S-CO₂ cycle design and control strategy for the SFR application

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S-CO$_2$ Power Cycle Development

Small Modular sized SFR design

<table>
<thead>
<tr>
<th>Name</th>
<th>CEFR</th>
<th>PFBR-500</th>
<th>PRISM</th>
<th>4S</th>
<th>ARC-100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal power class</td>
<td>Small</td>
<td>Medium</td>
<td>Medium</td>
<td>Small</td>
<td>Small</td>
</tr>
<tr>
<td>Efficiency, %</td>
<td>30</td>
<td>40</td>
<td>37</td>
<td>37</td>
<td>38</td>
</tr>
<tr>
<td>Core outlet temperature, °C</td>
<td>530</td>
<td>547</td>
<td>510</td>
<td>510</td>
<td>510</td>
</tr>
<tr>
<td>Developer</td>
<td>CIAE</td>
<td>IGCAR</td>
<td>GE-Hitachi</td>
<td>Toshiba</td>
<td>Advanced Reactor Concepts</td>
</tr>
<tr>
<td>Country</td>
<td>China</td>
<td>India</td>
<td>U.S.A</td>
<td>Japan</td>
<td>U.S.A</td>
</tr>
<tr>
<td>Power conversion system</td>
<td>Steam Rankine</td>
<td>S-CO$_2$ Brayton</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
S-\text{CO}_2 \text{ Power Cycle Development}

- The benefits of the S-\text{CO}_2 cycle:
  - relatively high efficiency under the mild turbine inlet temperature condition
  - simple layout and compact size
  - Potentially enhanced the safety of the SFR system

- Thermal efficiencies of power conversion systems and applications

- Comparison of sodium reaction with water and \text{CO}_2 in a pipe [J. Eoh (2010)]
S–CO₂ Power Cycle Development

S–CO₂ cycle design flow chart

Innovative Brayton Cycle for SFR application

S–CO₂ Cycle Design

Design Phase
- Layout selection
- Component design
- Size estimation

S–CO₂ System Analysis Code Development

Steady-state design code

TM Design
- ns-ds
- 1-D design

HX Design
- PCHE

Quasi-state analysis code

TM off-design performance

S–CO₂ Integral Experiment Loop

Design Phase
- Layout selection
- Component design

Performance Experiment
- Compressor test
- Simple cycle test
- Recuperation cycle test
- Recompression cycle test

System code implementation

CO₂ Recovery System Design

Development of Critical Flow Model

Calculating the Leakage Rate in Turbo-machinery

CO₂ Critical Flow Code Implementation

Optimization of CO₂ Recovery System

CO₂ Recovery System Design
S-CO₂ Power Cycle Development

S-CO₂ cycle design

- The KAIST-Closed Cycle Design (KAIST_CCD) code, an in-house code developed by KAIST research team is based on the MATLAB.
- Enthalpy and other fluid properties information for the code calculation is provided directly by the NIST reference fluid thermodynamic and transport properties database (REFPROP).

▲ S-CO₂ cycle condition for SFR application


▲ T-s diagram and sensitivity analysis through the KAIST_CCD
S–CO₂ Component Design

S–CO₂ cycle turbomachinery design

- Generally, in a large scale system, axial type turbomachineries are favored over other types.
- However, in the S–CO₂ cycle, radial type turbomachineries can be more appropriate even for the relatively large scale MW output system due to the high density and low pressure ratio cycle characteristics.

- Operating characteristics between axial and radial turbomachinery (Gong et al., 2006)

<table>
<thead>
<tr>
<th>Radial</th>
<th>Axial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relatively constant flow, variable head</td>
<td>Relatively constant head, variable flow behavior</td>
</tr>
<tr>
<td>Best suited for lower flow rate</td>
<td>Best suited for higher flow rate</td>
</tr>
<tr>
<td>Higher pressure ratio applications</td>
<td>Moderate pressure ratio applications</td>
</tr>
<tr>
<td>Fewer or single stage</td>
<td>Commonly used with multi stage configurations</td>
</tr>
<tr>
<td>Shorter axial length due to fewer stages</td>
<td>Longer axial length due to multi stages</td>
</tr>
<tr>
<td>Relatively wider operating range</td>
<td>Limited operating range</td>
</tr>
<tr>
<td>Lower efficiency by up to 4% in general compared to the axial machine</td>
<td>Higher efficiency, especially if shrouded</td>
</tr>
</tbody>
</table>

- Turbomachinery Technology options for S–CO₂ cycle [Sienicki, J., 2011]
Ideal gas based correlations cannot be used for S-CO₂

Governing Equation (Continuity equation + Euler equation)

\[ \dot{m} = \rho (h_s, P_s)AV \]

\[ h_{02} - h_{01} = U_2 W_{W2} - U_1 W_{W1} \]

Ideal gas correlations

\[ T_s C_p = T_p C_p + \frac{V^2}{2} \]

\[ \frac{T_p}{T_s} = 1 + \frac{V^2}{2C_p T_s} = 1 + \frac{\gamma - 1}{2} M^2 \]

\[ \frac{P_p}{P_s} = \left( \frac{T_p}{T_s} \right)^{\frac{\gamma}{\gamma - 1}} = \left( 1 + \frac{\gamma - 1}{2} M^2 \right)^{\frac{\gamma}{\gamma - 1}} \]

Call from NIST property database

▲ Predicted off-design performance map (Sandia National Lab.)
**Code validation and verification (V&V)**

- The Sandia National Laboratory (SNL) data are the only available compressor performance data on the S-CO₂ cycle research field so far.
- To validate KAIST_TMD, the compressor off design map from it compared with experimental data from SNL.
- KAIST_TMD has similar tendency in pressure ratio, whereas the efficiencies were predicted with some errors.
- It suggests that internal loss models based on air yield reasonable results with S-CO₂.
- Three external impeller loss models are considered such as recirculation, disk friction, and leakage.
- External losses are added only to the impeller exit stagnation enthalpy without any pressure change. It means external losses only affect efficiencies.

*Source: S.A. Wright. et al., Operation and Analysis of a S-CO₂ Brayton cycle, 2010*
S-CO$_2$ Component Design

S-CO$_2$ cycle turbomachinery design

**Turbine Performance**
- Impeller diameter: 0.95m
- Rotating speed: 7200rpm→3600rpm

**Main Compressor Performance**
- Impeller diameter: 0.55m
- Rotating speed: 7200rpm→3600rpm

**Recompression compressor Performance**
- Impeller diameter: 0.74m
- Rotating speed: 7200rpm→3600rpm
Operating condition
- High pressure ($P_{\text{min}} > 7.4 \text{ MPa}$)
- High temperature

Printed Circuit Heat Exchanger
- Highly compact & effective – Excellent choice for gas heat exchanger
- Parallel core stacking - Enables to use on large systems
S-CO$_2$ Component Design

Heat exchanger design code [KAIST_HXD]

- **Heat exchanger design**
  - All heat exchanger is assumed to be the Printed Circuit Heat Exchanger (PCHE) type.
  - KAIST-HXD(Heat Exchanger Design) in-house code is used.

  - Material: SUS 316
  - Material density = 8000 kg/m$^3$
  - Material melting point = 1375~1400 °C
  - Channel diameter, $d_c$ = 1.8~2.2 mm
  - t(Plate thickness) = 0.5 mm
  - $P_c$ (Channel pitch) = 2.2~2.6 mm, $P_c = d_c + t_f$ => $t_f = 0.4$ mm
  - Recuperator Effectiveness(%): 95

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**Fig. PCHE configuration**

<table>
<thead>
<tr>
<th>Fluid</th>
<th>sodium</th>
<th>helium</th>
<th>CO$_2$</th>
<th>N$_2$</th>
<th>water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nu Correlation</td>
<td>$Nu = 7 + 0.025 \cdot Pe^{0.8}$</td>
<td>$Nu = 4.065 + 0.00305 \cdot Re$</td>
<td>$Nu = 0.1696 \cdot Re^{0.629} \cdot Pr^{0.317}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$f$ Correlation</td>
<td>$f = 0.0014 + 0.125 \cdot Re^{-0.32}$</td>
<td>$f = \frac{16.51}{Re} + 0.1627$</td>
<td>$f = 0.01924 \cdot Re^{-0.991}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Applicable range, [N$_{Re}$]</td>
<td>Not limited</td>
<td>250-350</td>
<td>2,500-33,000</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table. Heat exchanger design parameters of 75MWe S-CO$_2$ cycle**

<table>
<thead>
<tr>
<th>Heat exchanger</th>
<th>HTR</th>
<th>LTR</th>
<th>PC</th>
<th>IHX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat, MW</td>
<td>108.2</td>
<td>268.7</td>
<td>102.1</td>
<td>178.8</td>
</tr>
<tr>
<td>Effectiveness, %</td>
<td>97.1</td>
<td>93.1</td>
<td>73.8</td>
<td>90.5</td>
</tr>
<tr>
<td>Volume, m$^3$</td>
<td>6.9</td>
<td>8.5</td>
<td>3.07</td>
<td>2.3</td>
</tr>
<tr>
<td>Geometry, m (L x W x H)</td>
<td>1.1 x 2.5 x 2.5</td>
<td>1.4 x 2.5 x 2.5</td>
<td>1 x 1.75 x 1.75</td>
<td>0.6 x 2.1 x 2.1</td>
</tr>
</tbody>
</table>
S-CO$_2$ Component Design

Heat exchanger design code [ KAIST_HXD ]

- **Code validation and verification (V&V)**
  - Developed KAIST_HXD can be used for:
    1. Design optimization
    2. Steady state performance analysis
  - Lab-scale PCHE was designed with the design code and manufactured by a Korean manufacturer.
  - Manufactured PCHE was installed to a KAIST S-CO$_2$ cycle experimental facility (S-CO$_2$PE) and the performance test was conducted.
  - Experimental data was accumulated for reliable design code validation.

View of the S-CO$_2$PE facility & designed PCHE

Designed PCHE & Experimental data of CO$_2$ side
S-CO₂ Pipe Design

Determination of Pipe Diameter and Thickness for S-CO₂ Cycle

**Flow Velocity**

\[ V = f_{pv}/\rho^{0.3} \]

by Ronald W. Capps (Chem. Eng. 1995.6)

\( V \): optimal flow velocity \([m/s]\)
\( f_{pv} \): pipe velocity factor \([m(\text{kg/m}^3)^{0.3}/s]\)
\( \rho \): density of flow \([\text{kg/m}^3]\)

**Minimum thickness**

\[ t_m = \frac{P D_0}{2(S E + P Y)} + A \]

\( t_m \): minimum required wall thickness \([m]\)
\( P \): internal design pressure \([\text{Pa}]\)
\( D_0 \): outside diameter of pipe \([\text{m}]\)
\( S \): maximum allowable stress \([\text{Pa}]\)
\( E \): weld joint efficiency
\( Y \): coefficient
\( A \): additional thickness \([\text{m}]\)

<table>
<thead>
<tr>
<th>PIPE VELOCITY FACTORS</th>
<th>Motive Energy Source</th>
<th>( m(\text{kg/m}^3)^{0.3}/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centrifugal Pump, Blower</td>
<td></td>
<td>14</td>
</tr>
<tr>
<td>Compressor Pipe dia&lt;6in.</td>
<td></td>
<td>24</td>
</tr>
<tr>
<td>Pipe dia&gt;6in.</td>
<td></td>
<td>29</td>
</tr>
<tr>
<td>Steam Boiler</td>
<td></td>
<td>63 ~ 68</td>
</tr>
</tbody>
</table>

- Conceptual design of S-CO₂ Recompression Cycle
  - 3D Schematic

**Piping was selected in accordance with the ASME standard**

<table>
<thead>
<tr>
<th>S.C.</th>
<th>Nominal Pipe Size</th>
<th>External Diameter (m)</th>
<th>Velocity (m/s)</th>
<th>Thickness (m)</th>
<th>Material type</th>
<th>Pressure drop (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>①</td>
<td>24</td>
<td>0.610</td>
<td>31.8</td>
<td>0.03493</td>
<td>Nickel and High Nickel Alloys, N06600, B 168</td>
<td>46.68</td>
</tr>
<tr>
<td>②</td>
<td>28</td>
<td>0.711</td>
<td>42.7</td>
<td>0.01905</td>
<td>Nickel and High Nickel Alloys, N06600, B 168</td>
<td>28.47</td>
</tr>
<tr>
<td>③</td>
<td>28</td>
<td>0.711</td>
<td>25.3</td>
<td>0.01905</td>
<td>Low and Intermediate Alloy Steel, P91 A335</td>
<td>60.78</td>
</tr>
<tr>
<td>④</td>
<td>28</td>
<td>0.711</td>
<td>15.8</td>
<td>0.01748</td>
<td>Low and Intermediate Alloy Steel, P91 A335</td>
<td>8.50</td>
</tr>
<tr>
<td>⑤</td>
<td>28</td>
<td>0.711</td>
<td>10.3</td>
<td>0.01748</td>
<td>Low and Intermediate Alloy Steel, P91 A335</td>
<td>13.17</td>
</tr>
<tr>
<td>⑥</td>
<td>24</td>
<td>0.610</td>
<td>3.9</td>
<td>0.01588</td>
<td>Low and Intermediate Alloy Steel, P91 A335</td>
<td>0.91</td>
</tr>
<tr>
<td>⑦</td>
<td>24</td>
<td>0.610</td>
<td>3.7</td>
<td>0.03493</td>
<td>Nickel and High Nickel Alloys, N06600, B 168</td>
<td>2.25</td>
</tr>
<tr>
<td>⑧</td>
<td>24</td>
<td>0.610</td>
<td>7.7</td>
<td>0.03493</td>
<td>Nickel and High Nickel Alloys, N06600, B 168</td>
<td>22.95</td>
</tr>
<tr>
<td>⑨</td>
<td>24</td>
<td>0.610</td>
<td>7.6</td>
<td>0.01588</td>
<td>Low and Intermediate Alloy Steel, P91 A335</td>
<td>4.75</td>
</tr>
<tr>
<td>⑩</td>
<td>24</td>
<td>0.610</td>
<td>4.4</td>
<td>0.03493</td>
<td>Nickel and High Nickel Alloys, N06600, B 168</td>
<td>2.81</td>
</tr>
<tr>
<td>⑪</td>
<td>24</td>
<td>0.610</td>
<td>12.5</td>
<td>0.03493</td>
<td>Nickel and High Nickel Alloys, N06600, B 168</td>
<td>6.94</td>
</tr>
<tr>
<td>⑫</td>
<td>24</td>
<td>0.610</td>
<td>23.8</td>
<td>0.03493</td>
<td>Nickel and High Nickel Alloys, N06600, B 168</td>
<td>89.39</td>
</tr>
</tbody>
</table>

Total pressure drop uncluding minor loss (kPa) 287.60
CO₂ Recovery System Design

The suggested concept

- Conventional leak rate is assumed, which the conventional leak rate is less than $1\text{kg/s}$ per seal.
- To reduce the thermal efficiency loss with CO₂ recovery
- It is not only simple and intuitive but also has relatively very low additional $W_{\text{comp}}$.
- It does not need additional compressor.
- Calculate the $W_{\text{net,loss}} \rightarrow 0.312 \text{ MW}_e$
- Thermal efficiency loss caused by CO₂ inventory recovery system is 0.17 %.

Inventory total mass

$= \text{CO₂ in Pipe + CO₂ in HX}$

$= (1224.2+2766.0) \text{ kg}$

$= 3990.2 \text{ kg}$

(It considers the HXs and Pipes)

One loss was considered

- $W_{\text{net,loss}}$

\[ W_{\text{net,loss}} = W_{\text{net,design}} - W_{\text{net,new}} \]

\[ = W_{\text{net,design}} - (W_{\text{turb,new}} - W_{\text{comp,new}}) \]

<table>
<thead>
<tr>
<th>Storage tank (Low-pressure tank)</th>
<th>Leakage position (High-pressure tank)</th>
<th>$T$ (°C)</th>
<th>$P$ (MPa)</th>
<th>$\dot{m}$ (kg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1. TB inlet</td>
<td>508.6</td>
<td>19.36</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2. MC outlet</td>
<td>61.6</td>
<td>20.21</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>3. RC outlet</td>
<td>156.2</td>
<td>20.20</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total mass flow rate</td>
<td></td>
<td></td>
<td>3.0</td>
</tr>
</tbody>
</table>

Preliminary design on CO₂ inventory recovery system of S-CO₂ power cycle for 75MWe SFR application
**CO₂ Recovery System Design**

**CO₂ critical flow model**

- **Description of CO₂ critical flow model**

  - Initial \( P_0, T_0 \) of CO₂
  - Critical pressure ratio check
  - Mach number check (choked or not)
  - Mass flux calculation
  - Changed \( P_0, T_0 \) of CO₂

  ![Experimental Facility for CO₂ leak simulation](image)

  ![Isentropic Critical Flow Model](image)

  High Pressure CO₂ tank  \( \rightarrow \)  Low Pressure CO₂ tank

  **Mass/Energy balance**  \[ \dot{m}_{CO₂} \]

  **Mass balance**

**Design specifications for experimental system**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>High/Low-pressure tank</td>
<td></td>
</tr>
<tr>
<td>Pressure (MPa)</td>
<td>22</td>
</tr>
<tr>
<td>Temperature (℃)</td>
<td>200</td>
</tr>
<tr>
<td>Volume (L)</td>
<td></td>
</tr>
<tr>
<td>I.D.: 200mm H: 1,500mm</td>
<td></td>
</tr>
<tr>
<td>Pipe connecting two tanks</td>
<td></td>
</tr>
<tr>
<td>I.D. (mm)</td>
<td>57</td>
</tr>
<tr>
<td>Length (mm)</td>
<td>1090</td>
</tr>
<tr>
<td>Heater (Jacket-type)</td>
<td></td>
</tr>
<tr>
<td>Electric capacity (kW)</td>
<td>5</td>
</tr>
<tr>
<td>Valve type</td>
<td>Ball valve</td>
</tr>
</tbody>
</table>

**Governing equations**

\[
G = \rho V_{velocity} = constant
\]

\[
\frac{P_0}{P_{critical}} = \left(1 + \frac{\gamma - 1}{2}\right)^{\frac{\gamma}{(\gamma - 1)}}
\]

\[
M = \sqrt{\frac{2}{\gamma - 1}} \left(\frac{P}{P_0}\right)^{\frac{\gamma - 1}{\gamma}} - 1
\]

\[
G = \frac{P}{\sqrt{R T_0}} \sqrt{\gamma M} \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma + 1}{2(\gamma - 1)}}
\]
CO₂ Recovery System Design

CO₂ critical flow model

- **Code validation and verification (V&V)**
  - KAIST research team conducted experiments with CO₂ critical flow simulation facility in turbine inlet and compressor outlet conditions.
  - The mass flux calculated by using the measured values has similar trend with the result of CO₂ critical flow model in all cases.
S-\(\text{CO}_2\) Cycle Control Strategy

Part load operation control strategy of S-\(\text{CO}_2\) cycle

▲ S-\(\text{CO}_2\) cycle quasi-static analysis code algorithm

▲ Comparison of S-\(\text{CO}_2\) cycle performance in part load conditions

▲ Comparison of compressor surge margin in part load conditions
Conclusions and Future Work

**Conclusions**

- The S-CO₂ power conversion system is suitable for the small modular SFR application due to the safety, high efficiency, and small footprint.
- The S-CO₂ cycle design can be potentially applied with existing lab-scale experimental data.
- KAIST research team has accumulated many reliable data of main component’s software and hardware for the S-CO₂ cycle design, but further code V&V should be performed for the complete power system design with control strategy.

**Future work**

- Code V&V for turbomachinery and heat exchanger design codes will be further performed.
- The leakage flow and physical phenomena in the turbomachinery seal sections will be further studied in the future.
- To establish the most efficient strategy for the part load conditions, the potential of the valve and inventory controls will be further investigated.
- Real time simulation in various operation conditions will be conducted through the transient analysis code.
- For the safety analysis of Sodium leak scenario, study of Na-CO₂ reaction in heat exchanger will be performed.