Preliminary design study of S-CO_2 power conversion system for PG-SFR

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1. Introduction

PG-SFR, which stands for Prototype Generation IV - Sodium-cooled Fast Reactor is currently under development mainly by KAERI. The original design adopted a conventional steam Rankine cycle for the power conversion system but violent Sodium Water Reaction (SWR) raises a concern on the system safety. To suggest an alternative option, previous studies explored the SFR application of various gas Brayton cycles to increase the safety and simplify the safety system [1, 2, 3].

A previous study [4] compared and evaluated the performance of S-CO_2, helium and nitrogen Brayton cycles for the SFR power conversion systems. Among those Brayton cycles, S-CO_2 cycle can achieve high efficiency even comparable with the steam Rankine cycle [4]. This paper discusses the preliminary S-CO_2 cycle design for PG-SFR condition considering the size and efficiency.

S-CO_2 cycle design condition				
Compressor Outlet Pressure [MPa]	20	State	T [^oC]	P [MPa]
Turbine Inlet Temperature [^oC]	505	Turbine in	505	19.9
Turbine efficiency [%]	90	Turbine out	394.6	7.62
Main Compressor / Recompressing Compressor efficiency [%]	80	High Temperature Recuperator hotside out	141.6	7.56
Recompressing fraction [%]	27	Precooler in	65.3	7.52
HTR / LTR effectiveness [%]	95	Main Compressor in	31.3	7.5
HTR hot / cold pressure drop [kPa]	60 / 30	Main Compressor out	62.1	20
LTR hot / cold pressure drop [kPa]	40 / 20	Low Temperature Recuperator coldside out	119.1	19.98
PC [CO_2] pressure drop [kPa]	20	Recompressing Compressor out	159.1	19.98
IHX [CO_2] pressure drop [kPa]	50	High Temperature Recuperator coldside in	128.9	19.98
Thermal efficiency [%]	40.66	Intermediate heat exchanger in	337.5	19.95

Table I. Design variables of S-CO_2 cycle

	A	B	C
Heat [MWth / Unit]	368.9	184.45	122.97
Electric Power [MWe / Unit]	150	75	50
CO_2 mass flow [kg/s]	1792.9	896.4	597.6

Table II. Design options of S-CO_2 cycle

2. S-CO_2 cycle design

Even though sodium reacts more mildly with CO_2 compared to water, the Na-CO_2 reaction is exothermic and must be controlled for the reactor safety. To ensure the safety, several options of S-CO_2 power conversion systems are considered. As Table I and II shows, three PCS options (single, double and triple PCS) and two TM options (single shaft design and triple shaft design) can be considered and analyzed in terms of size and total CO_2 inventory.

2.1 Turbomachinery design

The preliminary study for the turbomachinery is performed by considering specific speed (n_s) and specific diameter (d_s) of turbomachineries [5]. For a Brayton cycle application, many designs adopt single shaft design in which all turbomachineries are connected to a single shaft. As compressors operate with the mechanical work delivered from turbines, the motor requirements are reduced. To overcome the rotating speed limitation while the motor requirements are minimized, Triple Shaft Design (TSD) is suggested by Lee [6]. In this design, the electricity is generated by the power turbine and two additional turbines provide mechanical work to two compressors. TSD is advantageous because all turbomachineries can be designed with a single stage which can be beneficial both for operation and maintenance. These two designs are compared in Table III.

2.2 Heat exchanger design

Major studies and researches have been conducted on Printed Circuit Heat Exchanger (PCHE) for the S-CO_2 cycle application. PCHE has a wide operational range up to 900^{o}C and 40 MPa while the high compactness can be achieved as well [7]. KAIST-HXD is constructed by KAIST research team to design and evaluate the PCHE performance. KAIST-HXD utilizes the experimental correlation based on the open literature data and NGO correlation for Nusselt number is applied for the turbulent regime up to 22,000 Reynolds number [8]. Future studies on a correlation applicable to higher Reynolds number are required.

For the intermediate heat exchanger design, the sodium properties are referred from the previous research work [9]. Hejzlar recommended a general correlation for the liquid metal heat transfer and friction factor [10]. The total heat exchanger volume and CO_2 mass for each case are shown in Table II.

<table>
<tr><td></td><td colspan="5">150 MWe</td><td colspan="5">75 MWe</td><td colspan="5">50 MWe</td></tr>
<tr><td>TM-design</td><td colspan="15">SSD</td></tr>
<tr><td>component</td><td colspan="2">RPM</td><td>D (mm)</td><td colspan="2">efficiency</td><td colspan="2">RPM</td><td>D (mm)</td><td colspan="2">efficiency</td><td colspan="2">RPM</td><td>D (mm)</td><td colspan="2">efficiency</td></tr>
<tr><td>turbine</td><td colspan="2">3,600</td><td>1,830</td><td colspan="2">>90</td><td colspan="2">7,200</td><td>929</td><td colspan="2">>85</td><td colspan="2">10,800</td><td>586</td><td colspan="2">>90</td></tr>
<tr><td>MC</td><td colspan="2">3,600</td><td>940</td><td colspan="2">>70</td><td colspan="2">7,200</td><td>478</td><td colspan="2">>80</td><td colspan="2">10,800</td><td>321</td><td colspan="2">>80</td></tr>
<tr><td>RC</td><td colspan="2">3,600</td><td>1,218</td><td colspan="2">>65</td><td colspan="2">7,200</td><td>583</td><td colspan="2">>70</td><td colspan="2">10,800</td><td>398</td><td colspan="2">>75</td></tr>
<tr><td>TM-design</td><td colspan="15">TSD</td></tr>
<tr><td>Component</td><td colspan="2">RPM</td><td>D (mm)</td><td colspan="2">efficiency</td><td colspan="2">RPM</td><td>D (mm)</td><td colspan="2">efficiency</td><td colspan="2">RPM</td><td>D (mm)</td><td colspan="2">efficiency</td></tr>
<tr><td>power turbine</td><td colspan="2">3,600</td><td>1,536</td><td colspan="2">>85</td><td colspan="2">7,200</td><td>700</td><td colspan="2">>90</td><td colspan="2">10,800</td><td>505</td><td colspan="2">>90</td></tr>
<tr><td>MC turibne</td><td colspan="2">6,600</td><td>671</td><td colspan="2">>80</td><td colspan="2">9,400</td><td>478</td><td colspan="2">>80</td><td colspan="2">11,500</td><td>390</td><td colspan="2">>75</td></tr>
<tr><td>RC turbine</td><td colspan="2">7,000</td><td>678</td><td colspan="2">>70</td><td colspan="2">10,000</td><td>476</td><td colspan="2">>70</td><td colspan="2">11,000</td><td>414</td><td colspan="2">>75</td></tr>
<tr><td>MC</td><td colspan="2">6,600</td><td>517</td><td colspan="2">>80</td><td colspan="2">9,400</td><td>341</td><td colspan="2">>80</td><td colspan="2">11,500</td><td>279</td><td colspan="2">>80</td></tr>
<tr><td>RC</td><td colspan="2">7,000</td><td>798</td><td colspan="2">>70</td><td colspan="2">10,000</td><td>558</td><td colspan="2">>70</td><td colspan="2">11,000</td><td>509</td><td colspan="2">>75</td></tr>
<tr><td>HX-design</td><td>IHX</td><td>HTR</td><td>LTR</td><td>PC</td><td>total</td><td>IHX</td><td>HTR</td><td>LTR</td><td>PC</td><td>total</td><td>IHX</td><td>HTR</td><td>LTR</td><td>PC</td><td>total</td></tr>
<tr><td>effectiveness %</td><td>NA</td><td>95.7</td><td>95.1</td><td>NA</td><td></td><td>NA</td><td>95.1</td><td>95.1</td><td>NA</td><td></td><td>NA</td><td>95.3</td><td>95.1</td><td>NA</td><td></td></tr>
<tr><td>Hot channel pressure drop kPa</td><td>8.6</td><td>52.8</td><td>36.8</td><td>4.8</td><td rowspan="2">150.6</td><td>8.6</td><td>32.1</td><td>23.5</td><td>4.8</td><td rowspan="2">112.0</td><td>8.6</td><td>57.8</td><td>22.3</td><td>4.8</td><td rowspan="2">144.1</td></tr>
<tr><td>Cold channel pressure drop kPa</td><td>25.3</td><td>16.7</td><td>14.0</td><td>174.4</td><td>25.4</td><td>10.7</td><td>15.4</td><td>174.4</td><td>25.4</td><td>19.1</td><td>14.7</td><td>174.4</td></tr>
<tr><td>Volume m3</td><td>2.3</td><td>13.8</td><td>18.7</td><td>2.6</td><td>37.4</td><td>1.1</td><td>7.3</td><td>9.3</td><td>1.3</td><td>19.1</td><td>0.8</td><td>4.4</td><td>6.4</td><td>0.9</td><td>12.4</td></tr>
<tr><td>Length m</td><td>0.3</td><td>0.8</td><td>1.3</td><td>0.3</td><td>NA</td><td>0.3</td><td>0.7</td><td>1.1</td><td>0.3</td><td>NA</td><td>0.3</td><td>0.8</td><td>1.1</td><td>0.3</td><td>NA</td></tr>
<tr><td>CO_2 mass kg</td><td>107</td><td>1049</td><td>2605</td><td>228</td><td>3988</td><td>53</td><td>555</td><td>1114</td><td>114</td><td>1836 (3872)</td><td>36</td><td>331</td><td>763</td><td>76</td><td>1205 (3615)</td></tr>
<tr><td>Pumping power kW</td><td>88.4</td><td>NA</td><td>NA</td><td>928</td><td>1016</td><td>44.2</td><td>NA</td><td>NA</td><td>463.9</td><td>508 (1016)</td><td>29.5</td><td>NA</td><td>NA</td><td>309.3</td><td>339 (1017)</td></tr>
</table>

Table III. S-CO_2 cycle module component design variables

3. Summary and future works

For the power conversion system of PG-SFR, 150, 75, 50MWe S-CO_2 cycle modules were designed considering turbomachinery for multiple cycle layouts. In a single shaft design, all turbomachineries are connected to a single shaft, which the motor requirements are reduced but the rotating speed is limited at the same time. On the other hand, a power turbine and compressor turbines are connected in a different shaft which rotating speed is less limited and all turbomachineries can be designed with a single stage in a triple shaft design. Further studies for the Double Shaft Design (DSD) in which the main and recompressing compressors and turbines are connected to a single shaft while only power turbine is separated will be performed in the future.

For the heat exchanger volume and CO_2 mass analysis, the total mass does not increase linearly as the power conversion system size increases. As the number of module increases, the CO_2 mass in S-CO_2 cycle decreases. In addition, as number of modules increases, less CO_2 leaks in a system when the system fails. Future studies on the sodium and CO_2 reaction will be necessary to ensure the safety of S-CO_2 power conversion system coupled to PG-SFR.

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