The effect of turbomachinery performance degradation on the load-following performance of S-CO\textsubscript{2} direct-cycle Micro Modular Reactor (KAIST-MMR).

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1. Introduction
The Supercritical CO\textsubscript{2} (S-CO\textsubscript{2}) power cycle is considered to be one of the promising next generation power cycles. A S-CO\textsubscript{2} power cycle gain benefits such as a small footprint and high efficiency by utilizing the unique properties near the critical point. Nuclear engineering is one of the first areas to exploit advantages of S-CO\textsubscript{2} power systems [1]. In particular, in the nuclear power field, not only indirect cycles, but also S-CO\textsubscript{2} direct-cycle reactors are being studied. The Sandia National Laboratory (SNL) research team has developed a 200MW\textsubscript{th} scale SC-GFR concept [2], and the Massachusetts Institute of Technology (MIT) research team has also conducted a concept study on the 2400MW\textsubscript{th} scale S-CO\textsubscript{2} direct-cycle Gas-cooled Fast Reactor (GFR) by Pope et al., [3]. Korea Advanced Institute of Science and Technology (KAIST) research team has developed a concept of KAIST-Micro Modular Reactor (KAIST-MMR), a 10MWe scale S-CO\textsubscript{2} cooled direct-cycle GFR that can be transported via truck [4].

Although S-CO\textsubscript{2} is reported as a powerful cleaning agent [5-6], the performance of a power system operating with S-CO\textsubscript{2} will also inevitably degrade over time. Previous researchers have shown that turbomachinery deterioration could be a major subject regarding the system performance degradation [7]. Nevertheless, no quantitative evaluation has yet been made so far.

In this study, an impact of performance degradation of S-CO\textsubscript{2} turbomachinery during a load-following scenario is analyzed quantitatively. Health Parameter concept is used to simulate turbomachinery degradation. In order to quantify the impact, the KAIST-MMR is selected as the target system. A transient analysis platform is built using a nuclear system safety analysis code and the Deep Neural Network (DNN) based S-CO\textsubscript{2} turbomachinery off-design performance model [8] based on the GAMMA+ code [9]. In the course of load-following operation, the effect of performance degradation of the turbomachinery on the control is evaluated, and analysis is performed from the viewpoint of reactor safety.

2. Methodology

2.1. KAIST-MMR
KAIST-MMR is a reactor concept developed by KAIST, and it is a 10MWe class S-CO\textsubscript{2} direct-cycle GFR shown in Figure 2. It utilizes a S-CO\textsubscript{2} simple recuperated cycle. The controllers covered in this study are turbine bypass controller and inventory controller. In this study, the controllers which are designed in the absence of degradation are evaluated whether the controllers will still work well when the system is degraded.

2.2. Turbomachinery Degradation Model
In this study, the degradation of turbomachinery performance is simulated using the concept of health parameter developed for performance degradation of a gas turbine system or an aviation turbine [10-11]. DI means health parameter of the turbine and EI means health parameter of the compressor. \(\Delta m\) and \(m\) is mass flow rate of the turbine or compressor, and \(\eta\) is isentropic efficiency. The models are shown below:

For Turbines:
\[
\frac{\Delta m_T}{m_T} = 1 + 0.5DI \\
\frac{\Delta \eta_T}{\eta_T} = 1 - DI
\]

For Compressor:
\[
\frac{\Delta m_C}{m_C} = 1 - 0.5FI \\
\frac{\Delta \eta_C}{\eta_C} = 1 - FI
\]

3. Result and Discussion
The scenario for load following operation was selected from the report published by International Atomic
Energy Agency (IAEA) [12]. The scenario used is to reach 20% relative electric output (REO) at full-power operation, then hold for 5 minutes and then return to full power operation as shown in Figure 3.

These results show that turbomachinery degradation in the load-following scenario affects the dynamic response. However, PID control failures in the analyzed range were not observed. Also, it was confirmed that peaks of FCT and PCT may occur in the ramp-up process from the core point of view, but it is not expected to cause safety problems.

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