Printed Circuit Heat Exchanger and Finned-Tube Heat Exchanger Modeling for a Supercritical CO₂ 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
sCO₂ 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 sCO₂ 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.


>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 \( \text{sCO}_2 \) power cycles, finned-tube HX are used for exhaust gas-to-\( \text{CO}_2 \) (heat source) heat transfer.
- Air cooled condenser/cooler (ACC): In \( \text{sCO}_2 \) power cycle finned-tube HX are used for \( \text{CO}_2 \)-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 \( \text{sCO}_2 \) applications, they were modeled based on manufacturer-supplied design point data.
Test System: 7.3MWe net power sCO₂ cycle

Focus of current study

EPS100 – commercial sCO₂ 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

**Heat Exchanger Outlet Temperature**

Recuperator and HRHX outlet temperatures from validation simulation

**Heat Exchanger Pressure Drop**

Recuperator and HRHX pressure drops from validation simulation
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 Outlet Temperatures

ACC CO₂ Outlet Temperature

PHX CO₂ and exhaust outlet temperatures from validation

ACC CO₂ outlet temperatures from validation (seven bays simulation)
Results: Recuperator (PCHE)
Results: Heat rejection HX (PCHE)
Results: HRHX transient response

HRHX HTR and CO2 Flow: Test Data

- TestData: CO2 Side kW
- TestData: Water Side kW
- TestData: CO2 Flow

Water outlet temperature measuring instrumentation was 70 feet away from HRHX.

HRHX HTR: Simulation

- Simulation: CO2 kW
- Simulation: Water kW
- Simulation: Water kW (Estimated)

Calculated water side heat transfer rate from simulation data with outlet temperature considered at 70 feet away from HRHX (to match the test measurement conditions).
Results: PCHE transient response - RHX

Recuperator Heat Transfer Rate Comparison

- Test Data: Hot
- Test Data: Cold
- Simulation: Hot Side
- Simulation: Cold Side

Heat transfer rate [kW]

Time [s]
Results: Fin-tube transient response – PHX

PHX Transient Response for Step Change in Exhaust Temperature

- Simulation: Exhaust Heat Transfer Rate
- Simulation: CO2 Heat Transfer Rate
- Exhaust Temperature

PHX Transient Response for Step Change in Exhaust Flow

- Simulation: Exhaust Heat Transfer Rate
- Simulation: CO2 Heat Transfer Rate
- Exhaust Flow
Results: Fin-tube transient response – ACC

![Graph 1: ACC Heat Transfer Rate for Step Change in CO2 Flow](image1)

![Graph 2: ACC Heat Transfer Rate for Step Change in CO2 Inlet Temperature](image2)
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.

\[ mc \frac{dT}{dt} = UA (\Delta T_m - \Delta T_{m,ss}) \]

\[ \tau = \frac{mc}{UA} \]

<table>
<thead>
<tr>
<th>Paper # 139</th>
<th>HRHX (PCHE)</th>
<th>Recuperator (PCHE)</th>
<th>PHX (Finned-tube HE)</th>
<th>ACC (Finned-tube HE)</th>
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<tbody>
<tr>
<td>Mass (kg)</td>
<td>14890</td>
<td>3470</td>
<td>54431</td>
<td>46274 (One Bay)</td>
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<tr>
<td>UA (kW/K)</td>
<td>4811</td>
<td>201</td>
<td>196</td>
<td>402</td>
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<td>( \tau ) (seconds)</td>
<td>1.5</td>
<td>9</td>
<td>139</td>
<td>60</td>
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</table>
System Model: Boundary Conditions

Cold water flowrate (kg/s)

Cold water temperature (°C)
Boundary conditions