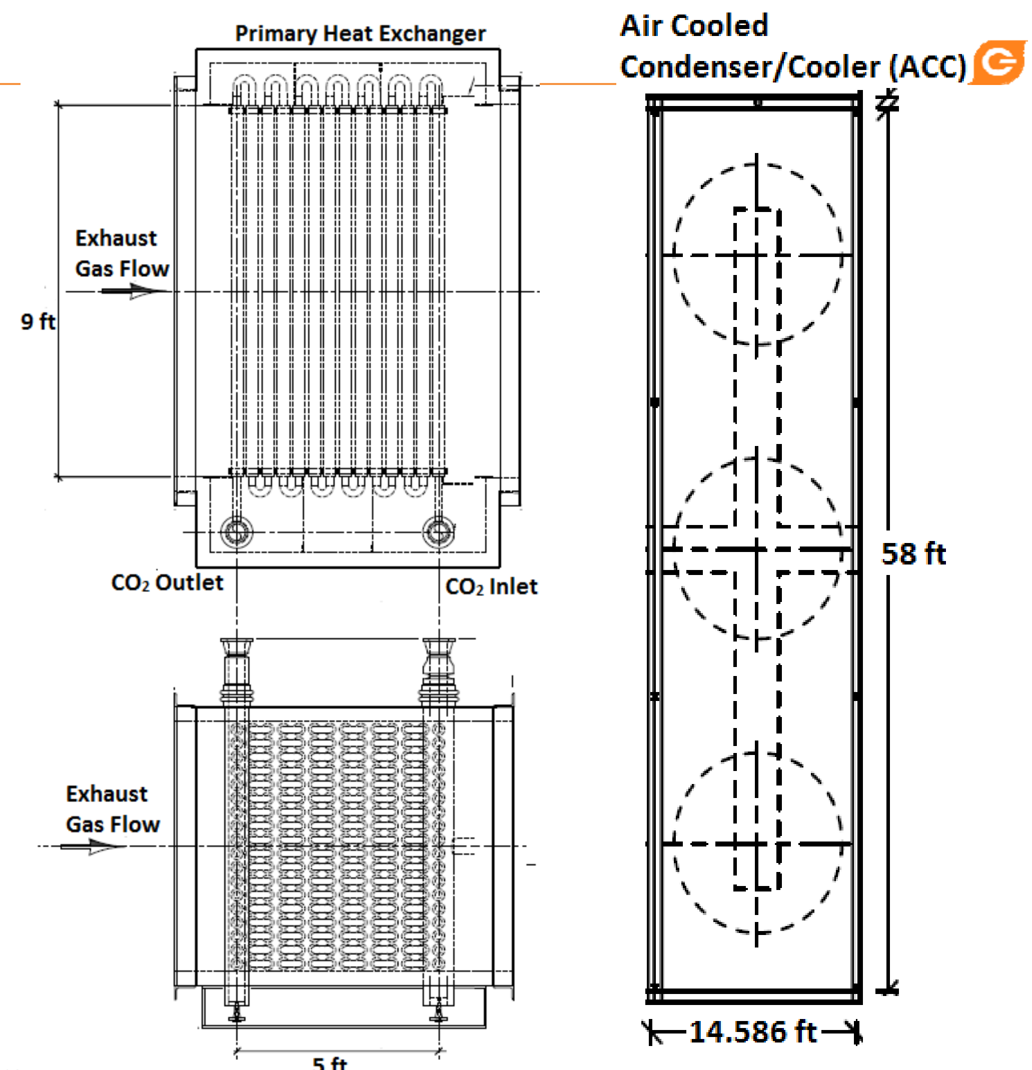
From Southall, D., 2009, "Diffusion Bonding in Compact Heat Exchangers," *sCO_2 Power Cycle Symposium*.

>15MW
>300m² heat transfer area
~13000kg
Core ~ 1.5 x 1.5 x 0.5 m

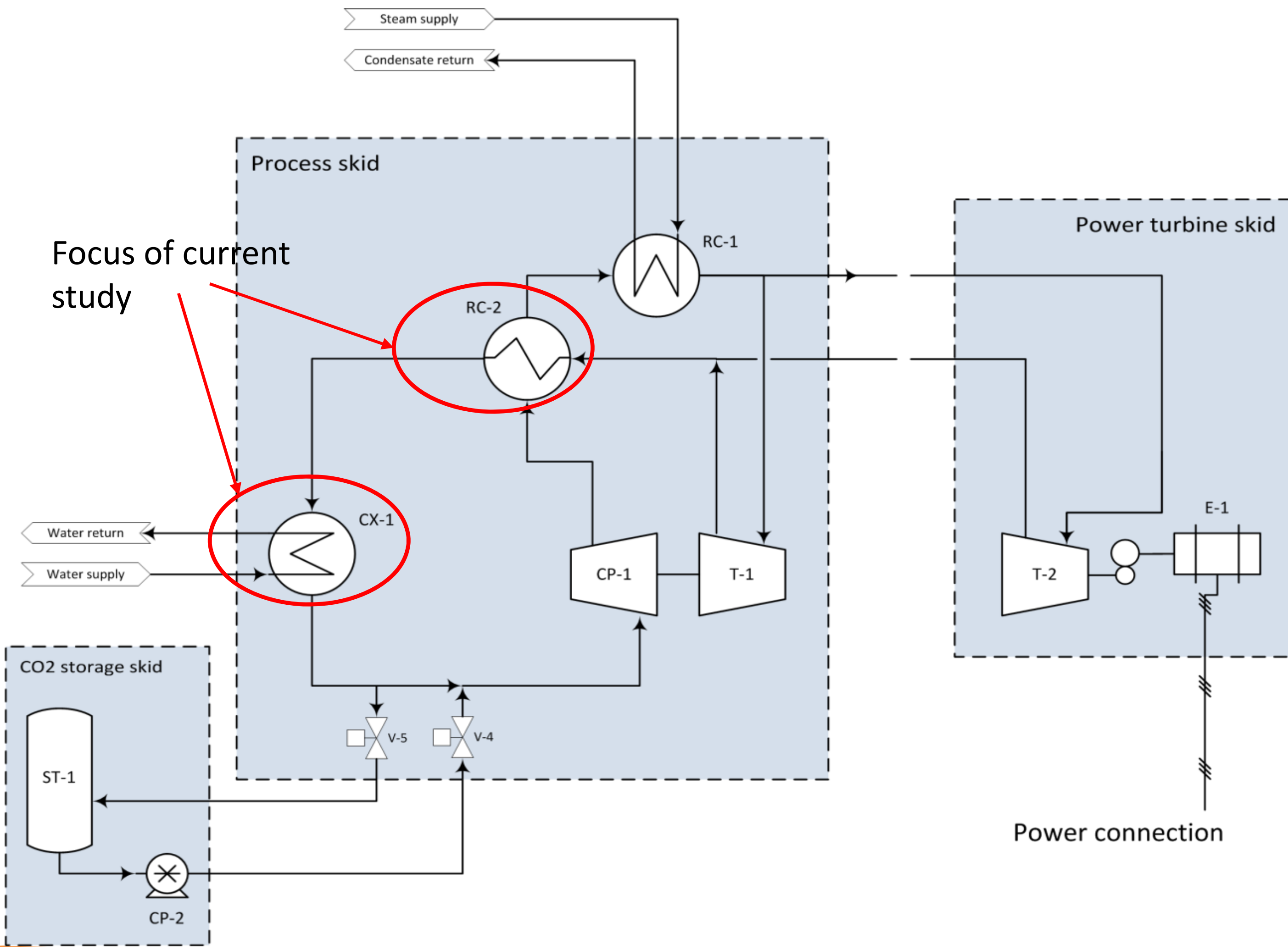
Comparable S&T:
>850m²
~50000kg
Shell ~ 1.2m diameter x 12m length

Finned-Tube Heat Exchangers

- Primary heat exchangers (PHX): In gas turbine exhaust heat recovery of sCO_2 power cycles, finned-tube HX are used for exhaust gas-to-CO_2 (heat source) heat transfer.
- Air cooled condenser/cooler (ACC): In sCO_2 power cycle finned-tube HX are used for CO_2-to-air (heat sink) heat transfer which also allow for complete water-free operation.
- Consists of series of tube banks with circular louvered fins brazed on surface of each tube.
- As no test data was available from testing of these heat exchangers in sCO_2 applications, they were modeled based on manufacturer-supplied design point data.



Test System: 7.3MWe net power sCO_2 cycle

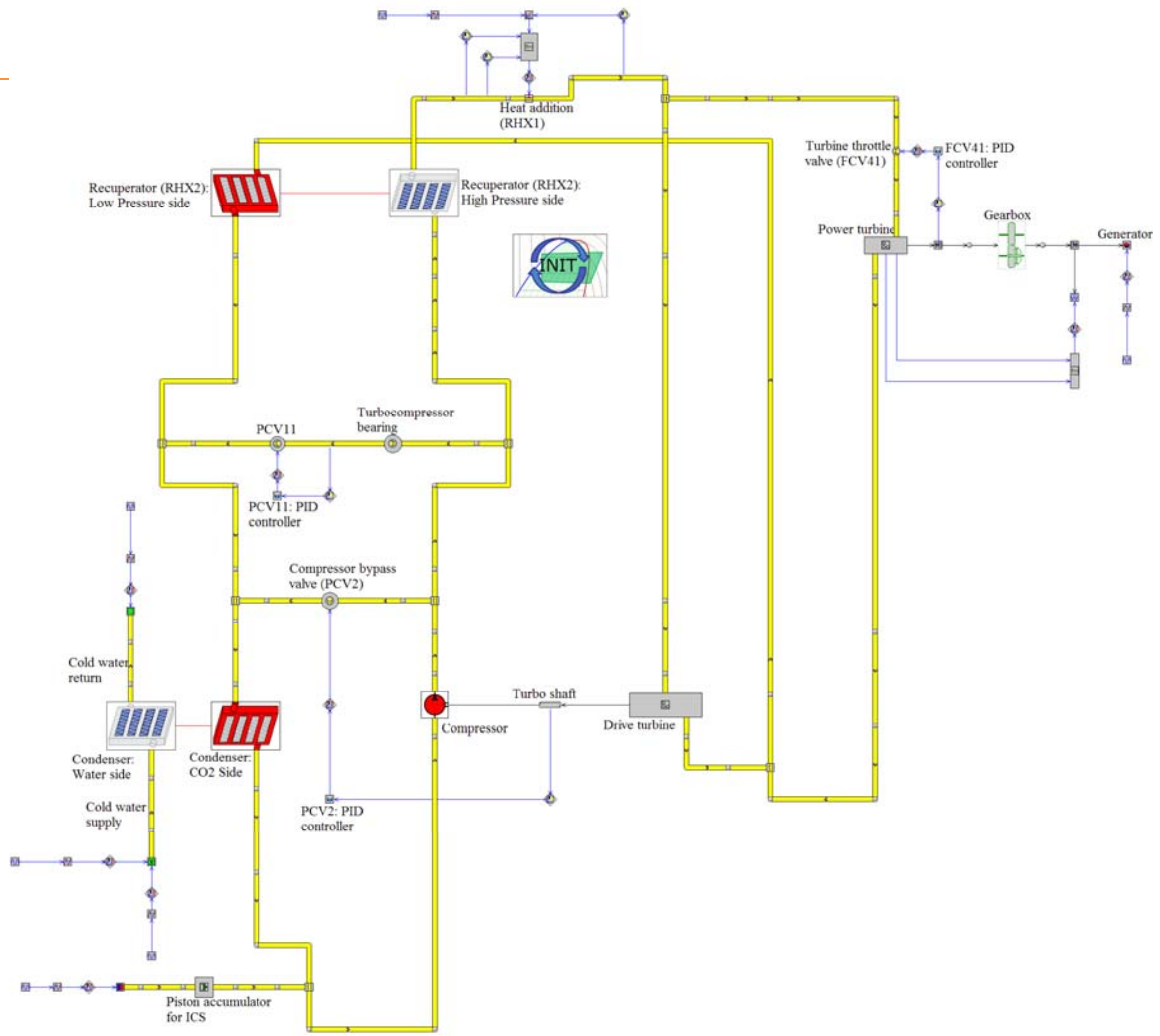


EPS100 – commercial sCO_2 power cycle

- 350 hours of testing
- 3.1MWe max output power
- Numerous transient events (planned & otherwise)

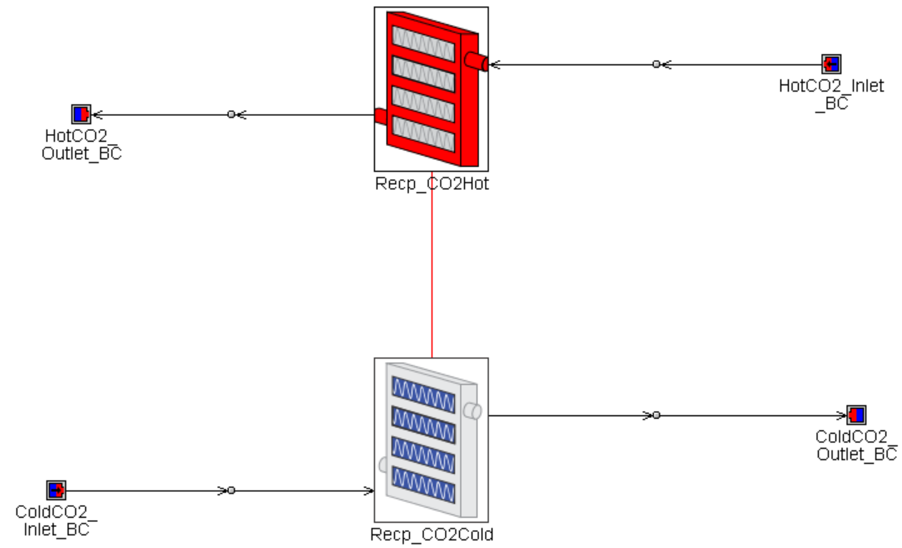
Modeling Platform

- GT-SUITE 1D engineering system simulation software was used
- Component templates can be GT supplied or user defined templates or Fortran models
- Individual component models were first developed and validated against test data
- Described in ASME GT2017-63279

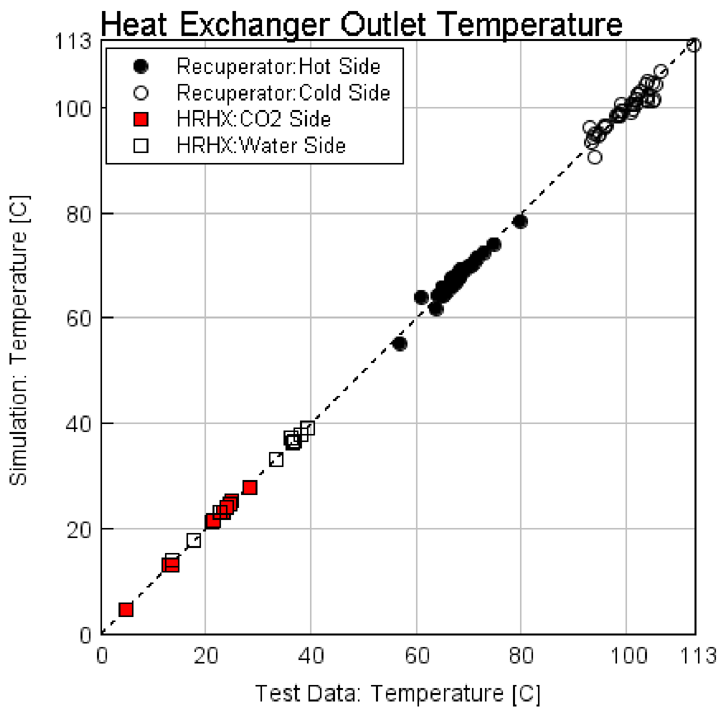


PCHE Model: RHX and HRHX

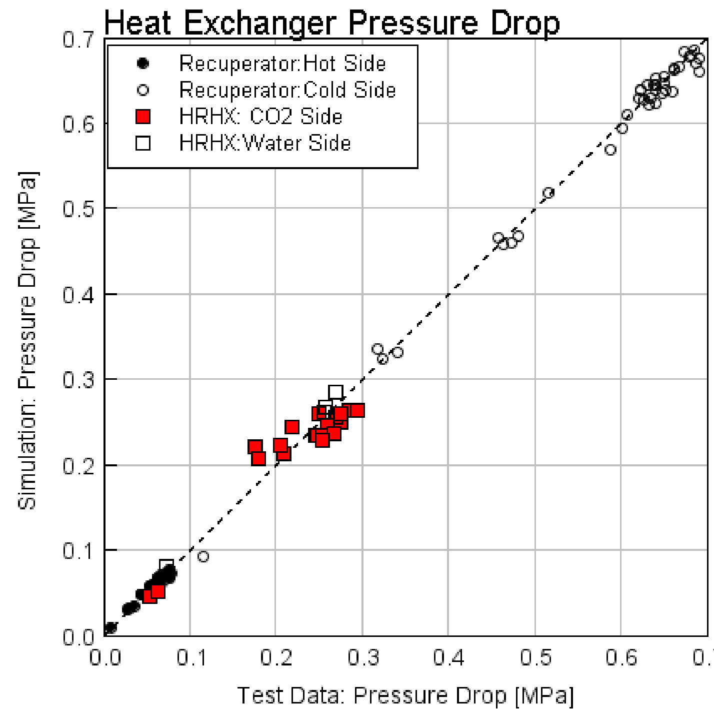
- Counterflow model based on Plate & Frame heat exchanger template
- Inlet temperatures, pressures and flows are imposed boundary conditions
- Heat transferred (hot and cold sides independently) and hot/cold side pressure drops are outputs
- HTC and dP models include calibration to selected steady-state data points
- RHX was modeled as single-phase heat transfer where as the HRHX is modeled as two-phase heat transfer



HRHX and RHX Model Validation



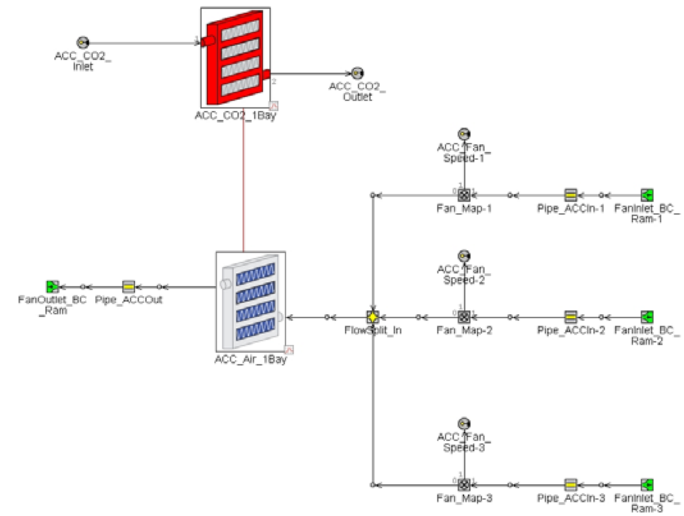
Recuperator and HRHX outlet temperatures from validation simulation

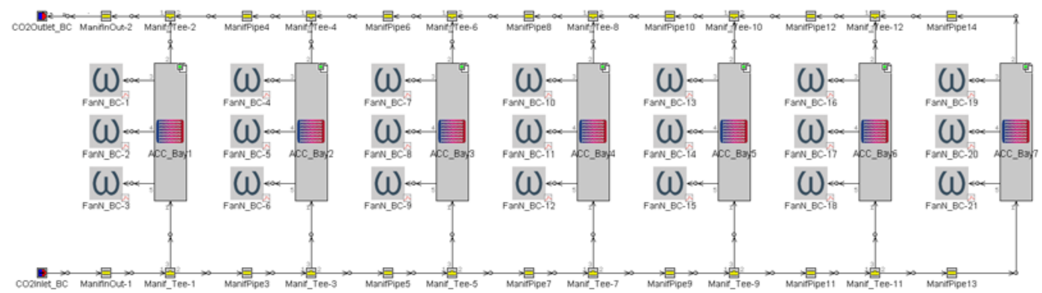


Recuperator and HRHX pressure drops from validation simulation

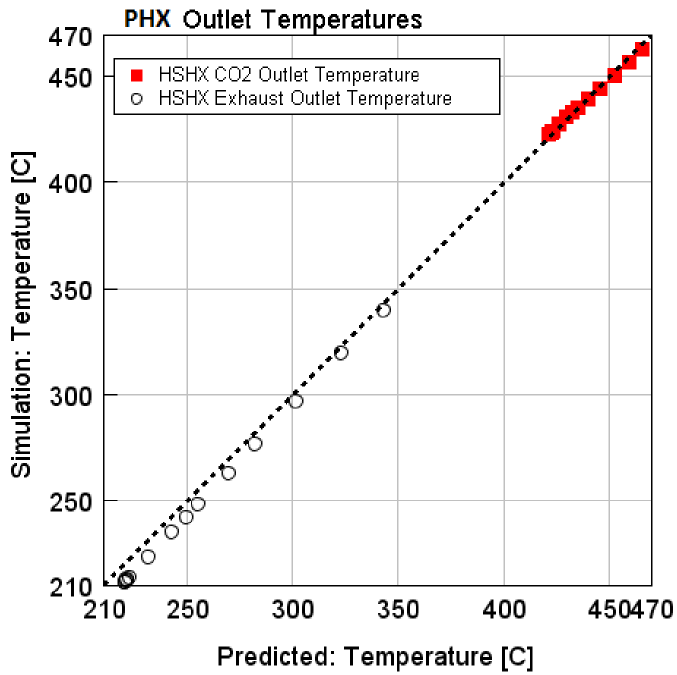
Finned-tube Model: PHX and ACC

- Crossflow model based on built-in fin-tube heat exchanger template
- Manufacturer-provided design point data was used for calibration
- PHX is a single tube-bundle heat exchanger unit and modeled as single-phase heat transfer with CO_2 on tube side and gas turbine exhaust on fin side.
- ACC has 7-bays with each bay consisting of single tube-bundle heat exchanger unit and 3-fans per bay.
- ACC is modeled as two-phase heat transfer with CO_2 on tube side and air on fin side.

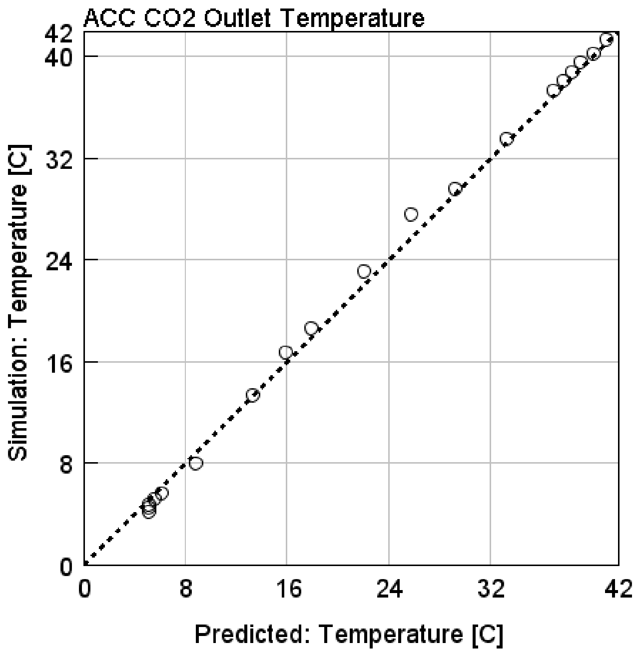




PHX and ACC Model Validation

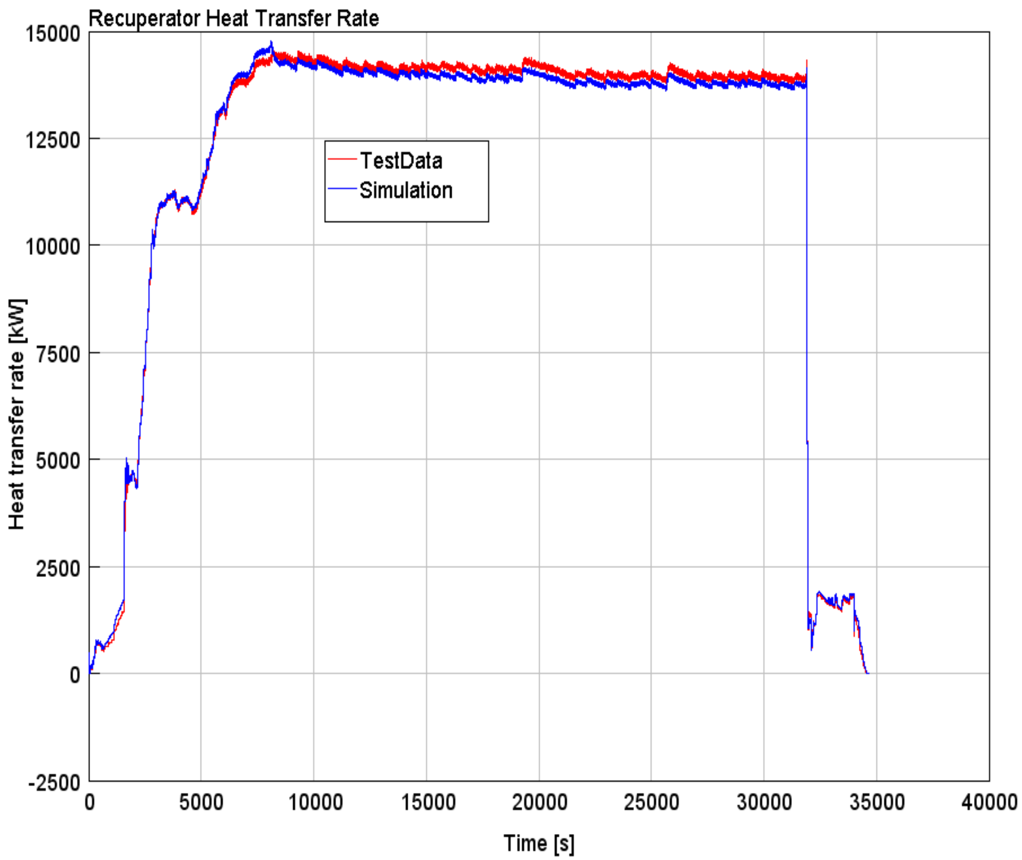


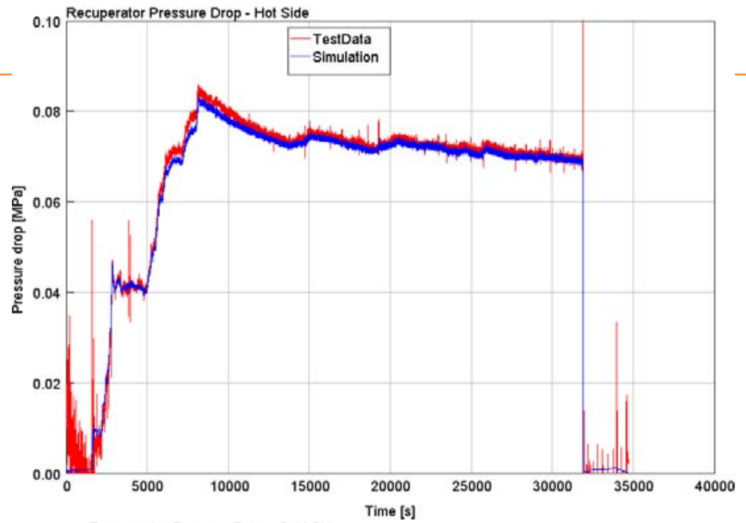
PHX CO_2 and exhaust outlet temperatures from validation

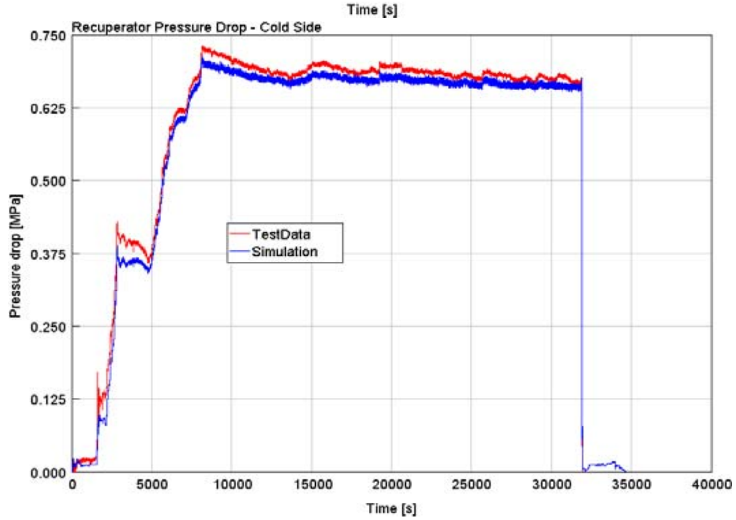


ACC CO_2 outlet temperatures from validation (seven bays simulation)

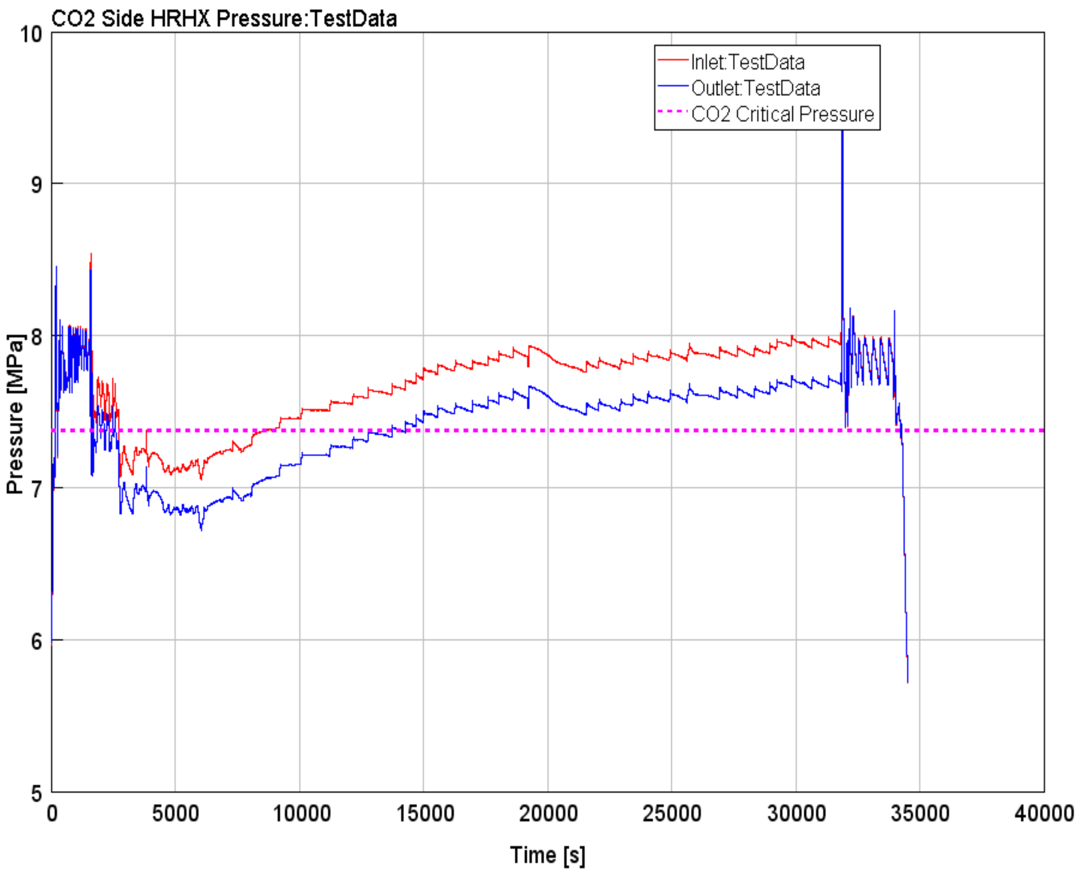
Results: Recuperator (PCHE)

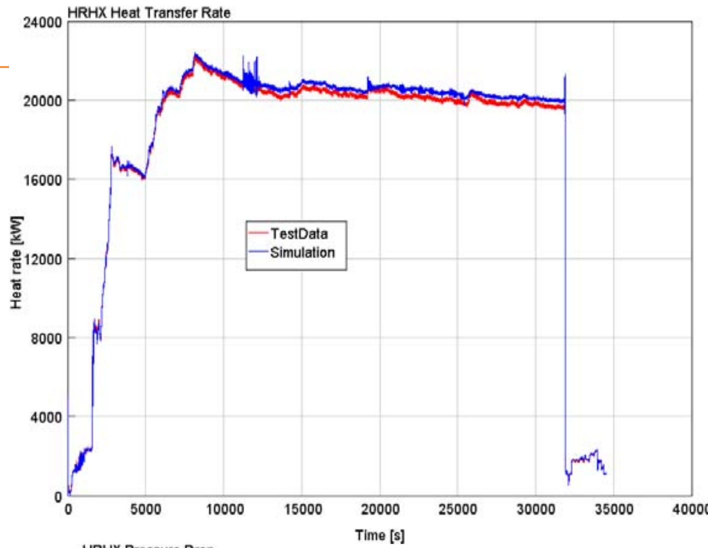


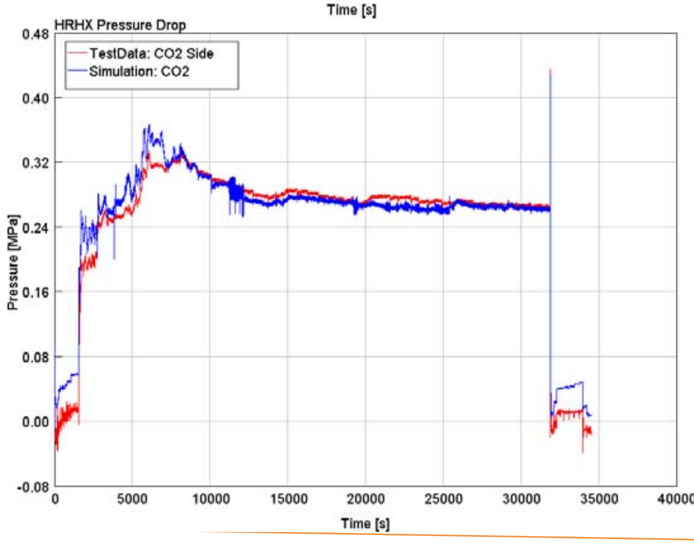




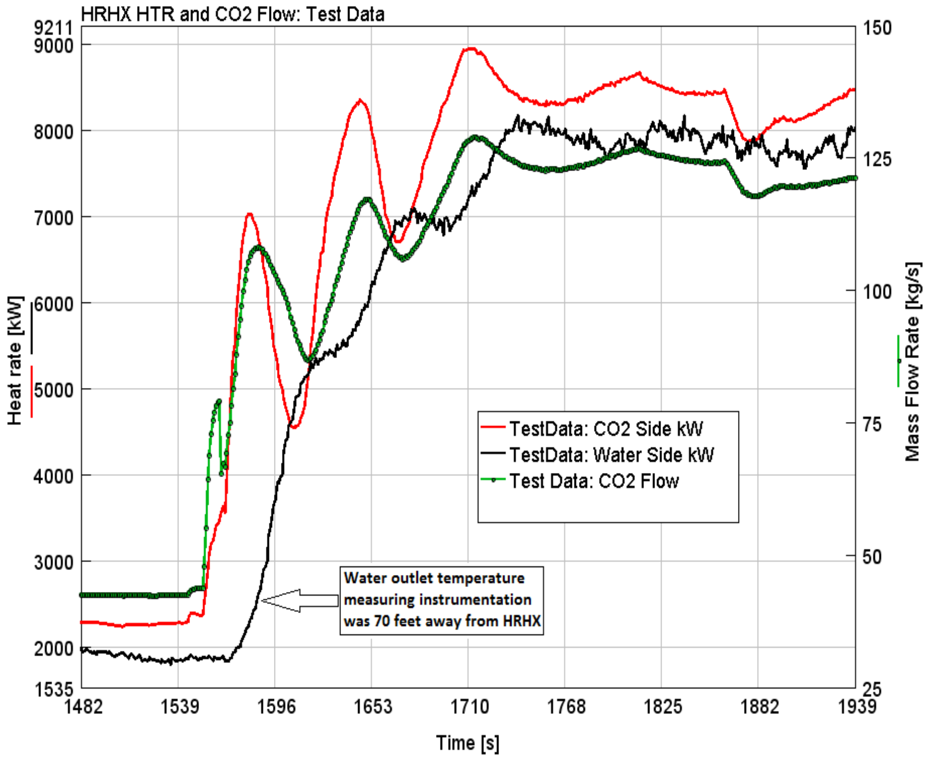
Results: Heat rejection HX (PCHE)

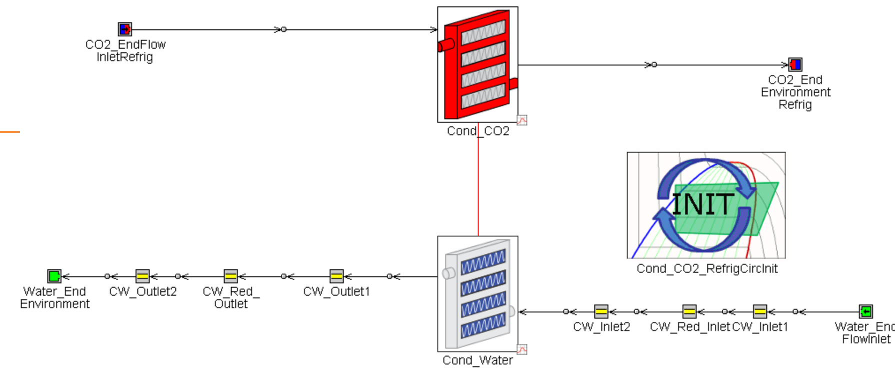


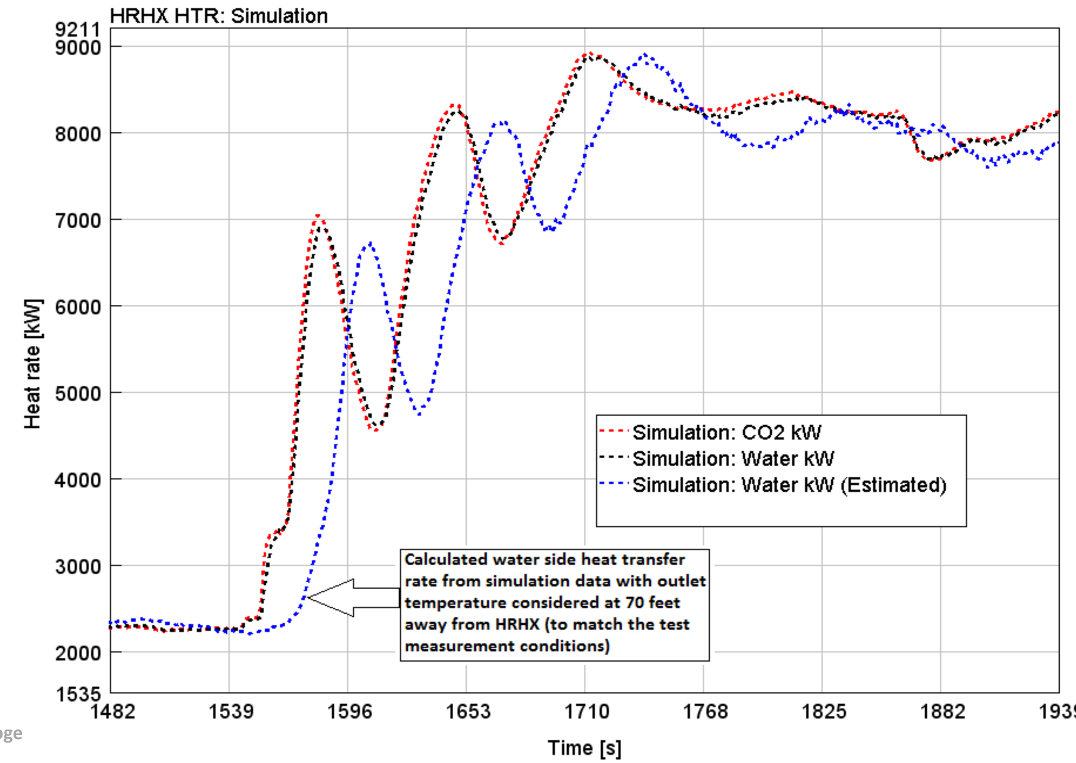




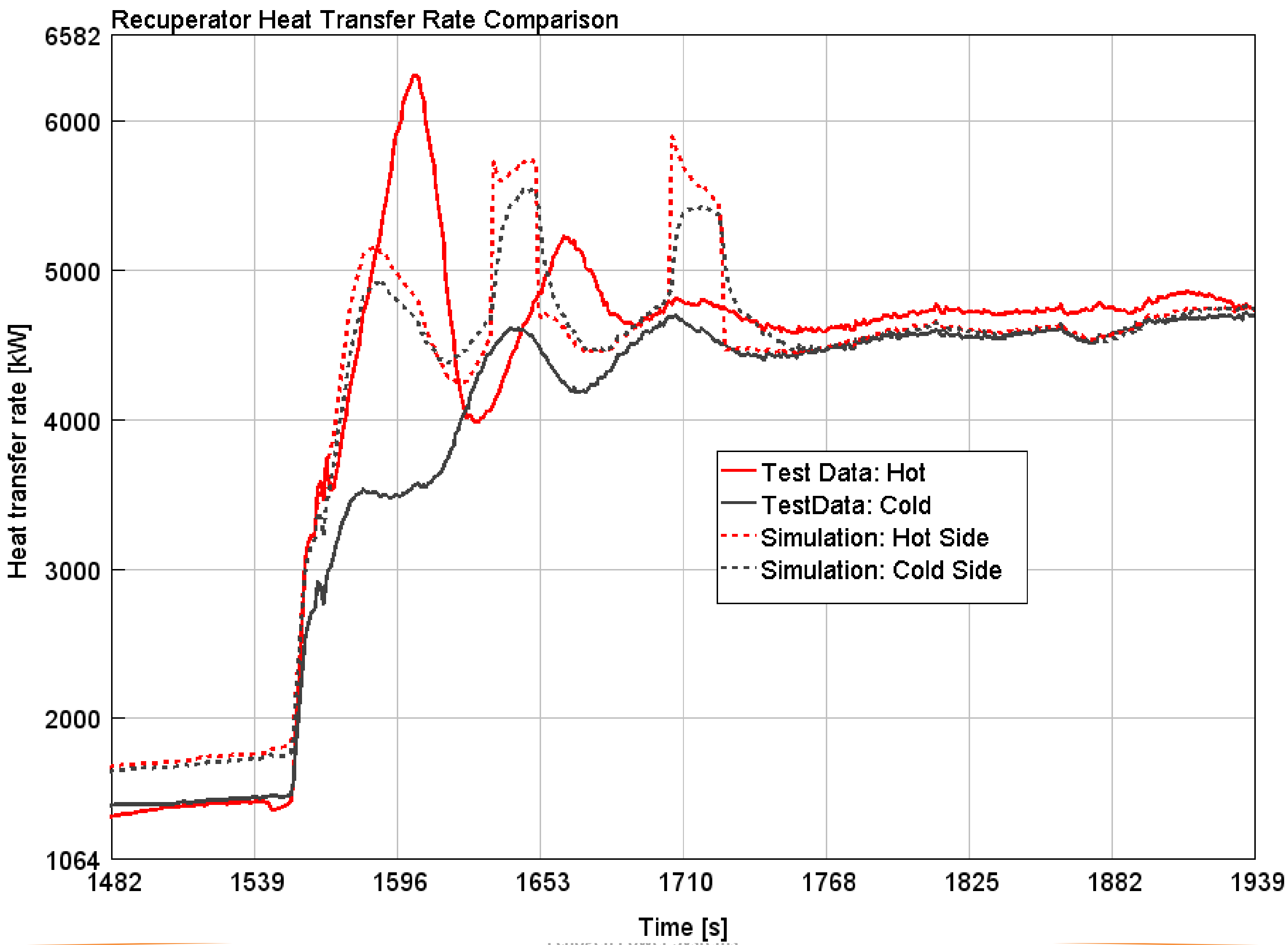
Results: HRHX transient response



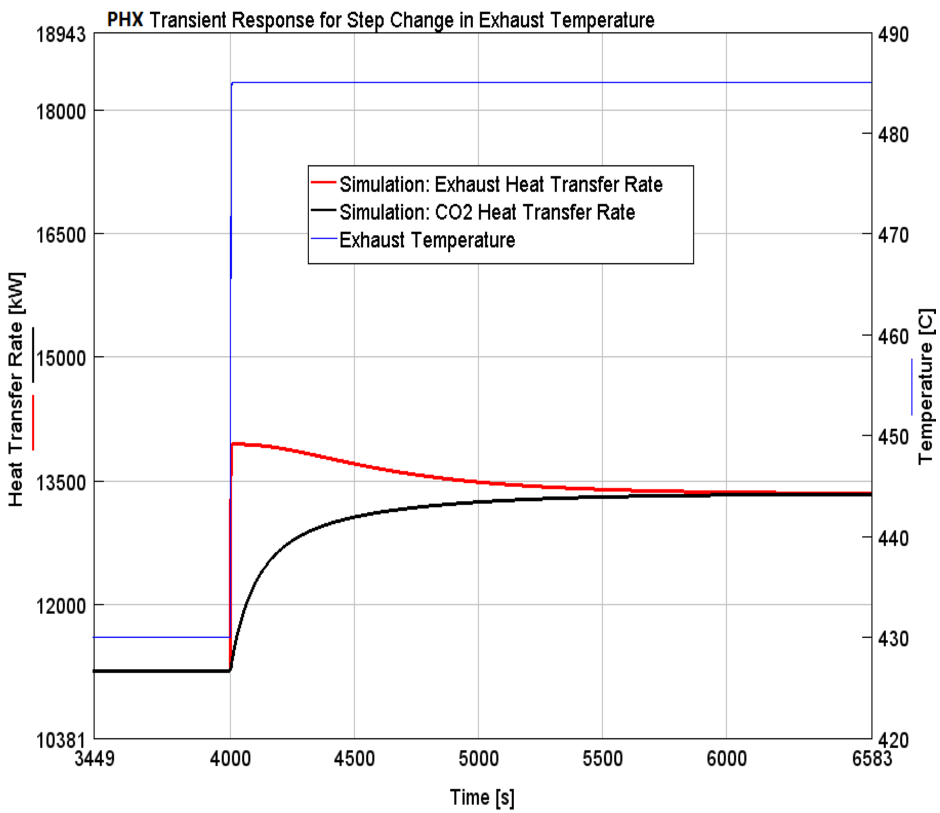


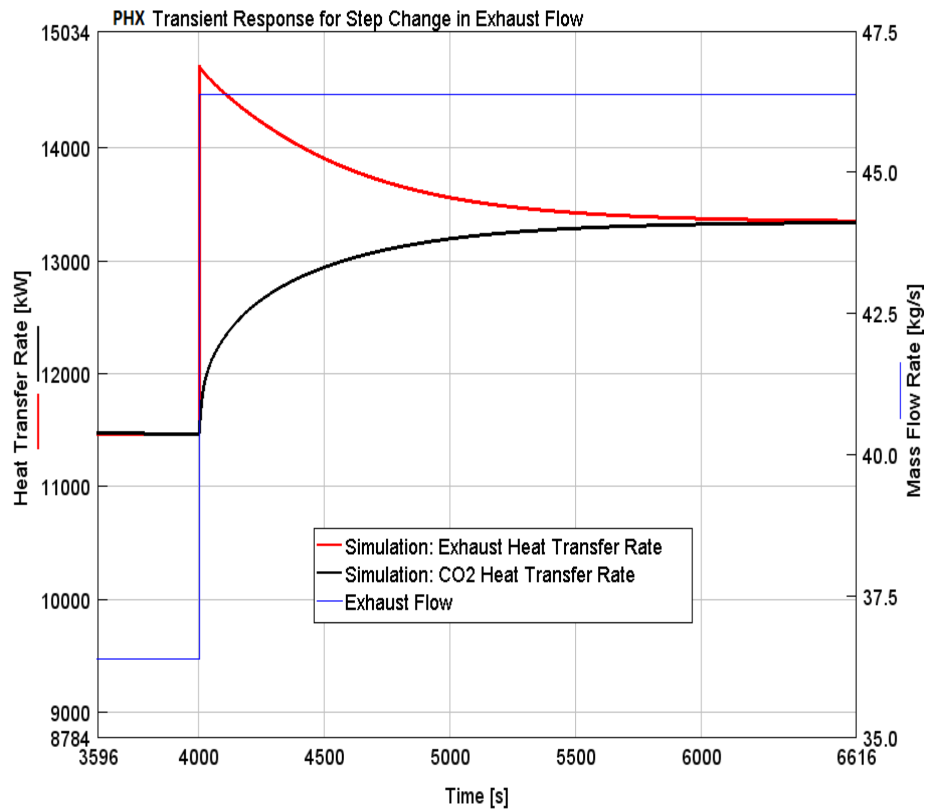


Results: PCHE transient response - RHX

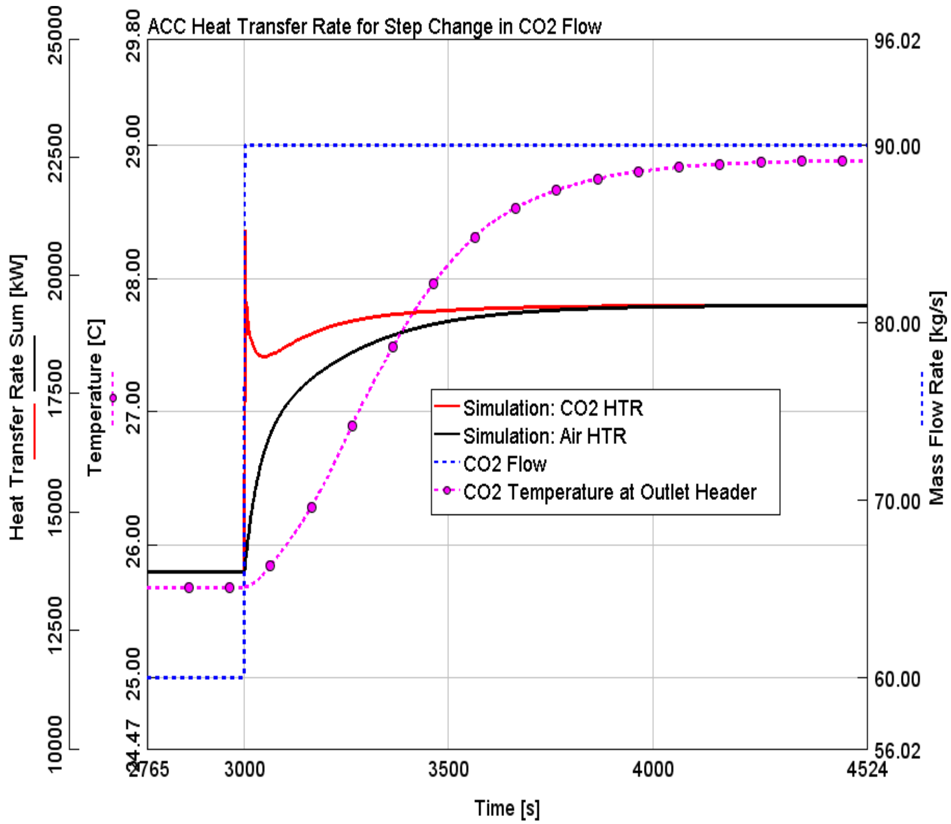


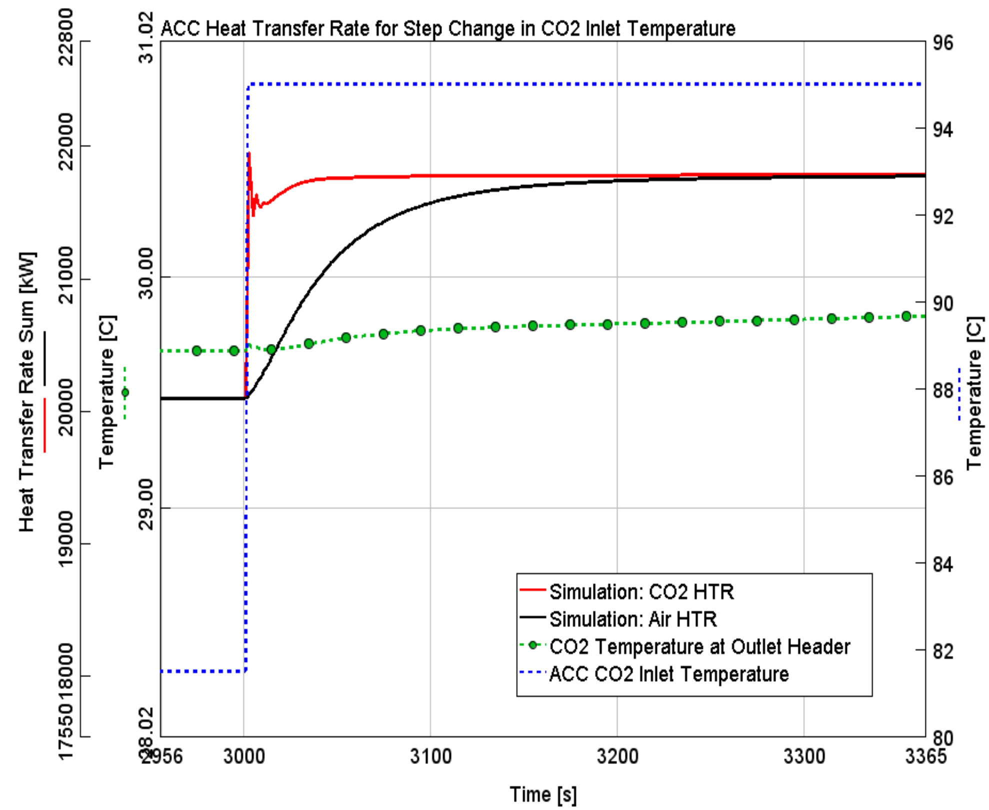
Results: Fin-tube transient response – PHX



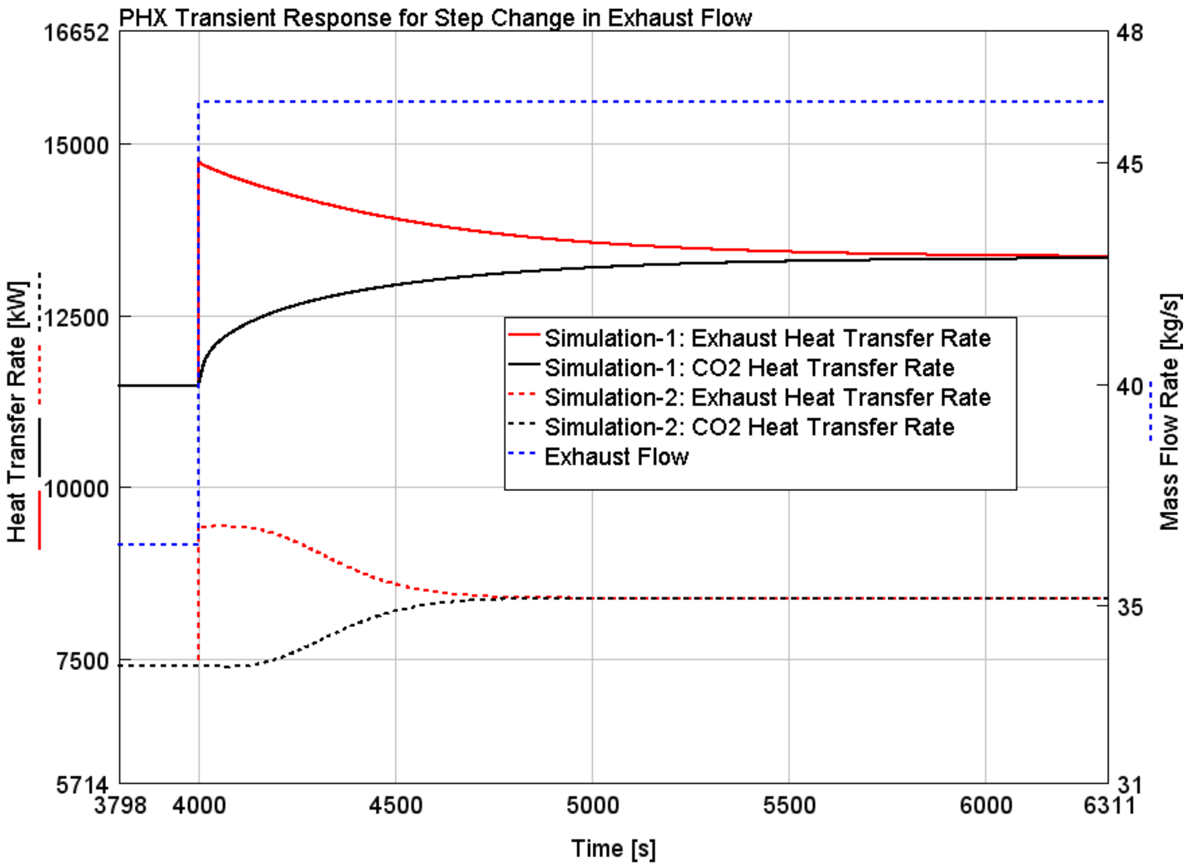


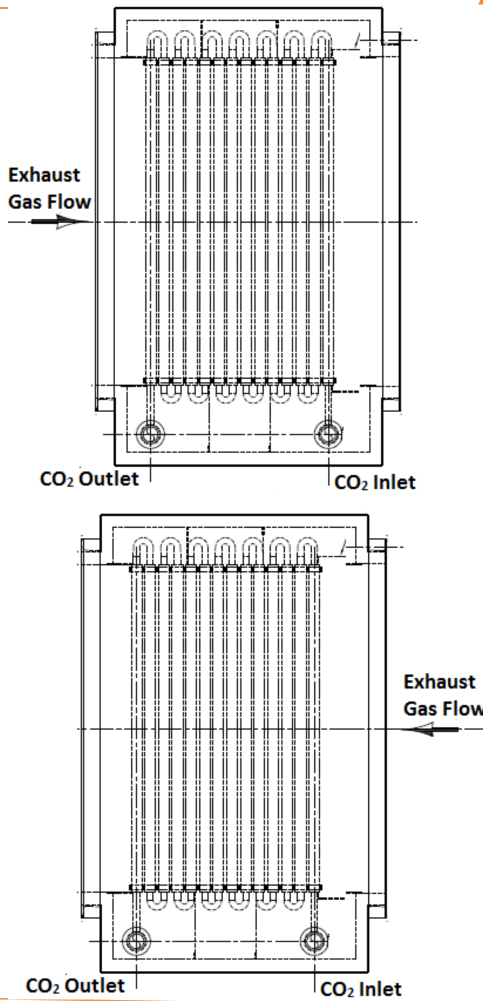
Results: Fin-tube transient response – ACC





Results: PHX transient response – Exhaust flow direction





Summary

- GT-SUITE 1D system simulation code was used to study the transient and steady state response of PCHE and Fin-tube HX
- The quasi-steady-state as well as transient heat transfer behavior of the heat exchangers, and the single-phase and two-phase pressure drop behavior, can be modeled with reasonable accuracy. Good agreement between transient simulation results and test data was observed.
- Due to highly compact nature of PCHEs, the transient response time for a fluid is very short for any changes in inlet conditions on other fluid side, while the finned-tube heat exchangers have a transient response time approximately two orders of magnitude longer.
- In an sCO2 power cycle field installation, the finned-tube heat exchangers will define the system time constants, which will also define the plant control system requirements.

$$mc\frac{dT}{dt} = UA\left(\Delta T_m - \Delta T_{m,ss}\right)$$

m = mass of HX

c = specific heat of HX material

$$\text{Characteristic time } (\tau) = \frac{mc}{UA}$$

	HRHX (PCHE)	Recuperator (PCHE)	PHX (Finned-tube HE)	ACC (Finned-tube HE)
Mass (kg)	14890	3470	54431	46274 (One Bay)
UA (kW/K)	4811	201	196	402
τ (seconds)	1.5	9	139	60

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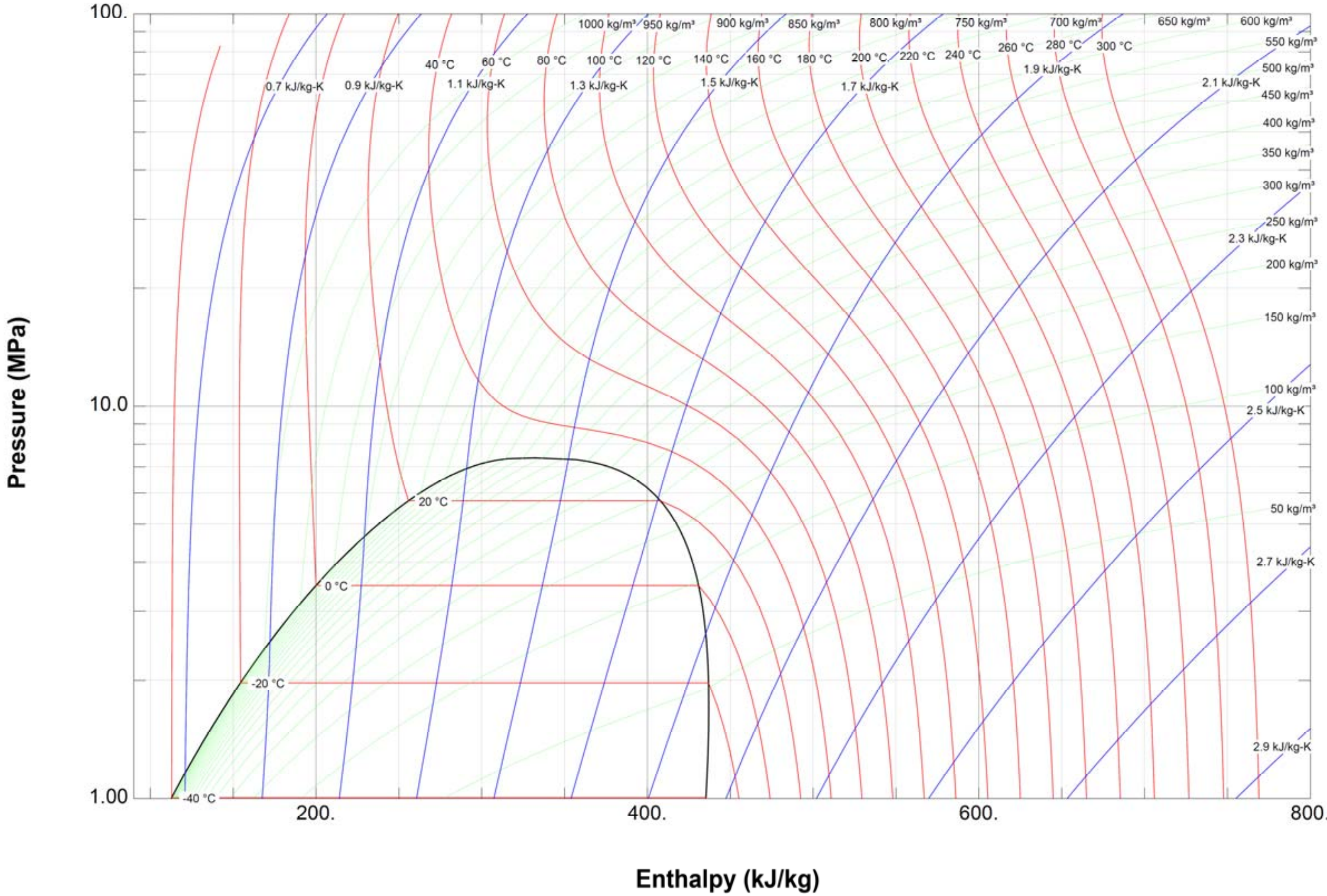
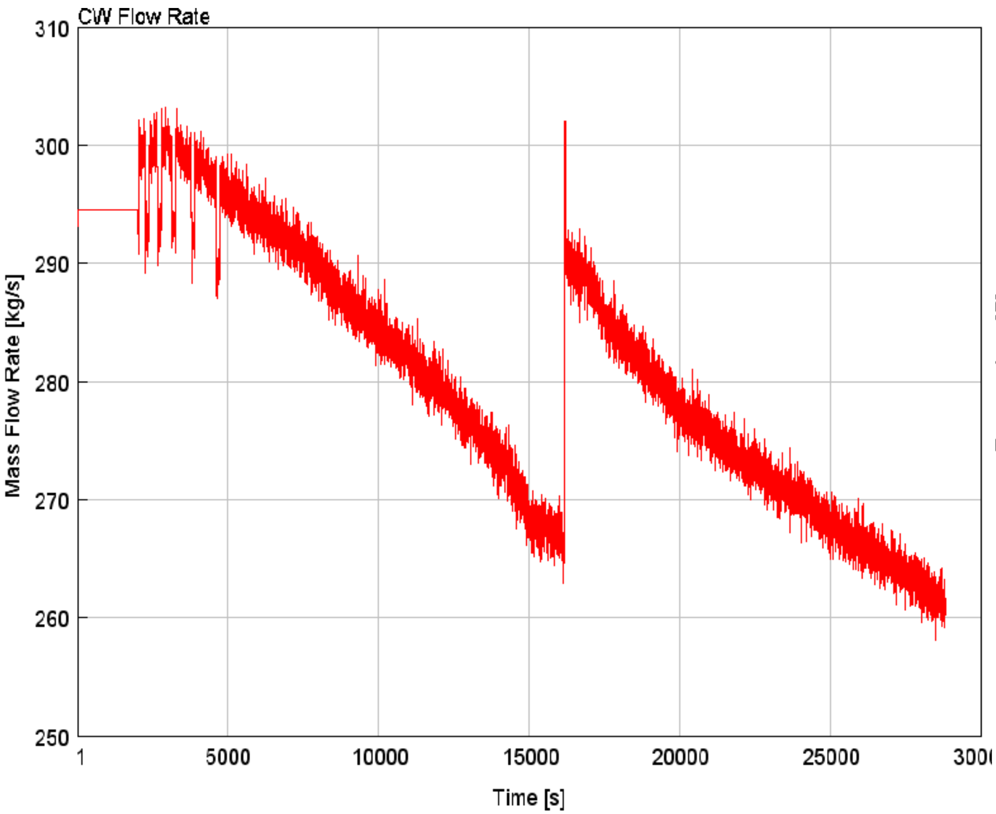


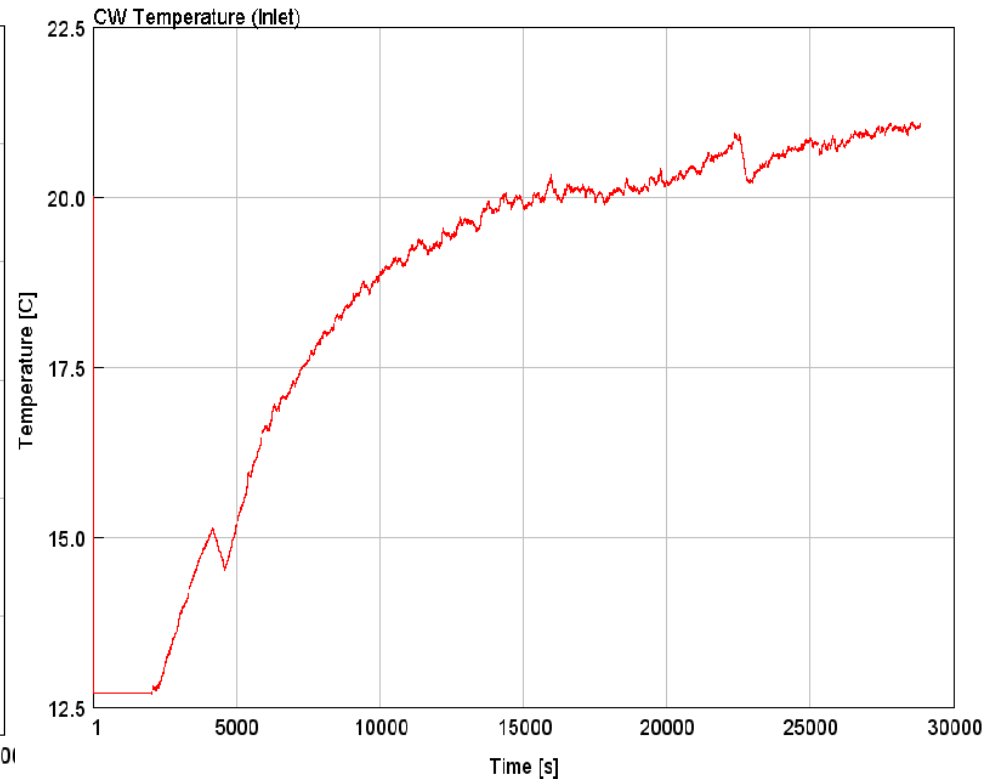
Pressure (MPa)
Enthalpy (kJ/kg)
100.
10.0
1.00
200.
400.
600.
800.
1000 kg/m³
950 kg/m³
900 kg/m³
850 kg/m³
800 kg/m³
750 kg/m³
700 kg/m³
650 kg/m³
600 kg/m³
550 kg/m³
500 kg/m³
450 kg/m³
400 kg/m³
350 kg/m³
300 kg/m³
250 kg/m³
200 kg/m³
150 kg/m³
100 kg/m³
50 kg/m³
40 °C
60 °C
80 °C
100 °C
120 °C
140 °C
160 °C
180 °C
200 °C
220 °C
240 °C
260 °C
280 °C
300 °C
0.7 kJ/kg-K
0.9 kJ/kg-K
1.1 kJ/kg-K
1.3 kJ/kg-K
1.5 kJ/kg-K
1.7 kJ/kg-K
1.9 kJ/kg-K
2.1 kJ/kg-K
2.3 kJ/kg-K
2.5 kJ/kg-K
2.7 kJ/kg-K
2.9 kJ/kg-K
20 °C
0 °C
-20 °C
-40 °C

System Model: Boundary Conditions

Cold water flowrate (kg/s)



Cold water temperature (^oC)



Boundary conditions