Similitude models for turbine off-design performance prediction under supercritical CO_2 condition

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1. Introduction

Recently, the development of a small modular reactor (SMR) is ongoing in many research institutes and companies worldwide [1]. In contrast to a conventional GWe scale nuclear power plant, the power capacity of SMR varies from 10MWe to 100MWe scale. Therefore, due to its relatively small output, SMR is suitable for distributed power source and expected to have a load following capacity.

The majority of the nuclear power plants in practice mostly use the steam Rankine cycle as a power conversion system. However, the steam Rankine cycle tends to have large components and it hinders the modularization of nuclear power plants. One of alternative solutions is to utilize a supercritical CO_2 (S-CO_2) cycle [2]. S-CO_2 is a variation of the gas Brayton cycle. The state of working fluid in the Brayton cycle is a gas phase, but the fluid is a supercritical state in the S-CO_2 Brayton cycle. In the S-CO_2 cycle, noble characteristics of S-CO_2 and non-linear behaviors near the critical point benefit the cycle efficiency and system layout.

Provided that S-CO2-cooled SMR should have the capability to follow electricity demand, it is necessary to observe the off-design behavior of the power conversion system for the safe and reliable operation of the nuclear power plant. Aforementioned system level off-design analysis requires the component level off-design analysis such as heat exchanger, compressor and turbine. Subsequently, the accuracy of system level analysis heavily depends upon the accuracy of component level analysis.

Component design and analysis in the Brayton cycle application are mostly based on the ideal gas assumption. On the contrary, these practices may need to be reconfirmed or even modified under S-CO_2 conditions. In this paper, performance predictions of a turbine off-design with similitude models have been evaluated. From the open literatures, five existing similitude models had been collected [3,4,5,6] and their applicability for S-CO_2 turbine have been evaluated.

2. Method

2.1 Similitude model

Normally, off-design performances of a turbine are expressed as turbomachinery performance map, which is $\mathrm{fn}(\dot{m}, N) = \eta, \Delta H$ (or PR). This equation assumes that inlet temperature and pressure do not change from the design point condition. However, it is not entirely acceptable, because the inlet temperature and pressure actually vary operation. Thus, the concept of corrected mass flow rate and rpm was introduced based on the similitude model. The models convert variation of temperature and pressure into variation of mass flow rate and rpm. This conversion uses the equalities of non-dimensionalized mass flow rate and rpm by temperature and pressure, so the differences among models are how to non-dimensionalize mass flow rate and rpm. These parameters are summarized in Table 2.1. By adopting these similitude models, it is possible to simplify the complexity of turbine performance prediction from 4^{th} order to 2^{nd} order calculations or experiments.

Table 2.1. Summary of parameters for existing similitude models

	Flow parameter	Speed parameter	Head parameter
IG	$\frac{\dot{m}\sqrt{\gamma RT}}{\gamma P}$	$\frac{N}{\sqrt{\gamma RT}}$	$\frac{\Delta H}{\gamma RT}$
IGZ	$\frac{\dot{m}\sqrt{\gamma ZRT}}{\gamma P}$	$\frac{N}{\sqrt{\gamma ZRT}}$	$\frac{\Delta H}{\gamma ZRT}$
Glassman	$\frac{\dot{m}\sqrt{\gamma RT_{cr}}}{\gamma P_{cr}}$	$\frac{N}{\sqrt{\gamma RT_{cr}}}$	$\frac{\Delta H}{\gamma RT_{cr}}$
BNI	$\frac{\dot{m}\sqrt{\gamma ZRT_{cr}}}{\gamma P_{cr}}$	$\frac{N}{\sqrt{\gamma ZRT_{cr}}}$	$\frac{\Delta H}{\gamma ZRT_{cr}}$
CEA	$\frac{\dot{m}\sqrt{n_s ZRT}}{n_s P}$	$\frac{N}{\sqrt{n_s ZRT}}$	$\frac{\Delta H}{n_s ZRT}$

2.2 Prediction error quantification procedure

To evaluate the accuracy of existing similitude models, the procedure below was carried out, using KAIST-TMD [7], which is a 1-D turbomachinery design and analysis code developed for S-CO_2 conditions.

1. Generate performance data with respect to different mass flow rates and rpms at design point (temperature, pressure).
2. Prescribe the off-design temperature and pressure range, and choose one similitude model for evaluation.
3. Select one off-design operating conditions, and calculate its performance.

4. Convert the off-design performance into corrected performance with the selected similitude model. One-to-one matching of mass flow rate and rpm is imposed.

5. The inlet condition temperature and pressure are the same as the design condition due to the conversion. Then, if mass flow rates and rpms are the same, the performance of reference data and corrected data should be the same.

6. However, there will be discrepancy between the converted results and the reference. Therefore, the error could be quantified as mean absolute percent error (MAPE).

$$\mathrm{MAPE} = \frac{100\%}{N} * \sum \left| \frac{Real\ value - Estimation}{Real\ value} \right|$$

7. Repeat the same procedure for other off-design conditions and similitude models.

The calculations for air and S-CO_2 condition have been carried out. The design points of air and S-CO_2 turbines are summarized in Tables 2.2 and 2.4, respectively. Furthermore, to observe the wide range of off-design operations, the calculations were carried out within the range as shown in Tables 2.3 and 2.5.

Table 2.2 Air turbine design

Design point			
T_{in}(°C)	200	ρ(kg/m³)	3.5
P_{in}/P_{out}(kPa)	200/100	γ	1.41
m(kg/s)	6	Z	1
rpm(rev/min)	10500	n_s	1.4
Efficiency(%)	90.4		

Table 2.3 Studied inlet condition (Air turbine)

	Min	Max	Resolution
T(°C)	100	500	17
P(kPa)	100	500	17

Table 2.4 S-CO_2 turbine design

Design point			
T_{in}(°C)	500	ρ(kg/m³)	253.24
P_{in}/P_{out}(kPa)	20000/8000	γ	1.5
m(kg/s)	129.15	Z	0.9
rpm(rev/min)	20000	n_s	1.44
Efficiency(%)	91.3		

Table 2.5 Studied inlet condition (S-CO_2 turbine)

	Min	Max	Resolution
T(°C)	300	800	51
P(kPa)	5000	50000	226

3. Results

The results of the air turbine are presented in Table 3.1. Regardless of models, the predictions are highly accurate, which is expected, due to the fact this method has been widely used for air condition. These precise results of air turbine imply that KAIST-TMD can be used for the evaluation of the similitude models.

Table 3.1 Average prediction error [%] (Air)

Similitude model	PR MAPE	Eff MAPE	ΔH MAPE
IG	1.28	0.19	0.26
IGZ	1.32	0.30	0.48
Glassman	0.79	0.26	0.36
BNI	0.82	0.39	0.58
CEA	1.20	0.29	0.43

Tables 3.2-3.5 illustrate the average and local maximum errors for performance prediction of the S-CO_2 turbine. Noticeably, pressure ratio and the prediction of enthalpy rise show different prediction accuracy, which differs from air turbine case. IG and Glassman models can predict pressure ratio well, but this model performs poorly for enthalpy rise. On the other hand, the enthalpy rise predictions of IGZ, BNI, and CEA models outperform the prediction of pressure ratio. The noticeable difference of these two groups of models is compressibility factor as shown in Table 2.1. More specifically, compressibility factor may improve enthalpy rise prediction, but probably ameliorate pressure ratio prediction. In terms of efficiency prediction, all models show less than 2% prediction error except for the IG model.

In addition to the average prediction errors for the S-CO_2 turbine, it is necessary to observe the local maximum error. Thus, the maximum prediction errors are summarized in Tables 3.3-3.5. To begin with pressure ratio prediction, the IG model shows about 4% prediction error, but overall maximum errors vary 10-50%. On the contrary, all but IG model of 35.3% error show approximately less than 11% error for the prediction of enthalpy rise. Although the IG model has the best prediction accuracy of pressure ratio, the accuracy of its efficiency prediction is considerably low compared to the other existing models.

Table 3.2 Average prediction error [%] (S-CO_2)

Similitude model	PR MAPE	Eff MAPE	ΔH MAPE
IG	0.74	8.98	13.23
IGZ	3.47	0.27	0.79
Glassman	2.15	1.57	3.59
BNI	2.06	0.37	0.87
CEA	7.25	0.39	0.43

Table 3.3 Maximum pressure ratio prediction error [%] (S-CO_2)

Similitude model	MAPE (Max)	Location	
		(°C)	(kPa)
IG	3.92	300	50000

IGZ	20.20	300	50000
Glassman	11.03	300	50000
BNI	10.60	300	50000
CEA	50.65	300	50000

Table 3.4 Maximum enthalpy rise prediction error [%] (S-CO_2)

Similitude model	**MAPE (Max)**	**Location**	
		(°C)	**(kPa)**
IG	35.30	300	5000
IGZ	2.57	300	50000
Glassman	10.7	680	50000
BNI	2.10	300	22200
CEA	1.58	300	44600

Table 3.5 Maximum efficiency prediction error [%] (S-CO_2)

Similitude model	**MAPE (Max)**	**Location**	
		(°C)	**(kPa)**
IG	21.52	300	5000
IGZ	0.80	800	5000
Glassman	4.08	680	50000
BNI	1.01	800	5000
CEA	1.81	300	50000

4. Summary and conclusions

Nowadays, most nuclear power plants convert thermal energy through the steam Rankine cycle. However, to develop an SMR, S-CO_2 Brayton cycle can be a suitable candidate for power conversion system. Since the design and analysis methods of Brayton cycle components are based on the ideal gas assumption, the conventional methods have to be re-evaluated for S-CO_2 conditions. One of these methods is a turbine off-design prediction method. In this paper, the applicability of off-design performance prediction models based on the similitude was evaluated. To ensure the validity of the analysis, the model applicability for air turbine had been evaluated first, and it showed results as what the authors expected. Next, the same procedure was followed for the S-CO_2 turbine off-design performance prediction. In contrast to the air turbine results, the prediction accuracies for the S-CO_2 turbine differed between the models. In conclusion, it requires a careful selection of the similitude models and performance indicators among the existing models to analyze the S-CO_2 turbine off-design behavior. So far, the CEA model seems to provide the best predicting capability, considering the evaluation results of efficiency and enthalpy rise prediction with similitude models in this paper. Accordingly, system level analysis codes such as GAMMA+[8] can adopt CEA model to simulate the off-design behavior of S-CO2-cooled SMR including the turbine off-design behavior.

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