Development of A Transient Analysis Code for S-CO2 Power Conversion System

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CONTENTS

◆ Introduction

◆ SCTRAN/CO2 development

◆ Initial verification for component model

◆ Initial verification for loop simulation

◆ Conclusion & expectation
PART 1 INTRODUCTION

S-CO2 Brayton Cycle

S-CO2 Brayton Cycle Advantage:
✓ High thermal efficiency
✓ Simple configuration
✓ Compact turbomachinery

A Simple Brayton Cycle Layout

Transverse analysis code used in S-CO2 Brayton Cycle

<table>
<thead>
<tr>
<th>Built up method</th>
<th>Analysis code</th>
<th>Applied in</th>
</tr>
</thead>
<tbody>
<tr>
<td>Developed with an exist Transient analysis code</td>
<td>TRACE</td>
<td>S-CO2 Brayton cycle</td>
</tr>
<tr>
<td></td>
<td>GAMMA+</td>
<td>KAIST Micro Modular Reactor(MMR)</td>
</tr>
<tr>
<td></td>
<td>MARS</td>
<td>Supercritical CO2 Integral Experimental Loop (SCIEL)</td>
</tr>
<tr>
<td></td>
<td>RELAP5-3D</td>
<td>SCO2 cooled fast reactors</td>
</tr>
<tr>
<td></td>
<td>MMS-LMR</td>
<td>Sodium cooled fast reactor KALIMER-600</td>
</tr>
<tr>
<td></td>
<td>GAS-PASS</td>
<td>S-CO2 Brayton cycle coupled to lead-cooled fast reactor</td>
</tr>
<tr>
<td>Developed with nothing</td>
<td>Plant Dynamics Code (PDC)</td>
<td>S-CO2 Brayton cycle</td>
</tr>
</tbody>
</table>
PART 2  SCTRAN/CO2 Development

- SCTRAN introduction

- Component model needed for SCTRAN/CO2
  - Constitutive model
  - Compressor model
  - Gas turbine model
  - Shaft model
2.1 SCTRAN Introduction

- SCTRAN
- A safety analysis code for SCWR

- SCTRN/CO2
- Thermal Property for CO₂
- Heat Transfer & Friction Correlation
- Compressor model & Gas Turbine model

- Transient Analysis Code for S-CO₂ Brayton Loop

PART 1 INTRODUCTION
PART 2 SCTRAN/CO₂ DEVELOPMENT
PART 3 COMPONENT MODEL VERIFICATION
PART 4 LOOP SIMULATION VERIFICATION
PART 5 CONCLUSION
2.2 Constitutive Model

Property of carbon dioxide

\[ F(p, h) = \sum_{i=0}^{4} \sum_{j=0}^{4} a_i p^i h^j, \quad p \leq p_{\text{critical}}, \quad h < h_i(p) \quad \text{or} \quad p > p_{\text{critical}}, \quad h \leq h_{\text{sat}20} \]

\[ F(p, h) = \sum_{i=0}^{4} \sum_{j=0}^{4} b_{ij} p^i h^j, \quad p \leq p_{\text{critical}}, \quad h_{\text{sat}11} < h \leq h_{\text{sat}20} \]

\[ F(p, h) = \sum_{i=0}^{4} c_p p^i h^j, \quad h > h_{\text{sat}31} \]

\[ F(p, h) = F(p, h) + \left( \frac{h - h_{\text{sat}20}}{h_{\text{sat}21} - h_{\text{sat}20}} \right) \left[ F(p, h_{\text{sat}21}) - F(p, h_{\text{sat}20}) \right] \]

\[ 5 < p < 5.5 \text{MPa} \]
### 2.2 Constitutive Model

- **Heat transfer correlation**
  
  Gnielinski Correlation:

  \[
  N_u = \frac{hD_e}{\lambda} = \frac{(f / 8)(Re-1000)Pr}{1+12.7\sqrt{(f / 8)(Pr^{2/3} - 1)}}, \quad 2300 < Re < 5 \times 10^6, \quad 0.5 < Pr < 200
  \]

- **Friction correlation**

  \[
  \frac{1}{\sqrt{f}} = -2\log\left\{ \frac{\varepsilon}{3.7D_e} + \frac{2.51}{Re} \left[ 1.14 - 2\log\left( \frac{\varepsilon}{D_e} + \frac{21.25}{Re^{0.9}} \right) \right] \right\} , \quad Re > 3400
  \]

  \[
  f = \frac{64}{Re}, \quad Re < 2300
  \]
2.3 Compressor Model

- Compressor model: Solution

- Compressor torque

\[ \tau_t = \tau_s + \tau_d = \frac{m}{\omega} (h_{2s} - h_{01}) + m \left( \frac{h_{02}}{2} - h_{2s} \right) \]

- Ideal outlet fluid enthalpy

\[ h_{2s} = h_{01} + \int_{P_1}^{P_2} v_m \cdot dp \]

among, \( P_2 = P_1 \cdot R_P \)

- Realistic outlet fluid enthalpy

\[ \eta_{ad} = \frac{h_{2s} - h_{01}}{h_{02} - h_{01}} \]
2.3 Compressor Model

- Compressor model: Integrated in SCTRAN

  - Total torque of compressor
    \[ \tau_t = \tau_s + \tau_d = \frac{m}{\omega} (h_{2s} - h_{01}) + \frac{m}{\omega} (h_{02} - h_{2s}) = \frac{m}{\omega} \frac{1}{\eta_{ad}} (h_{2s} - h_{01}) = \frac{m}{\omega} \frac{1}{\eta_{ad}} \frac{P_1^e}{\rho_m} (R_p - 1) = \frac{m}{\omega} \frac{1}{\eta_{ad}} \frac{P_1^e}{\rho_m} (P_2 - P_1) \]

  - Compressor work added on fluid
    \[ W = \tau_t \times \omega \]

  - Pressure rise
    \[ \Delta P = P_1 (R_p - 1) \]
2.3 Compressor Model

- Compressor model: Performance Map

Compressor Pressure Ratio

Compressor Efficiency
2.4 Turbine Model

- Fluid enthalpy increase
  \[ \Delta h = \frac{h^T_2 - h^T_1}{\eta_{md}} \]
- Pressure drop
  \[ \Delta P = P_1 (R_p - 1) \]
- Total torque of gas turbine
  \[ \tau = \frac{m \eta (P_1 - P_2)}{\omega \rho_m} \]
2.5 Shaft Model

✓ Mode 1 (without control system)

\[ \omega_{T,i} = \omega_{C,k} = \omega_{Shaft} = \text{User defined} \]

✓ Mode 2 (with control system)

\[ \sum_i I_i \frac{d\omega}{dt} = \sum_m \tau_{T,m} - \sum_n \tau_{C,n} + \tau_g \]

Among:

\[ \tau_g = C \ast \tau_{g,i} \]
PART 3 COMPONENT MODEL VERIFICATION

- Thermal property verification
- PCHE model verification
- Compressor model verification
### 3.1 Thermal Property Package Verification

Relative prediction error of the developed CO2 property package compared to NIST REFPROP 9.0

<table>
<thead>
<tr>
<th>CO₂ Property</th>
<th>Symbol</th>
<th>Regions</th>
<th>Relative Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saturated Liquid Enthalpy</td>
<td>(h_f)</td>
<td>-</td>
<td>±0.015%</td>
</tr>
<tr>
<td>Saturated Vapor Enthalpy</td>
<td>(h_g)</td>
<td>-</td>
<td>±0.009%</td>
</tr>
<tr>
<td>Temperature</td>
<td>(T)</td>
<td>Subcooled area</td>
<td>(-0.05% ,0.1%), 99% of which is within relative errors of ±0.05%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Superheated region 1</td>
<td>(-0.2%, +0.2%) , 99% of which is within relative errors of ±0.1%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Superheated region 2</td>
<td>(-0.1%,0.25%), 99% of which is within relative errors of ±0.05%</td>
</tr>
<tr>
<td>Specific Volume</td>
<td>(v)</td>
<td>Subcooled area</td>
<td>(-0.5%,1%) , 99% of which is within relative errors of ±0.5%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Superheated region 1</td>
<td>(-1%,4%) , 99% of which is within relative errors of ±1.0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Superheated region 2</td>
<td>(-0.5%,0.1%) , 99% of which is within relative errors of ±0.1%</td>
</tr>
<tr>
<td>Thermal Condutivity</td>
<td>(\lambda)</td>
<td>-</td>
<td>(-30%, 40%) near the critical region , (-2%,+2%) at other regions</td>
</tr>
<tr>
<td>Dynamic Viscosity</td>
<td>(\mu)</td>
<td>-</td>
<td>(-1.5%,0.5%) , 99% of which is within relative errors of ±0.5%</td>
</tr>
</tbody>
</table>
3.2 PCHE Model Verification

- Friction model code programming verification

**Experimental Conditions:**
The temperature range: 30-150°C;
The pressure range: 3.5-40 MPa;
The Reynolds number range: 200-2.0 × 10⁶;
The surface relative roughness (ratio of roughness over tube diameter): 0.005, 0.015 and 0.025.

**Comparison with experimental data for friction coefficient of various roughness**


Wang et al. Experimental Loop
3.2 PCHE Model Verification

- PCHE model verification

**Built in:**
ANL

**Composed of:**
- Cooling water system
- CO₂ Circle System
- Pressure Stabilizing System

**Focused on:**
- Water and CO₂ heat transfer characteristic in PCHE
3.2 PCHE Model Verification

- PCHE model verification

<table>
<thead>
<tr>
<th>TEST_NO.</th>
<th>CO₂ Side</th>
<th>H₂O Side</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pressure</td>
<td>Flowrate</td>
</tr>
<tr>
<td>B6</td>
<td>8.003</td>
<td>100.53</td>
</tr>
<tr>
<td>B7</td>
<td>8.001</td>
<td>200.77</td>
</tr>
<tr>
<td>B8</td>
<td>7.972</td>
<td>297.14</td>
</tr>
<tr>
<td>B9</td>
<td>8.003</td>
<td>401.01</td>
</tr>
<tr>
<td>B10</td>
<td>7.995</td>
<td>500.61</td>
</tr>
<tr>
<td>B11</td>
<td>8.003</td>
<td>100.03</td>
</tr>
<tr>
<td>B12</td>
<td>8.005</td>
<td>199.73</td>
</tr>
<tr>
<td>B13</td>
<td>7.998</td>
<td>301.31</td>
</tr>
<tr>
<td>B14</td>
<td>8.02</td>
<td>404.29</td>
</tr>
<tr>
<td>B15</td>
<td>7.998</td>
<td>501.79</td>
</tr>
</tbody>
</table>

Test Conditions:
PCHE fluid inlet temperatures and Mass flowrate

PCHE modeling results: PCHE fluid outlet temperatures
3.3 Compressor Model Verification

Compressor model verification

Boundary conditions:
TDV 341: 9.08MPa, 363K

Operation parameters:
Relative flowrate: 0.4-1.0
Relative speed: 0.5, 0.8, 1.0

Result:
The compressor model in SCTRAN/CO2 is able to predict the compressor consuming power.

\[ W_{c,v} = \frac{\dot{m}}{\eta_{ad}} \frac{P_i}{\rho_m} (R_p - 1) \]
PART 4  LOOP SIMULATION VERIFICATION

- S-CO$_2$ PE Loop
- IST Loop
4.1 S-CO2 PE Loop Simulation Verification

S-CO2 PE Loop Steady State Simulation

Simplification:
1. SCTRAN/CO2 applies a heat flux boundary to simulate the heat exchanger in the steady state.
2. The pressure ratio and efficiency keeps constant in the steady and transient simulation.

Steady Result:
1. The Temp Error is within 0.2 °C
2. The Pressure Error is within 0.1 MPa
4.1 S-CO2 PE Loop Simulation Verification

- S-CO2 PE Loop Transient Simulation

**Transient:**
water flowrate from 0.25 kg/s to 0.17 kg/s in 60 second

**Result:**
the relative error of pressure is within 1%
the error of temp is within 2 °C.

*Pressure and temperature variation during the cooling reduction transient*
4.2 IST Loop Simulation Verification

IST Loop Full Power Heat Balance Simulation

**Comparison of SCTRAN/CO2 predicted and the IST designed steady state result**

<table>
<thead>
<tr>
<th></th>
<th>Designed</th>
<th>SCTRAN/CO2</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO2 Loop Flowrate(lbm/s)</td>
<td>11.1</td>
<td>10.99</td>
<td>-0.99%</td>
</tr>
<tr>
<td>Max Temperature Difference(F)</td>
<td>486.4</td>
<td>487.6</td>
<td>1.2</td>
</tr>
<tr>
<td>Max Pressure Difference(psi)</td>
<td>2345.3</td>
<td>2356.8</td>
<td>1.2%</td>
</tr>
</tbody>
</table>

**Conclusion:**
1. The SCTRAN/CO2 is able to simulate S-CO2 Brayton cycle.
2. Transient process isn’t presented.
PART 5 CONCLUSION & EXPECTATION

**Conclusion**

✓ The PCHE model can predict the fluid outlet temperature at steady state.

✓ The compressor model of SCTRN/CO2 can predict accurate compressor consuming power, which indicate it can be used for Brayton cycle simulation.

✓ Transient simulation of SCO2PE and steady state simulation of IST indicate that SCTRN/CO2 owns the ability to conduct transient simulations for S-CO2 Brayton cycle.

**Expectation**

✓ The fircion model for PCHE model should be validated

✓ The transient validation for PCHE model is wanted

✓ To do some control strategy analysis for brayton cycle with our newly developed code
THANK YOU
Welcome your suggestions!
NUSOL

A Team for Nuclear’s Solution