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Preliminary Study on Dynamic Response of S-CO_2 Cycle coupled to PWR Type SMR

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1. Introduction

ATOM (Autonomous Transportable On-demand reactor Module) is a water-cooled autonomous small modular reactor (SMR) under development by a university consortium led by KAIST. The Supercritical Carbon Dioxide (S-CO_2) cycle that replaces the steam cycle is adopted as a power generation system. In recent years, load following capability of nuclear power plants has been required to compensate for the intermittent nature of renewable energy. The ATOM reactor also aims to enable daily load following operation. It is known that the steam Rankine cycle has higher on-design efficiency than the S-CO_2 cycle in PWR temperature conditions. However, because the steam Rankine cycle is a two phase system which has very complex layout and many constraints in part load operation, the S-CO_2 cycle has the potential to be a good alternative for daily load following operation. In this paper, the authors preliminarily analyzed the response to the load variation of the S-CO_2 cycle under the PWR condition focusing on the power conversion system. The turbomachinery module of MARS-KS code has been modified for more realistic analysis. Control mechanism was designed to keep the plant stable when the load changes. The transient response and control performance of the plant for load reduction scenario were evaluated.

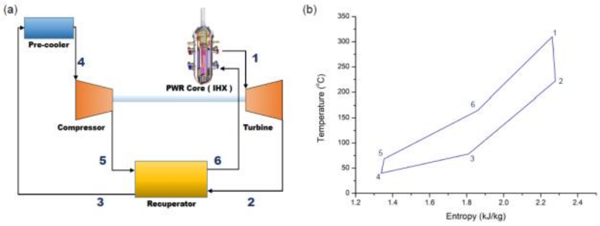

Fig. 1. S-CO_2 cycle coupled to ATOM reactor

2. Method

2.1 System Modeling with MARS-KS Code

MARS-KS code is one dimensional thermal hydraulic system code, which is mainly used for various accident simulations, analyzes nuclear power plants. The gas turbine module was modified in the original code and a compressor model was added to reflect more realistic characteristics of turbomachinery. In the modified MARS-KS code, the pressure ratio and isentropic efficiency of the turbomachinery are calculated through the pre-generated performance map. Fig. 2 shows the off-design performance map of turbine and compressor of ATOM+S-CO_2 system.

Fig. 3 shows the nodalization of the entire system. The primary system was considered as a pressurized water reactor with a nominal output of $330MW_{th}$ and the power conversion system was designed as a simple recuperated cycle with a single shaft. In this study, the primary side was modeled as simple heat structure with a fixed temperature distribution as shown in Fig. 4 to simulate the reduction of the reactor core power during load following operation. It is assumed that the average temperature of the primary circuit is constant by the feedback of the core heat output in the load reduction.

$$\dot{m}_{corrected} = \dot{m}\sqrt{\left(\frac{V_{cr}}{V_{cr,design}}\right)^2}\left(\frac{p_{o,design}}{p_{o,in}}\right)\varepsilon \quad (1)$$

$$N_{rpm} = N\sqrt{\left(\frac{V_{cr,design}}{V_{cr}}\right)^2} \quad (2)$$

$$V_{cr}^{\ 2} = \frac{\gamma}{\gamma+1}RT_o \quad (3)$$

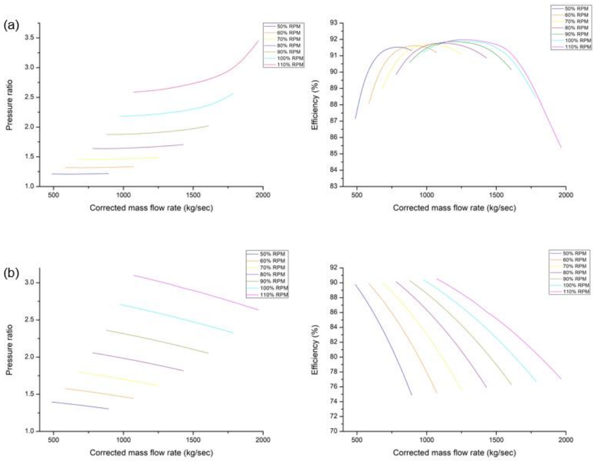

Fig. 2. Performance map of turbomachinery, (a) turbine (b) compressor

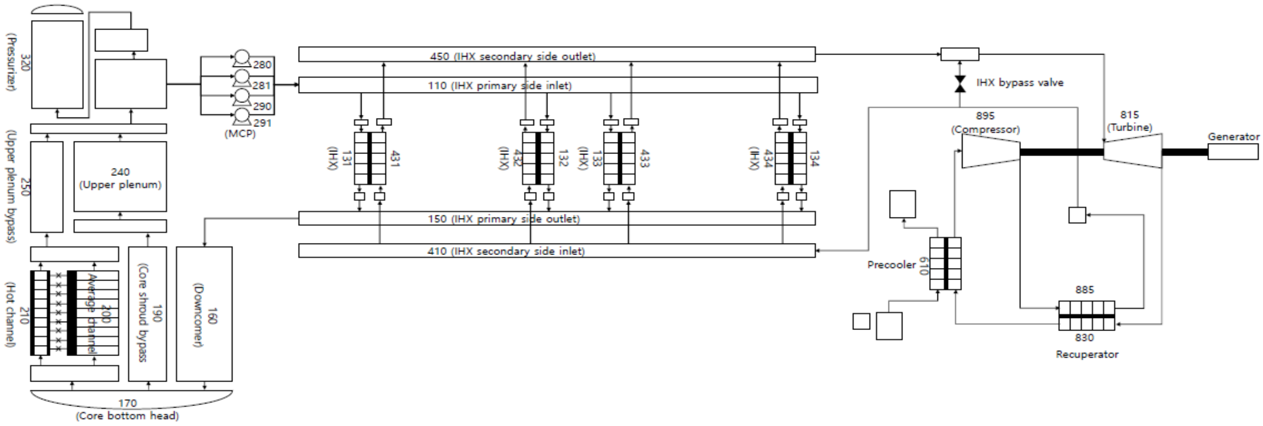

Fig. 3. Nodalization of ATOM+SCO2 system

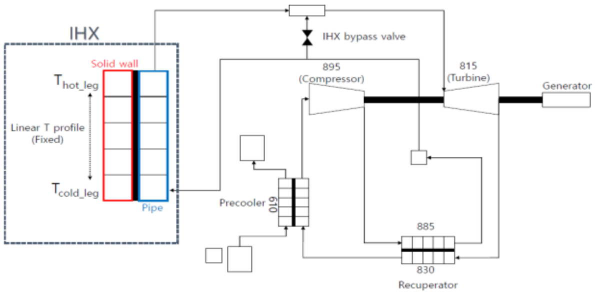

Fig. 4. Modeling for constant T_{avg} load following

2.2 Control Mechanism

The reduction of grid demand without any controller can induce over-speed of the shaft by Eq. (4), which has a serious effect on the integrity of the system. Therefore, a controller that can maintain the shaft speed constant when the load changes is needed. In this study, intermediate heat exchanger (IHX) bypass was adopted as the control mechanism as shown in Fig. 4. The pressure difference between two volumes connected to bypass valve is very small, allowing stable control without other complex controllers. The valve is operated by the Proportional Integral Differential (PID) controller and adjusts the valve opening fraction in response to load change and keeps the shaft speed constant. Since the shaft which connects turbine and compressor has not been fully designed and optimized yet, it is assumed that the moment of inertia of ATOM system is scaled from the GFR data which is 2400MW$_{th}$ direct S-CO$_2$ cooled fast reactor [1].

$$\frac{\partial \omega}{\partial t} = \frac{(W_{turb} - W_{comp})\varepsilon_{gen} - W_{grid}}{I_{tot}\omega} \qquad (4)$$

$$E_{BP} = \frac{\omega(t) - \ \omega_{design}}{\omega_{design}} \qquad (5)$$

$$f_{BP} = k_p^{BP} E_{BP} + k_d^{BP} \frac{dE_{BP}}{dt} + k_i^{BP} \int_0^t E_{BP}(t)\, dt \qquad (6)$$
$$\left(k_d = k_p \times T_d,\ k_i = \frac{K_p}{T_i}\right)$$

Table I: Rotator inertia of ATOM and GFR

System	ATOM	GFR (1 PCS)
Power	330MW$_{th}$	600MW$_{th}$
Generator	550.0	1000.0
Turbine	468.0	850.9
Compressor	62.2	113.1
Shaft	104.0	189.0
Total	1184.2	2153

2.3 PID parameters

Ziegler-Nichols rule was applied for tuning PID controllers [2]. Since the unit step response is not S-shape as shown in Fig. 5, the method based on the critical gain (K_{cr}) and the critical period (P_{cr}) is used. This method adopts proportional control action only, increasing K_p from 0 to a critical value K_{cr} at which the output first exhibits sustained oscillations. Ziegler and Nichols suggested that PID parameters were determined according to the formula shown in Table II. As shown in Fig. 6, K_{cr} and P_{cr} were obtained by increasing K_p and therefore PID parameters to be applied to bypass valve were derived.

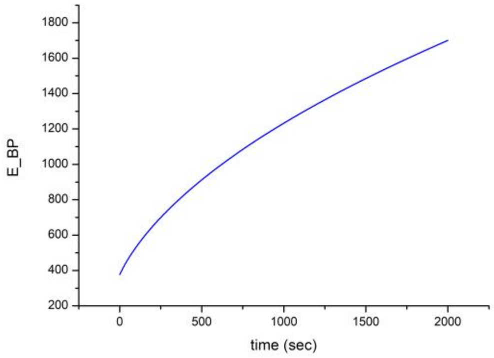

Fig. 5. Shaft rotational speed when 1% reduction of grid demand without any controller

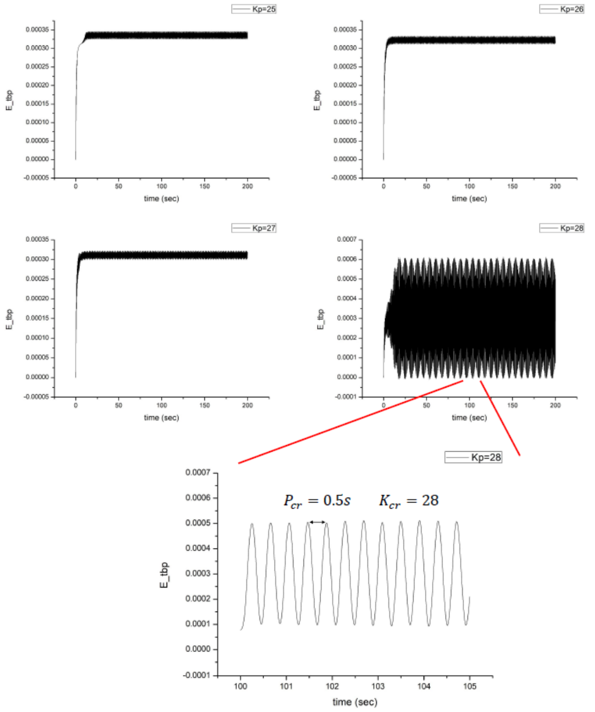

Fig. 6. Response when applying proportional control action only

Table II: Ziegler-Nichols Tuning Rule

Type	K_p	T_i	T_d
P	$0.5K_{cr}$	∞	0
PI	$0.45K_{cr}$	$P_{cr}/1.2$	0
PID	$0.6K_{cr}$	$0.5P_{cr}$	$0.125P_{cr}$

3. Results

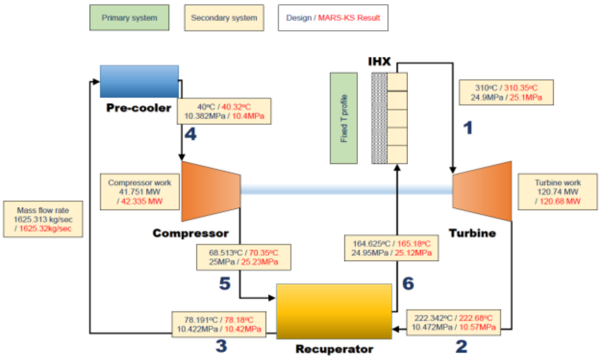

Fig. 7. MARS-KS code steady state results

Fig. 7 compares the design values with the converged steady state values from the modified MARS-KS simulation results. The steady state results show reasonable agreement which indicates transient analysis can be now performed with the developed code.

The transient situation was given to operate 100% load for 100 seconds and then reduce it to 95% by 1% every 100 seconds. The compressor inlet temperature remains nearly constant to maintain the integrity and cycle efficiency of the power system. The compressor inlet temperature control is easily accomplished by adjusting the flow rate of the precooler, which is an independent system.

Figs. 8-10 show that when the grid demand changes, the bypass valve is operated by the PID controller to maintain the shaft speed and follow the load. Because the average temperature of the primary circuit is constant, the S-CO_2 temperature at the IHX inlet and outlet decreases as the bypass flow increases. Fig. 13 shows the total heat transferred to the S-CO_2 cycle via IHX, which can be considered as a feedback of the reactor core power corresponding to the load reduction.

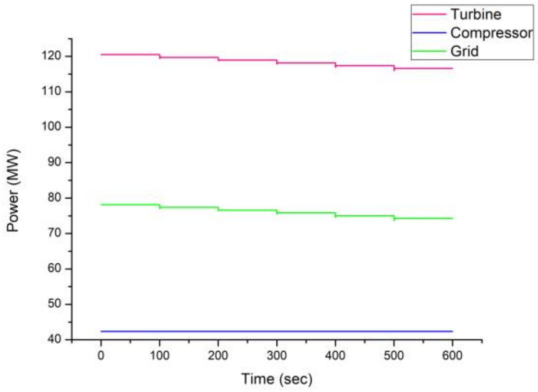

Fig. 8. Grid demand and turbomachinery work

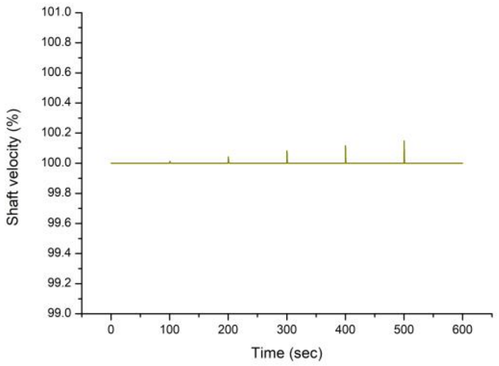

Fig. 9. Turbomachinery rotational speed

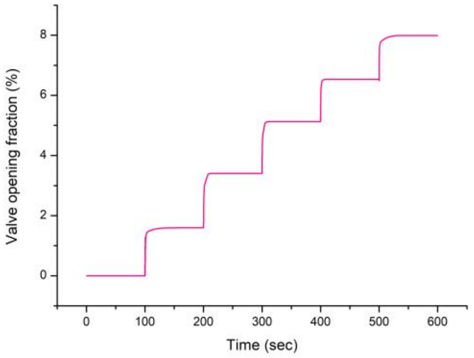

Fig. 10. Valve opening fraction

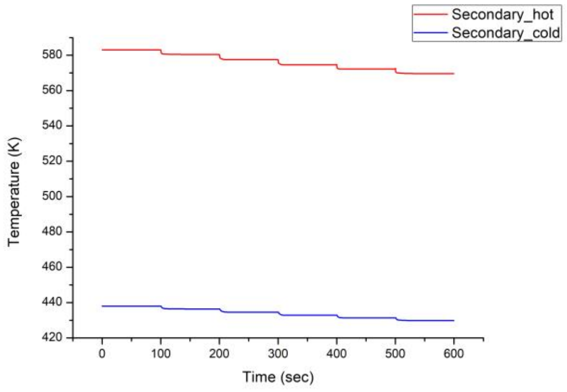

Fig. 11. Secondary side temperature at inlet and outlet of IHX

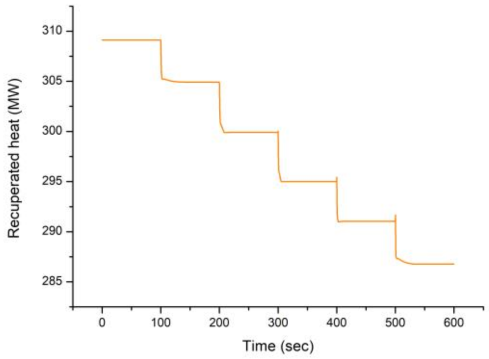

Fig. 12. Recuperated heat

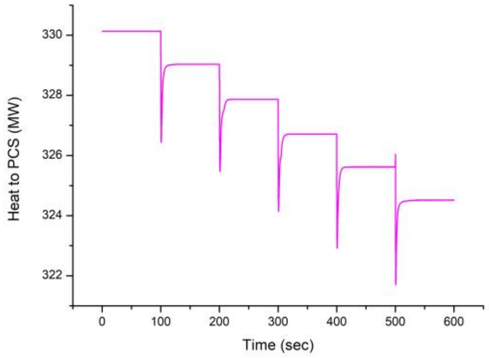

Fig. 13. Total heat transferred to power conversion system

3. Summary and further works

In this paper, the authors performed transient analysis under the grid demand reduction situation of S-CO_2 power cycle coupled to PWR type SMR. MARS-KS code was improved to reflect more realistic characteristics of turbomachinery. PID controller was designed to maintain shaft speed when grid demand changes. Control with IHX bypass valve showed that the system responds well to 5% demand reduction situations. More efficient control logic will be developed and transient analysis in various scenarios will be performed.

ACKNOWLEDGEMENT

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REFERENCES

[1] M. A. Pope, “Thermal Hydraulic Design of a 2400 MW_{th} Direct Supercritical CO2-cooled Fast Reactor,” Massachusetts Institute of Technology, Department of Nuclear Science and Engineering, 2006.
[2] J. G. Ziegler, N. B. Nichols, “Optimum Settings for Automatic Controllers,” Journal of Dynamics Systems, Measurement, and Control, vol. 115, pp. 220-222, 1993.