Numerical dimensioning of a Pre-Cooler for sCO$_2$

Power Cycles to utilize industrial Waste Heat

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Outline

1. Motivation and Introduction
2. Industrial Waste Heat Sources
3. Numerical Model
4. Numerical Results
5. Summary and Outlook
Motivation and Introduction

Industrial Waste Heat

... is heat that arises both from equipment inefficiencies and from thermodynamic limitations on equipment and processes. *DOE (2008)*

Global primary energy consumption

![Graph showing global primary energy consumption from 1800 to 2000.](image)

*Our World in Data (2018)*

Industrial waste heat potential in Europe

![Graph showing industrial waste heat potential in Europe.](image)

*Brückner (2015)*

\[ \eta_C = 1 - \frac{T_{ref}}{T_{src}} \]

→ Waste heat utilization by sCO₂
Industrial Waste Heat

Gas grid Europe

Gas compressor stations:
- Approximately each 100 km
- Compressor driven by gas turbine
- Exhaust gas stream potential waste heat
- Utilization by sCO2 power cycle

Industrial gas turbine

\[ T_{wh} = 515 \, ^\circ C \]
\[ m_{wh} = 49.1 \, kg/s \]
\[ Q_{wh} = 28.5 \, MW \]
Industrial Waste Heat

Cycle modelling

<table>
<thead>
<tr>
<th>Component</th>
<th>Turbine</th>
<th>Compressor</th>
<th>Recuperator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>90 %</td>
<td>85 %</td>
<td>90 %</td>
</tr>
</tbody>
</table>

Both cases possible.

Liquid cooler for not recuperated cycle: p = 7.5 MPa, T = 352 °C
Numerical model
Analytical pre-calculation

Analytical pre-calculation

Heat transfer and pressure drop

\[ \Delta T_{\text{CO}_2}, \Delta T_{\text{H}_2\text{O}}, \Delta \phi \in (\text{kg/m}^2\text{s}) \]

\[ \phi_{\text{calc}} \geq 500\,\text{kPa} \]

\[ \text{Motivation} \rightarrow \text{Industrial Waste} \rightarrow \text{Heat} \rightarrow \text{Numerical model} \rightarrow \text{Results} \rightarrow \text{Summary} \]
Numerical model

Model and Boundary Conditions

Conservation of mass
\[ \frac{\partial \bar{u}_j}{\partial x_j} = 0 \]

Conservation of momentum
\[ \frac{\partial (\rho \bar{u}_j \bar{u}_i)}{\partial x_j} = - \frac{\partial P}{\partial x_i} - \frac{\partial (\tau_{ij} + \rho \bar{u}_i' \bar{u}_j')}{\partial x_j} + S_M \]

Conservation of energy (static enthalpy)
\[ \frac{\partial (\rho \bar{u}_j \bar{h})}{\partial x_j} = - \frac{\partial (\bar{q}_j + \rho \bar{u}_j' \bar{h}')}{\partial x_j} + S_E \]

CFD Simulation
- solving steady-state RANS equations
- eddy viscosity modeled by SST turbulence model

Configurations
- Different mass flow rates
- Different channel diameters
- Different internal fin heights

Motivation
Industrial Waste Heat
Numerical model
Results
Summary

Li (2011)
Numerical model

Mesh independency and model validation

Validation by experiments of Kruizenga A. et al. (2011):

Mesh independency for 1.5 to 9.6 million elements:

Results

Numerical results – channel diameter

Channel – reduced diameter increases

- Heat transfer surface and heat flow
- Higher pressure drop
- Small impact on global performance

Motivation
Industrial Waste Heat
Numerical model
Results
Summary
Results

Numerical results – fin height

Internal fin design – fin height increases

- Heat transfer surface and heat flow
- Higher pressure drop
- Global performance optimum at $h = 0.04$ mm
Results

Design proposal

Modular design for industrial gas turbine

- $m_{\text{CO}_2} = 20 \text{ kg/s}$
- 860 plates, each 677 channels
- gas turbine WHR: 2 modules

**Motivation**

**Industrial Waste Heat**

**Numerical model**

**Results**

**Summary**
Summary and outlook

Design proposal

Summary

• Essential industrial waste heat sources identified
• Simple sCO2 power cycle model developed
• Analytical and numerical pre-cooler model developed and evaluated
• Numerical optimization of channel diameter and internal fin design
• Pe-cooler design proposal for application case

Outlook

• Extend model to further channel geometry
• Assess structural integrity
• Sophisticated flow arrangements (channel geometry)

Motivation Industrial Waste Heat Numerical model Results Summary
Thank you for your attention.

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Our Word in Data. URL: https://ourworldindata.org/. Retrieved: 26/05/2020

Finney, B., Jacobs, M. Phase diagram of CO$_2$. URL: https://upload.wikimedia.org/wikipedia/commons/1/13/Carbon_dioxide_pressure-temperature_phase_diagram.svg. Retrieved: 19/05/2020


MAN Diesel & Turbo. THM Gas Turbines.


Power cycle

Industrial Waste Heat Utilization

<table>
<thead>
<tr>
<th>Component</th>
<th>Turbine</th>
<th>Compressor</th>
<th>Recuperator</th>
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<td>Efficiency</td>
<td>90 %</td>
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</table>

Motivation

Waste Heat

Power Cycle Model

Analytical Model

Numerical Model

Design Proposal

Member of the Helmholtz Association

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Method – Analytical Model

Background

→ rapid assessment of different configurations
→ based on empirical heat transfer correlations
→ iterative process

Investigated parameter range

→ $d_{\text{CO}_2} = 0.5 – 3.0\,\text{mm}$
→ $d_{\text{H}_2\text{O}} = 0.5 – 3.0\,\text{mm}$
→ $G_{\text{CO}_2} = 100 – 900\,\text{kg/(m}^2\text{s)}$

Results

→ required PCHE body length
→ volumetric heat flux
→ sCO$_2$ and coolant pressure drop
# Heat Exchangers

![Shell-and-tube diagram]

<table>
<thead>
<tr>
<th>Heat exchanger design</th>
<th>$p_{\text{max}}$ (MPa)</th>
<th>$T_{\text{max}}$ (°C)</th>
<th>$\beta$ (m²/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shell-and-tube</td>
<td>60</td>
<td>500</td>
<td>100</td>
</tr>
<tr>
<td>PHE (gaskets)</td>
<td>2</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>PHE (braided)</td>
<td>3</td>
<td>220</td>
<td>200</td>
</tr>
<tr>
<td>PFHE</td>
<td>9</td>
<td>650</td>
<td>800-1500</td>
</tr>
<tr>
<td>TFHE</td>
<td>20</td>
<td>200</td>
<td>720-3300</td>
</tr>
<tr>
<td>Spiral</td>
<td>2</td>
<td>400</td>
<td>200</td>
</tr>
<tr>
<td>PCHE</td>
<td>&gt;40</td>
<td>&gt;800</td>
<td>200-5000</td>
</tr>
<tr>
<td>Perforated plate matrix</td>
<td>100</td>
<td>800</td>
<td>6000</td>
</tr>
<tr>
<td>Marbond</td>
<td>&gt;40</td>
<td>&gt;900</td>
<td>10000</td>
</tr>
<tr>
<td>Microstructure</td>
<td>&gt;50</td>
<td>&gt;800</td>
<td>10000-30000</td>
</tr>
</tbody>
</table>


sCO2 Power Cycle

Cycle Layouts

Basic cycle:

Compressor \[\xrightarrow{\text{Heater}}\] Turbine
Pre-cooler

Recuperated cycle:

Compressor \[\xrightarrow{\text{Recuperator}}\] Turbine
Pre-cooler

Recompression cycle:

Main comp. \[\xrightarrow{\text{Re-comp.}}\] Recup LT
Pre-cooler
Recup HT
Turbine

Heater
Supercritical Carbon Dioxide (sCO2)
Heat Transfer Correlations

Rate of heat flow:
\[ \dot{Q} = \alpha A_{ht} (T_w - T_b) \]

Nusselt number:
\[ Nu = \frac{\alpha L_c}{\lambda} \]

Reynolds number:
\[ Re = \frac{\rho u d_{hyd}}{\mu} \]

Prandtl number:
\[ Pr = \frac{\nu}{\alpha} \]

Relationship forced convection
\[ Nu = f(Re, Pr) \]

Gnielinski (1975):
\[ Nu_b = \frac{\frac{f_b}{8} Re_b Pr_b}{1 + 12.7 \sqrt{\frac{f_b}{8} \left( Pr_b^{\frac{2}{3}} - 1 \right)}} \]
\[ f_b = (1.8 \log_{10} Re_b - 1.5)^{-2} \]

Jackson (2002):
\[ Nu_b = 0.0183 Re_b^{0.82} Pr_b^{0.5} \left( \frac{\rho_w}{\rho_b} \right)^{0.3} \left( \frac{c_p}{c_{p,b}} \right)^n \]
\[ n = \begin{cases} 
0.4 & \text{for } T_b < T_w < T_{pc} \text{ or } 1.2 T_{pc} < T_b < T_w \\
0.4 + 0.2 \left( \frac{T_w}{T_{pc}} - 1 \right) & \text{for } T_b < T_{pc} < T_w \\
0.4 + 0.2 \left( \frac{T_w}{T_{pc}} - 1 \right) \left[ 1 - 5 \left( \frac{T_b}{T_{pc}} - 1 \right) \right] & \text{for } T_{pc} < T_b < 1.2 T_{pc} \text{ or } T_b < T_w 
\end{cases} \]
Industrial Waste Heat

Situation

Germany:

EU-27:
Industrial Waste Heat

Waste Heat Sources

![Graph showing waste heat amount versus temperature for different sources.]

- **Waste heat amount (PJ/a)**
- **Temperature (°C)**
- **η_c (%)**

Legend:
- Low
- Intermediate
- High

Sources:
- Cement kiln
- Gas turbine
Power Cycle Model
Results

Temperatures of thermodynamic states

- T₁, T₂, T₃, T₄, T₅

(a) Cement kiln WHR system
(b) Gas turbine WHR system

Specific net work and specific heats

- $w_{\text{net}}$, $q_{\text{heater}}$

(a) Cement kiln WHR system
(b) Gas turbine WHR system

Net power and heater heat duty

- $P_{\text{net, basic}}$, $P_{\text{net, recup}}$, $Q_{\text{heater, basic}}$, $Q_{\text{heater, recup}}$

(a) Cement kiln WHR system
(b) Gas turbine WHR system

Efficiency and power gradient

- $\eta_{\text{basic}}$, $\eta_{\text{recup}}$, $\text{grad}(P_{\text{net, basic}})$, $\text{grad}(P_{\text{net, recup}})$

(a) Cement kiln WHR system
(b) Gas turbine WHR system
Analytical Model
Calculation Scheme
Analytical Model

Results – Gas Turbine WHR

Appendix
Numerical Model

Geometry

Single-channel model

- Inlet sCO2
- Entrance
- sCO2 channel
- Exit
- Outlet sCO2
- $l_{\text{entr,CO2}}$, $l_{\text{ch,CO2}}$, $l_{\text{exit,CO2}}$
- $\dot{m}_{\text{ch,CO2}}/2$, $T_{\text{in,CO2}}$
- $q_w$, $T_w$
- $p_{\text{rel}} = 0 \text{ Pa}$
- Symmetry
- Wall (adiabatic)
- Wall (temperature/heat flux)

Pre-cooler model

- Inlet sCO2
- Entrance
- sCO2 channel
- Exit
- Outlet sCO2
- $l_{\text{entr,CO2}}$, $l_{\text{exit,CO2}}$
- $\dot{m}_{\text{ch,CO2}}/2$, $T_{\text{in,CO2}}$
- $\dot{m}_{\text{ch,H2O}}/2$, $T_{\text{in,H2O}}$
- $p_{\text{rel}} = 0 \text{ Pa}$
- Outlet coolant
- Coolant channel
- Inlet coolant
- Symmetry
- Wall (adiabatic)
- Periodicity
- Wall (conjugate heat transfer)
Numerical Model
Mesh

→ 1.5 – 9.6 million elements
→ inflation layer $y^+ < 1$
Numerical Model
Turbulence Model

Reynolds stresses
\[-\rho u'_i u'_j = \mu_t \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \rho k \delta_{ij} \]

Turbulent kinetic energy
\[
k = \frac{1}{2} u_i u_j
\]

Turbulent kinetic energy
\[
\frac{\partial (\rho u_j k)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k^3} \right) \frac{\partial k}{\partial x_j} \right] + P_k - \beta' \rho k \omega
\]

Turbulent frequency
\[
\frac{\partial (\rho u_j \omega)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_\omega^3} \right) \frac{\partial \omega}{\partial x_j} \right] + \frac{\omega}{k} P_k - \beta_3 \rho \omega^2 + \left( 1 - F_1 \right) \frac{2 \rho}{\sigma_\omega^2} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j}
\]

Blending function for wall distance
\[
F_1 = \tanh \left[ \left( \min \left( \max \left( \sqrt{k}, \frac{500 \nu}{\beta' \omega y}, \frac{4 \rho k}{C D_{k\nu} \sigma_\omega^2 y^2} \right) \right) \right)^4 \right]
\]

Kinematic eddy-viscosity
\[
\nu_t = \frac{a_1 k}{\max (a_1 \omega, SF_2)}
\]

Blending function to restrict eddy-viscosity limiter
\[
F_2 = \tanh \left( \left[ \max \left( \frac{2 \sqrt{k}}{\beta' \omega y}, \frac{500 \nu}{\omega y^2} \right) \right]^2 \right)
\]
Numerical Model
Mesh Independence Study

![Graphs showing relationships between mesh independence study parameters](image)
Numerical Model

Turbulence Models

- sCO2: SST
- Coolant: SST
- k-ε
- k-ω
- laminar

Appendix
Numerical Model
Experimental Validation

<table>
<thead>
<tr>
<th>#</th>
<th>$d_{CO2}$ (mm)</th>
<th>$l_{entr,CO2}$ (mm)</th>
<th>$l_{ch,CO2}$ (mm)</th>
<th>$l_{exit,CO2}$ (mm)</th>
<th>$G_{CO2}$ (kg/(m$^2$.s))</th>
<th>$\dot{q}_w$ (kW/m$^2$)</th>
<th>$T_{in,CO2}$ (°C)</th>
<th>$\rho_{ref}$ (kg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.9</td>
<td>200</td>
<td>500</td>
<td>100</td>
<td>326</td>
<td>-23.2</td>
<td>90</td>
<td>217.0</td>
</tr>
<tr>
<td>2</td>
<td>1.9</td>
<td>200</td>
<td>500</td>
<td>100</td>
<td>762</td>
<td>-33.9</td>
<td>60</td>
<td>233.4</td>
</tr>
</tbody>
</table>

# Numerical Model

## Correlation Comparison

<table>
<thead>
<tr>
<th>#</th>
<th>(d_{\text{CO}_2}) mm</th>
<th>(l_{\text{ch,CO}_2}) mm</th>
<th>(G_{\text{CO}_2}) kg/(m(^2)s)</th>
<th>(\dot{m}_{\text{CO}_2}) g/s</th>
<th>(u) m/s</th>
<th>(R_{\text{e}}) (\times 10^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1</td>
<td>0.50</td>
<td>60</td>
<td>100</td>
<td>0.010</td>
<td>0.4 to 1.6</td>
<td>1 to 2</td>
</tr>
<tr>
<td>Run 2</td>
<td>0.50</td>
<td>80</td>
<td>400</td>
<td>0.039</td>
<td>1.5 to 6.2</td>
<td>4 to 6</td>
</tr>
<tr>
<td>Run 3</td>
<td>0.50</td>
<td>90</td>
<td>700</td>
<td>0.069</td>
<td>2.6 to 10.9</td>
<td>7 to 11</td>
</tr>
<tr>
<td>Run 4</td>
<td>0.50</td>
<td>100</td>
<td>1000</td>
<td>0.098</td>
<td>3.7 to 15.5</td>
<td>10 to 16</td>
</tr>
<tr>
<td>Run 5</td>
<td>1.75</td>
<td>240</td>
<td>100</td>
<td>0.120</td>
<td>0.4 to 1.6</td>
<td>4 to 5</td>
</tr>
<tr>
<td>Run 6</td>
<td>1.75</td>
<td>320</td>
<td>400</td>
<td>0.481</td>
<td>1.5 to 6.2</td>
<td>15 to 22</td>
</tr>
<tr>
<td>Run 7</td>
<td>1.75</td>
<td>350</td>
<td>700</td>
<td>0.842</td>
<td>2.6 to 10.9</td>
<td>25 to 38</td>
</tr>
<tr>
<td>Run 8</td>
<td>1.75</td>
<td>370</td>
<td>1000</td>
<td>1.203</td>
<td>3.7 to 15.5</td>
<td>36 to 55</td>
</tr>
<tr>
<td>Run 9</td>
<td>3.00</td>
<td>440</td>
<td>100</td>
<td>0.353</td>
<td>0.4 to 1.6</td>
<td>6 to 9</td>
</tr>
<tr>
<td>Run 10</td>
<td>3.00</td>
<td>590</td>
<td>400</td>
<td>1.414</td>
<td>1.5 to 6.2</td>
<td>25 to 38</td>
</tr>
<tr>
<td>Run 11</td>
<td>3.00</td>
<td>660</td>
<td>700</td>
<td>2.474</td>
<td>2.6 to 10.9</td>
<td>44 to 66</td>
</tr>
<tr>
<td>Run 12</td>
<td>3.00</td>
<td>690</td>
<td>1000</td>
<td>3.534</td>
<td>3.7 to 15.5</td>
<td>62 to 94</td>
</tr>
</tbody>
</table>

## MRD and MARD

MRD = \(\frac{1}{N} \sum_{i=1}^{N} \frac{\alpha_{i,\text{corr}} - \alpha_{i,\text{CFD}}}{\alpha_{i,\text{CFD}}}\)

MARD = \(\frac{1}{N} \sum_{i=1}^{N} \left| \frac{\alpha_{i,\text{corr}} - \alpha_{i,\text{CFD}}}{\alpha_{i,\text{CFD}}} \right|\)
Numerical Model

Results

Volumetric heat flux

Overall heat transfer coefficient

sCO2 pressure drop

Coolant pressure drop

Appendix
Numerical Model

Results

Global performance sCO2 channel

Global performance coolant channel

(a) Cement kiln WHR system
(b) Gas turbine WHR system

\[ GPC = \frac{\dot{Q}_{tot}}{\Delta p_{tot} \dot{V}} \]
Numerical Model
Comparison Analytical and Numerical Model

Configuration:
GT-5-8-700
Numerical Model
Visualization

sCO2 bulk temperature

Configuration:
GT-5-8-700

(a) 40 mm
(b) 80 mm
(c) 120 mm
(d) 160 mm
(e) 200 mm

sCO2 velocity axial

(a) 40 mm
(b) 80 mm
(c) 120 mm
(d) 160 mm
(e) 200 mm
Numerical Model
Visualization

Configuration:
GT-5-8-700

sCO2 velocity radial

(a) 40 mm  (b) 80 mm  (c) 120 mm  (d) 160 mm  (e) 200 mm
Numerical Model
Visualization

Configuration:
GT-5-8-700

PCHE body temperature

Temperature (°C)

(a) 40 mm  (b) 80 mm  (c) 120 mm  (d) 160 mm  (e) 200 mm
Numerical Model
Visualization

Configuration:
GT-5-8-700

PCHE body heat flux

Heat flux (kW/m²)

(a) 40 mm  
(b) 80 mm  
(c) 120 mm  
(d) 160 mm  
(e) 200 mm
Numerical Model
Visualization

Configuration:
GT-5-8-700

PCHE temperature distribution
Design Proposal
Flow Distribution

(a) sCO2 plate

(b) Coolant plate