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Improvement of transient analysis of S-CO_2 cooled micro modular reactor using DNN based turbomachinery off-design model

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1. Introduction

The supercritical CO_2 (S-CO_2) power cycle is one of the most promising power conversion systems for the next-generation nuclear plants [1]. S-CO_2 power cycles can achieve small footprint and high-efficiency with a simple configuration. Also, CO_2 is chemically non-reactive, so it can be used as reactor coolant. Due to these advantages, S-CO_2 power cycles are now considered in various nuclear reactors such as small modular reactors, sodium-cooled fast reactors, and high-temperature gas-cooled reactors.

Although safety analysis is one of the most important fields in nuclear engineering, the safety analysis of the S-CO_2 system did not have high accuracy. The main cause of low accuracy is CO_2 property fluctuations near the critical point. This problem makes the prediction of the off-design performance of compressors operating especially near the critical point uncertain, causing errors in the prediction of system's off-design performance.

In the previous study, Son et al., [2] showed that applying the Deep Neural Net (DNN) based turbomachinery off-design model can improve the prediction accuracy of the quasi-steady state analysis of the S-CO_2 system. In this study, it is analyzed whether the analysis accuracy can be also improved when the model is applied to the transient analysis platform.

2. Methodology

2.1. KAIST-MMR

The study is selected an S-CO_2 direct-cycle nuclear reactor as a reference system, KAIST-MMR. KAIST-MMR is a 10MWe class micro modular reactor shown in Figure 1. KAIST-MMR is utilizing an S-CO_2 simple recuperated cycle. The cycle information of KAIST-MMR is summarized in Table 1.

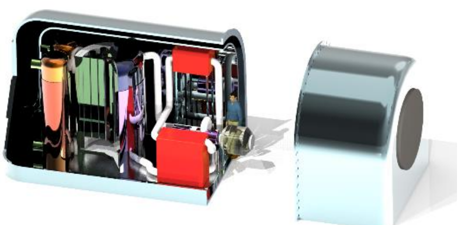

Figure 1. Concept art of KAIST-MMR

Table 1.2. Cycle information of KAIST-MMR

Parameter	**Value**
Maximum Temperature (Turbine Inlet)	823.15 K
Maximum Pressure (Compressor Outlet)	20 MPa
Turbine Efficiency	92 %
Minimum Temperature (Compressor Inlet)	333.15 K
Minimum Pressure (Compressor Inlet)	8 MPa
Compressor Efficiency	85 %
Turbomachinery RPM	19300
Recuperator Effectiveness	92 %
System mass flow rate	180 kg/s
Reactor Power	36.4 MW_{th}
Cycle Efficiency	34 %

2.2. DNN based turbomachinery off-design model

Normally, similarity methods are used to analyze the off-design performance of turbomachinery. However, for S-CO_2 systems, it has been pointed out that these methods can be source of errors [3-4]. According to Son et al., [2] this can be resolved by adopting the Deep Neural Network (DNN) based regression model of the 1D mean-line method without extra calculation time. In this research, this DNN based S-CO_2 turbomachinery off-design model is applied to the transient analysis platform. The structure of the utilized DNN is shown in Figure 2, and details of the turbine and compressor models are summarized in Table 2. Training is done using PyTorch v1.0 in Python 3.6 environment.

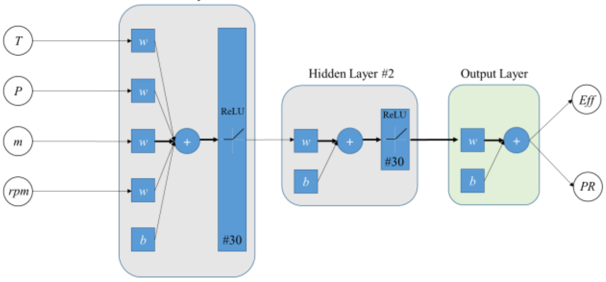

Figure 2. DNN based S-CO_2 turbomachinery off-design model for simulation

Table 2. DNN parameters for S-CO_2 turbomachinery off-design models

	Parameter	Turbine Value	Compressor Value	Note
Model Information	Input Size	4		$T, P, \dot{m}, rpm$
	Output Size	2		*Eff, PR/ΔH*
	Number of hidden layers	2		
	Hidden size	20/20		
	Activation Function	Rectified Linear Unit (ReLU)		
	Structure	Feed Forward Network		
Training Information	Original Database	KAIST-Turbomachinery Design (KAIST-TMD)		
	Number of Train Data	30000		
	Number of Validation Data	10000		
	Number of Test Data	10000		
	Batch Size	1000		
	Maximum Epoch	150		
Optimization Information	Optimizer	Adam		
	Loss Function	Mean Square Error		
Statics (Test Set)	Mean Absolute Percentage Error (%)	9.561 E-3	1.026 E-2	
	Mean Square Error	1.956 E-4	3.156 E-4	
	R^2 score	0.9909	0.9539	

2.3. Modified GAMMA$^+$

The system analysis tool used in this study is the General Analyzer for Multi-component and Multi-dimensional transient Application (GAMMA$^+$) code [5]. The GAMMA$^+$ code is being developed by the Korea Atomic Energy Research Institute (KAERI) as the best-estimate system analysis code to simulate transient behaviors of a High-Temperature Gas-cooled Reactor (HTGR). The governing equations for single-phase flow dynamics in the GAMMA$^+$ code are shown below.

Continuity equation

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial z}(\rho V) = \sum_s R_{s,w}$$

Energy conservation equation for sensible enthalpy

$$\frac{\partial}{\partial t}(\rho H) + \frac{\partial}{\partial z}(\rho H V) = \frac{\partial P}{\partial t} + V\frac{\partial P}{\partial z} + \frac{\partial q''}{\partial z} + \sum_s h_s R_s + q_W'''$$

Momentum conservation equation

$$\frac{\partial}{\partial t}(\rho V) + \frac{\partial}{\partial z}(\rho V V) = -\frac{\partial P}{\partial z} - \rho g - \rho\left(\frac{f'}{d} + K\right)V^2$$

3. Results and Discussion

The analysis was performed for a load-following operation with a relative electric output change profile of 100%-50%-75% assumed. As it can be seen from the results, the modified GAMMA$^+$ code can predict the S-CO_2 turbomachinery performance more accurately than any other previously used methods. It was confirmed that the modified GAMMA$^+$ code can greatly improve the accuracy of turbomachine performance prediction compared to the transition analysis results using the existing similitude methods. Figure 4 shows the results of comparing Glassman correlation (GLA) and CEA correlation, which are widely used for turbomachinery off-design analysis, and DNN based off-design model. The results show the off-design performance predicted by KAIST-TMD at each convergence point of the transition analysis and the off-design performance predicted by the off-design model used in the transient code. The correction equations used in the existing gas turbine do not accurately predict the off-design performance of the S-CO_2 system, which distorts the transition analysis result. This part can be improved with the developed DNN based S-CO_2 turbomachinery off-design model. A more detailed explanation will be presented with additional data at the conference president.

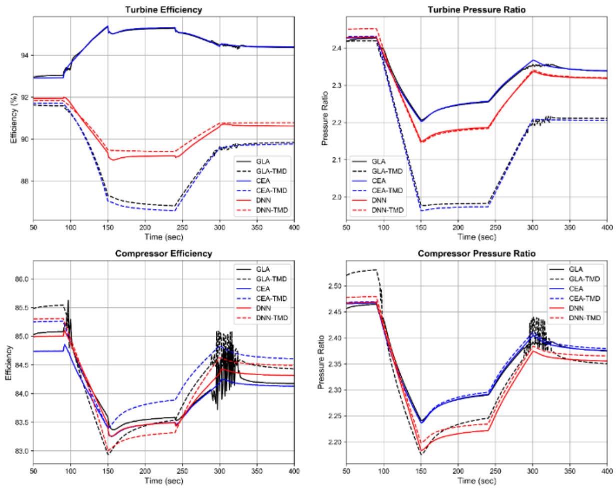

Figure 4. Comparison between existing similitude methods and DNN based turbomachinery off-design model on the transient scenario for KAIST-MMR

ACKNOWLEDGEMENT

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