Compressor Modeling for Transient Analysis of Supercritical CO_2 Brayton Cycle by using MARS code

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1. Introduction

The supercritical CO_2 Brayton cycle (SCO_2BC) has advantages of high thermal efficiency, system compactness and wide operation range for the power generation cycles [1]. The advantages attract SCO_2BC as a promising next generation power cycles. The high thermal efficiency comes from the operation of compressor near the critical point where the properties of SCO_2. The approaches to those of liquid phase, leading drastically lower the compression work loss. However, the advantage requires precise and smooth operation of the cycle near the critical point. However, it is one of the key technical challenges. Therefore it is important to understand the cycle behavior when the cycle experiences transient conditions in this operation. Therefore the analysis of the transient behavior of compressor near the critical point, SCO_2BC was modeled in the MARS code with employing the compressor model.

In this study, SCIEL (Supercritical CO_2 Integral Experimental Loop) [2] was chosen as a reference loop and the MARS code [3-4] was as the transient cycle analysis code. As a result, the compressor homologous curve was developed from the SCIEL experimental data and MARS analysis was performed and presented in the paper.

2. Development of compressor model for SCIEL SCO_2BC

In order to perform transient analysis of SCO_2BC using MARS, the nodalization of compressor was made in MARS. The compressor model of MARS need table data of compressor performance curve. As the first step of nodalization of compressor model, the homologous curve was developed from the SCIEL experimental data. Nodalization of the compressor model in MARS using the homologous curve and the SCIEL configuration was followed.

2.1 Compressor homologous curve

The homologous curve [5] is a condensed form of a performance curve of the compressor. The homologous curve represents compressor performance in terms of the actual head (H), torque (τ), volumetric flow (Q), and angular velocity (ω) in dimensionless forms such as the head ratio($h = \frac{H}{H_R}$), the torque ratio($\beta = \frac{\tau}{\tau_R}$), the volumetric flow ratio($v = \frac{Q}{Q_R}$), and the angular velocity ratio($\alpha = \frac{\omega}{\omega_R}$); the subscript R denoted the rated value. The ratios are defined as the actual value over the rated value. The rated values require the compressor parameters at the component input condition corresponding to a design point or a point of the maximum efficiency for the compressor. Usually, these data are generally available from vendor.

However, since the SCIEL compressor was manufactured in the custom-made production, these parameters should be obtained from experiments. In addition, although the target pressure ratio of the SCIEL compressor was 1.8 with the rotating speed of 70,000 rpm at the mass flow rate of 6.4 kg/s [2], the performance test of the compressor was conducted at the reduced speeds of 25,000 rpm, 30,000 rpm and 35,000 rpm.

From the experiments, first-for sets of data for the normal operation designated as HAN, HVN, BAN, and BVN; the H denoted head, the B denoted torque, the A denoted division by speed, and the N denoted first quadrant.

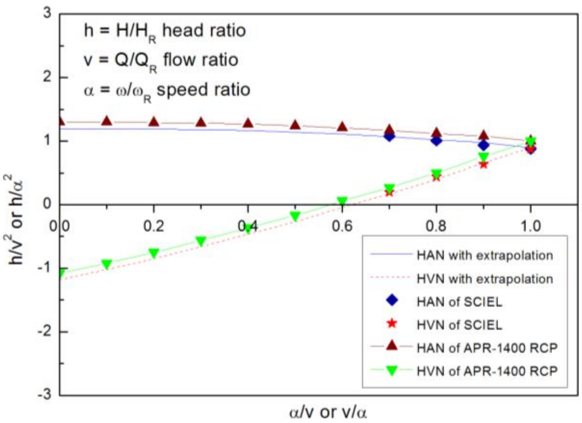

Fig. 1. Homologous head curve of SCIEL compressor in single-phase flow

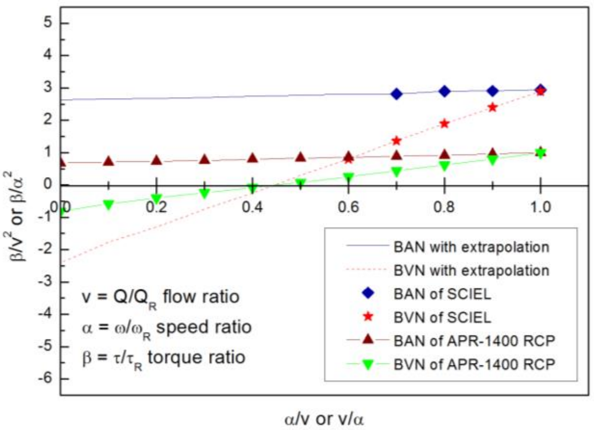

Fig. 2. Homologous torque curve of SCIEL compressor in single-phase

Fig. 1 shows homologous head curves, HAN was shown h/α^2 as a function of v/α and HVN was shown h/v^2 as a function of α/v. Fig. 2 shows homologous torque curves, BAN was shown β/α^2 as a function of v/α and BVN was shown β/v^2 as a function of α/v. In the plots, the design values were used as the rated values.

Since the homologous curve data of the SCIEL compressor shows similar characteristics with one used in the Reactor Coolant Pump (RCP) in APR-1400 it was decided to extrapolation the curves for the entire operation ranges.

2.2 Compressor Model

MARS is a multi-dimensional thermal-hydraulic system analysis code for nuclear power plant. For developing the compressor model, first, the nodalization of compressor components to simulate the SCIEL compressor was shown in Fig. 3.

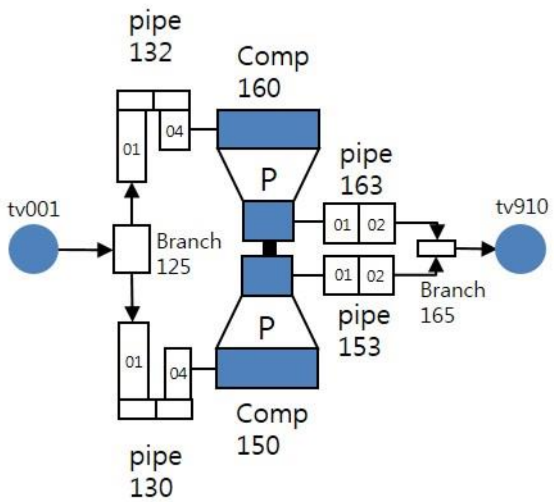

Fig. 3. The nodalization of compressor model in MARS

The actual geometrical values for the components such as the time dependent volume (TMDPVOL), the compressor (PUMP), the pipe (PIPE), the branch (BRANCH), the single junction (SNGLJUN) and the time dependent junction (TMDPJUN) as shown in Fig. 3 were used. SCIEL modeled in MARS was considered as an open loop. By providing the boundary conditions of the pressure boundary at the time dependent volume of 001 for inlet and 910 for outlet.

The experimental inlet and outlet conditions, and the design point values, which are referred as the rated value, were used for the MARS inputs. For the homologous curve embedded in the MARS input in a table form.

3. Results

The numerical calculation of the MARS compressor model was performed and compared with the experimental data from the SCIEL compressor as shown in Table 1.

Table 1: MARS calculation results with experimental data

Parameters	Experiment	Numerical solution
Pressure inlet (MPa)	7.59 ~ 7.601	7.59
Temperature inlet (K)	309.12	309.15
Pressure outlet (MPa)	7.836 ~ 7.88	7.85
Temperature outlet (K)	311.64	313.48
Compressor speed (rpm)	25,000	25,000
Compressor inlet mass flow rate (kg/s)	0.9	0.7

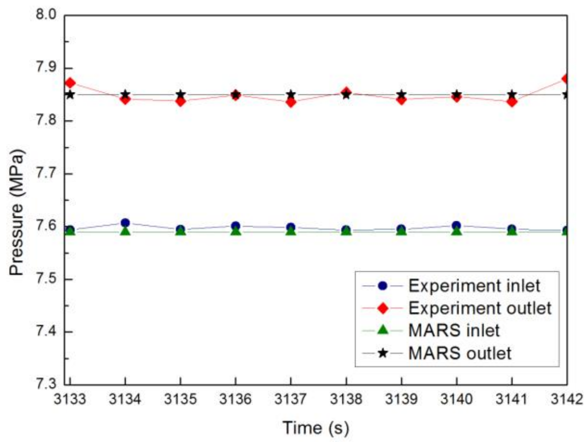

Fig. 4. Comparison of pressures at the compressor inlet and outlet obtained from MARS analysis to SCIEL experimental data

Fig. 4 shows pressure as a function of time for a comparison of pressures at the compressor inlet and outlet obtained from MARS analysis to SCIEL experimental data. The experimental data was steady state at compressor rotating speed of 25,000 rpm. The time, 3133 second, was starting point of steady state. Numerical solutions were well matched with the experimental data. The mass flow rate from the MARS analysis of approximately 0.7 kg/s was close to the experimental result of 0.9 kg/s. It is expected that the difference come from the measurement error in the experiment.

4. Conclusion

In this study, the compressor model was developed and implemented in MARS to study the transient analysis of SCO_2BC in SCIEL. We obtained the homologous curves for the SCIEL compressor using experimental data and performed nodalization of the compressor model using MARS code. In conclusions, it was found that numerical solutions from the MARS model were well matched with experimental data. However, the numerical solutions show well matched at mass flow rate. Further studies on transient analysis of compressor components will be conducted. And nodaization of the other components model, such as the precooler, the heater, and the turbine, will be performed.

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