Study on Passive Turbocharger System for PRHRS in ATOM-sCO$_2$

Jeong Yeol Baek, Jeong Ik Lee*
Dept. Nuclear & Quantum Eng., KAIST, 291 Daehak-ro, Yuseong-Gu, Daejeon 34141, Republic of Korea
**Corresponding author: jeongiklee@kaist.ac.kr*

1. Introduction

ATOM (Autonomous Transportable On-demand reactor Module) reactor is a water-cooled small modular reactor (SMR) being developed by a university consortium led by KAIST [1]. It adopts the supercritical CO$_2$ (sCO$_2$) recompression cycle as a power conversion system. The authors previously conducted various studies about the ATOM-sCO$_2$ system including the cycle optimization, the part load operation, and safety analysis [2]. Regarding the safety system, Na et al. suggested a passive residual heat removal system (PRHRS) coupled with dry air cooling tower (DACT) for mitigating water consumption in the emergency cooldown tank (ECT) [3]. The accident analysis using MARS code was conducted, and it was confirmed that long term cooling sustainability has been enhanced by combining DACT with PRHRS.

In this paper, the authors propose a passive turbocharger component coupled to PRHRS to improve the initial decay heat removal performance by increasing the mass flow in the natural circulation loop. The conceptual design of the turbomachinery under the ATOM-sCO$_2$ conditions has been carried out, and the case with and without the turbocharge system is compared with accident analyses using MARS code.

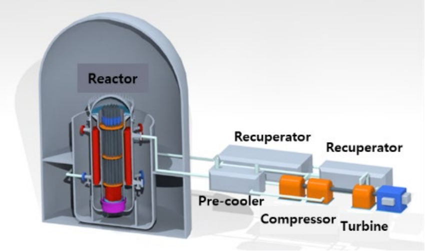


Fig. 1. Concept diagram of ATOM-sCO$_2$

2. Methods and Results

In this section, a concept design of turbocharger and transient simulation under accident situations are presented.

2.1 Concept of Passive Turbocharger System

Fig. 2 shows the concept of passive turbocharger system applied to PRHRS in ATOM-sCO$_2$. When reactor trip occurs, the sCO$_2$ power system is isolated and heat from the primary water side in the intermediate heat exchanger (IHX) is transferred via the PRHRS. Existing PRHRS passively removes residual heat by relying on natural circulation flow.

In the passive turbocharger component, a turbine and a compressor are attached to the IHX and PRHRS connections, so that the working fluid having high enthalpy drives the turbine, which in turn drives the compressor resulting improvement of circulation force in PRHRS loop at the initial stage of an accident. As decay heat removal proceeds, the turbine inlet enthalpy will decrease and the compression work becomes larger than the turbine expansion work. This will result in shaft rotation speed to reduce due to the work balance between the compressor and the turbine. If it falls below a certain level, it can act as a flow resistance, thus the two bypass valves are opened to return to the existing natural circulation loop.

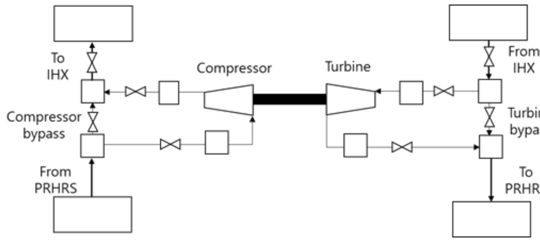


Fig. 2. Concept of passive turbocharger system

Each turbomachinery was designed by KAIST-TMD code, which is the sCO$_2$ turbomachinery design code based on the 1-D mean streamline method and well validated with various sCO$_2$ compressor test data [4]. In the case of passive turbocharger system, unlike the power conversion system, the design point of each turbomachinery is not determined. Therefore, it is necessary to set an appropriate design point to cover various accident conditions, and it is inevitable to repeat the process of component design and accident analysis. Table I shows the design points after several design iterations based on the accident analysis data in the original system. Fig. 3 shows the design results including the geometry and off-design performance maps of each turbomachinery. The rotational moment of inertia for each turbomachinery and shaft was scaled from the available data.

Table I: Design point of each turbomachinery

Design point	Compressor	Turbine
T_{in} [℃]	50	200
P_{in} [MPa]	10	12
Pressure ratio	1.2	1.143
$\dot{m}$ [kg/sec]	300	
RPM	8000	

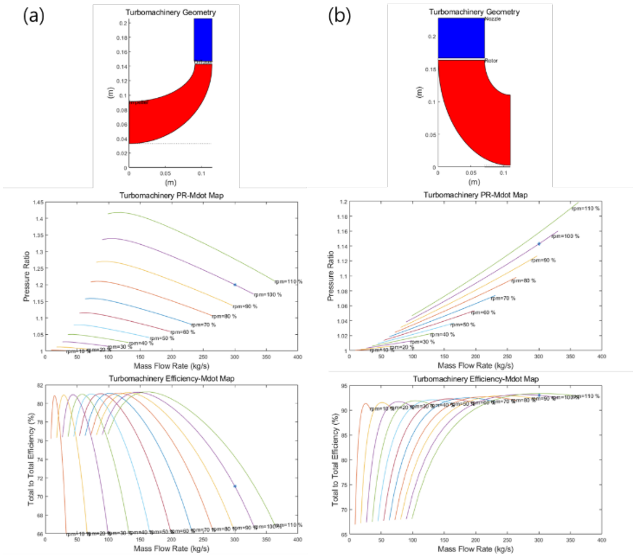


Fig. 3. Design results of each turbomachinery (a) compressor (b) turbine

2.2 Accident Analysis

In this paper, safety analysis was performed using MARS code. The authors previously revised original MARS code for the analysis of an sCO_2 system [5]. SBLOCA (Small Break Loss Of Coolant Accident) and MFLB (Main Feed Line Break) are adopted as accident conditions to compare both the primary side break and the secondary side break. Fig. 4 shows the input nodalization of ATOM-sCO2 system for MARS code simulation. The red dashed box represents each system in the existing input, and the blue dashed box represents the newly added passive turbocharger component. The turbocharger component was modeled as a configuration of a turbine, a compressor, two bypass valves and isolation valves. Each turbomachinery was modeled using design results shown in Fig. 3. During the accident analysis, the sCO_2 power cycle is deleted and entered as boundary conditions since it does not play a role.

Due to the nature of the analysis code, there is a limit to simulating the startup procedure of the shaft. Therefore, when the power conversion system is isolated, the initial rotational speed of the turbocharger is assumed to be the design value. The energy to be provided to initially operate at 100% RPM, is calculated from the rotational moment of inertia of the turbocharger. It is about 4.88 kWh. It can be assumed that this amount of energy is initially provided by an energy supply device such as a battery, flywheel, or super capacitor at the beginning but after the operation continuous power supply is not needed. The turbocharger bypass system was set to operate when the rotational speed was less than 10% of the design speed.

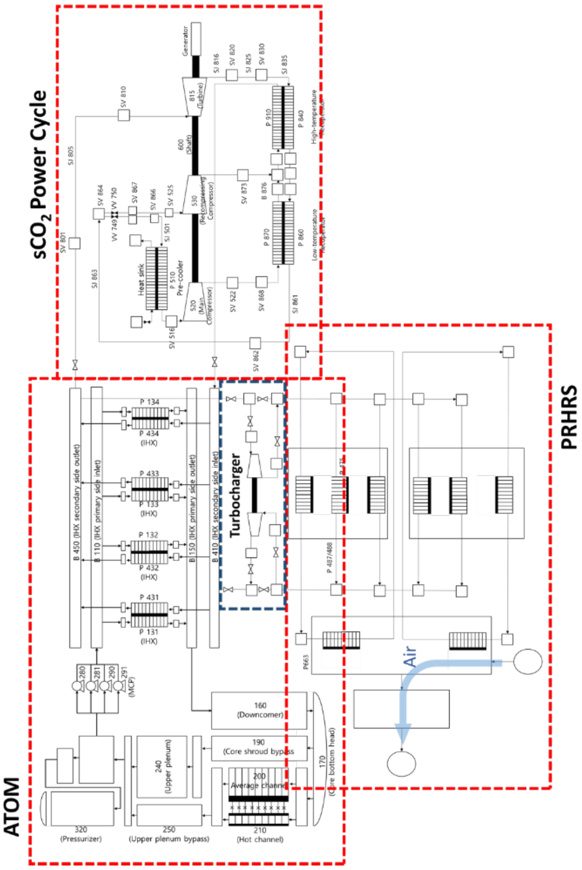
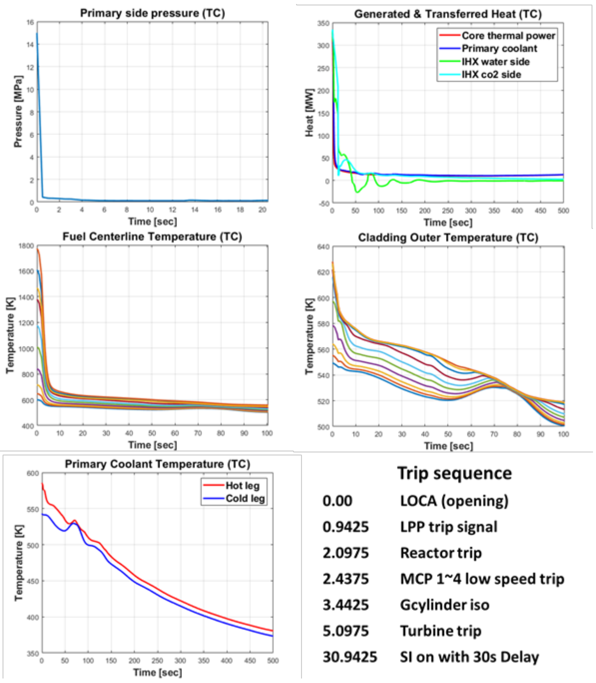


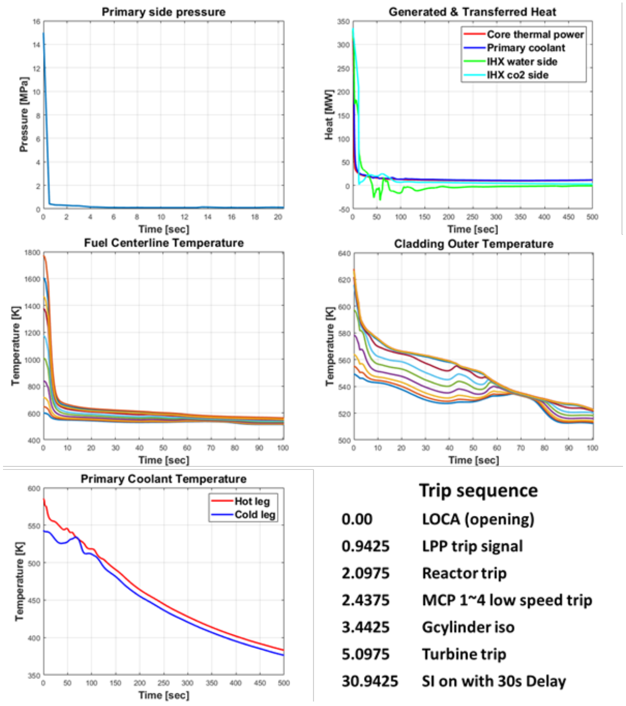
Fig. 4. Input nodalization of ATOM-sCO_2 with turbocharger

Fig. 5 and Fig. 6 show the results of LOCA analysis with and without the turbocharger, respectively. As the overall trend is similar, but as the authors have expected the initial response during the accident is better when the turbocharger component is added.



Trip sequence	
0.00	LOCA (opening)
0.9425	LPP trip signal
2.0975	Reactor trip
2.4375	MCP 1~4 low speed trip
3.4425	Gcylinder iso
5.0975	Turbine trip
30.9425	SI on with 30s Delay

Fig. 5. Results of LOCA analysis with turbocharger



Trip sequence

0.00	LOCA (opening)
0.9425	LPP trip signal
2.0975	Reactor trip
2.4375	MCP 1~4 low speed trip
3.4425	Gcylinder iso
5.0975	Turbine trip
30.9425	SI on with 30s Delay

Fig. 6. Results of LOCA analysis without turbocharger

Fig. 7 compares the LOCA analysis results in two cases. Due to the operation of a passive turbocharger, the mass flow rate of PRHRS increased, and the amount of heat removed from the sCO_2 side of the IHX increased. As a result, it can be confirmed that the initial residual decay heat cooling performance is improved. Furthermore, the turbocharger operation can contribute to remove any natural circulation loop instability such as flow direction reversal. As decay heat is removed and decreases, the rotational speed of the turbocharger is reduced by the work balance between the turbine and the compressor, and it can be expected that in the long term, it will be the same as the cooling method of the existing natural circulation loop.

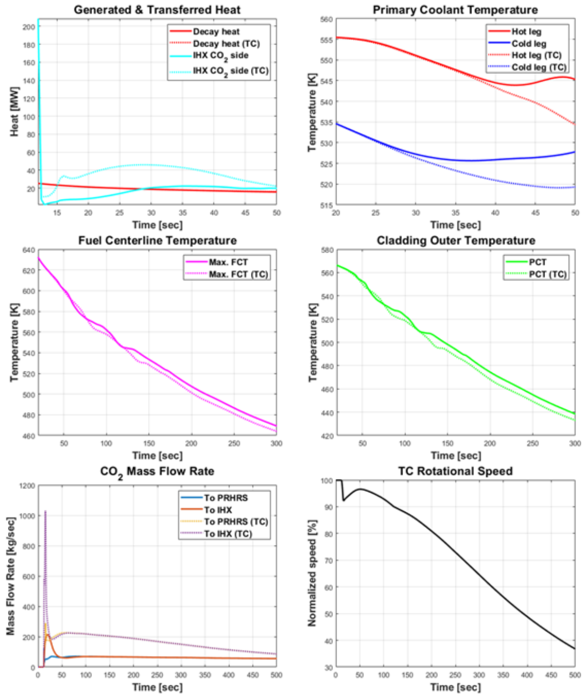
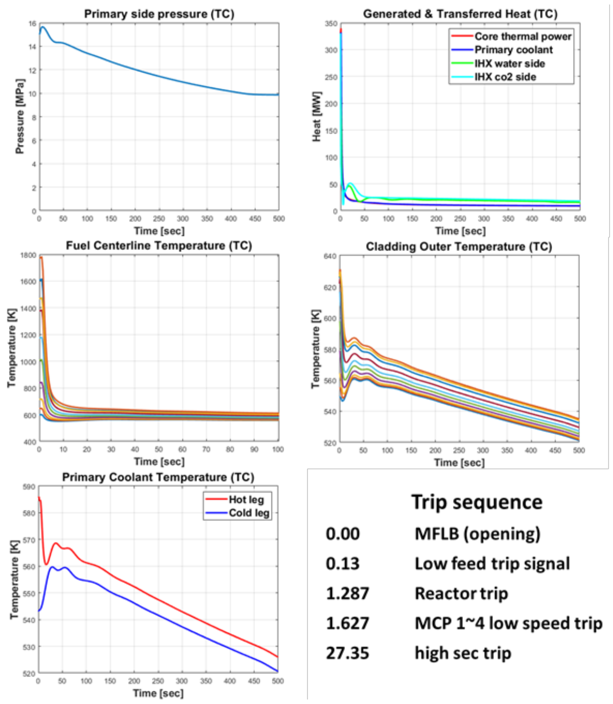


Fig. 7. Comparison of LOCA analysis results

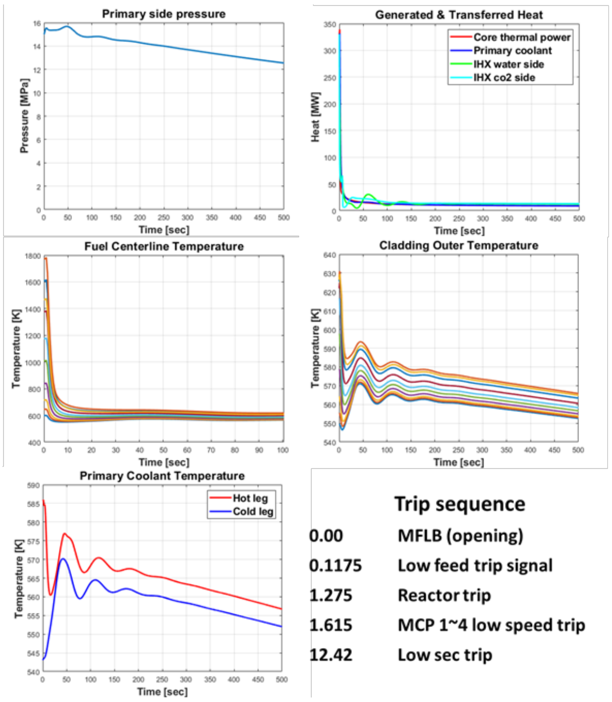
Figs. 8-10 show the results of the MFLB analysis, and it can be seen that the initial decay heat cooling performance is improved due to the increased PRHRS mass flow similar to the LOCA analysis.



Trip sequence

0.00	MFLB (opening)
0.13	Low feed trip signal
1.287	Reactor trip
1.627	MCP 1~4 low speed trip
27.35	high sec trip

Fig. 8. Results of MFLB analysis with turbocharger



Trip sequence

0.00	MFLB (opening)
0.1175	Low feed trip signal
1.275	Reactor trip
1.615	MCP 1~4 low speed trip
12.42	Low sec trip

Fig. 9. Results of MFLB analysis without turbocharger

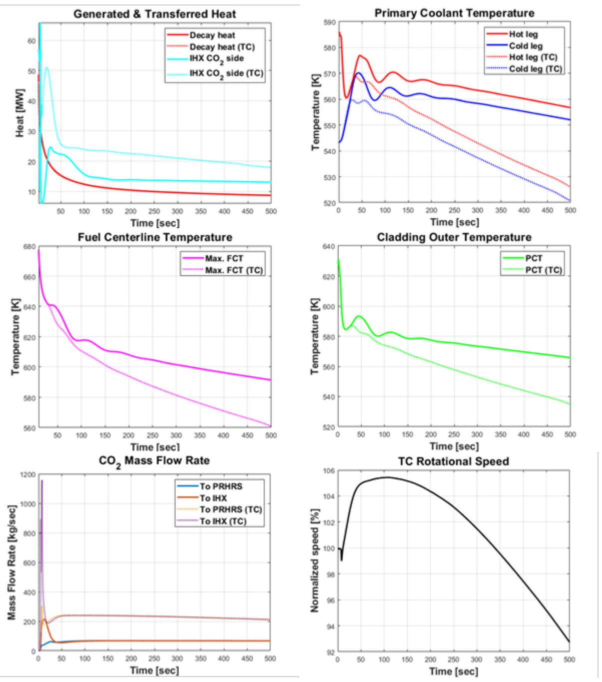


Fig. 10. Comparison of MFLB analysis results

3. Conclusions

In this paper, a passive turbocharger component was proposed to improve the initial cooling performance of PRHRS in ATOM-sCO$_2$. Each turbomachinery was designed using KAIST-TMD code. SBLOCA and MFLB accident analysis were performed by adding a turbocharger component to the existing ATOM-sCO$_2$ design. As a result of comparing the accident analysis results for two systems, it was confirmed that the initial cooling performance was improved by applying the passive turbocharger component to the existing natural circulation loop based PRHRS.

ACKNOWLEDGEMENT

This research was supported by the Challengeable Future Defense Technology Research and Development Program(912767601) of Agency for Defense Development in 2019.

REFERENCES

[1] A. A. E. Abdelhameed, X. H. Nguyen, J. Lee, and Y. Kim, “Feasibility of passive autonomous frequency control operation in a Soluble-Boron-Free small PWR,” *Ann. Nucl. Energy*, vol. 116, pp. 319–333, 2018.

[2] J. Y. Baek, and J. I. Lee, “Preliminary Study on Optimization for S-CO$_2$ Cycle Coupled to ATOM Reactor,” *Transactions of the Korean Nuclear Society Autumn Meeting*, Oct. 25-26, 2018.

[3] M. Y. Na, D. Shin, J. H. Park, J. I. Lee, and S. J. Kim, “Preliminary Assessment of Feasibility of the Indefinite Passive Residual Heat Removal System for the ATOM-SCO$_2$,” *Transactions of the Korean Nuclear Society Autumn Meeting*, Oct. 24-25, 2019.

[4] S. K. Cho, S. Son, J. Lee, S. Lee, Y. Jeong, B. S. Oh, and J. I. Lee, “Optimum loss models for performance prediction of supercritical CO$_2$ centrifugal compressor,” *Appl. Therm. Eng.*, vol. 184, 2021.

[5] J. Y. Baek, J. J. Lee, S. J. Kim and J. I. Lee, “Improvements of MARS Code for Analyzing S-CO$_2$ Cycle Coupled to PWR type SMR,” *Transactions of the Korean Nuclear Society Autumn Meeting*, Oct. 24-25, 2019.