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Improvements of MARS Code for Analyzing S-CO_2 Cycle Coupled to PWR type SMR

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1. Introduction

Recently, the marine applications of nuclear power such as nuclear propulsion ships and floating nuclear power plants have attracted attention in many countries [1]. In order to apply nuclear power to marine environment, the size of the entire system must be small due to spatial constraints. In this regard, the authors proposed a system that combines the supercritical carbon dioxide (S-CO_2) power cycle in the pressurized water-cooled reactor (PWR) type small modular reactor (SMR). Since the S-CO_2 cycle features a small pressure ratio and single phase, the size of the total system can be reduced innovatively compared to the Rankine cycle [2].

When nuclear power is applied to marine propulsion, the safety analysis of the reactor core as well as the performance analysis of the overall system under the off-design situation such as load fluctuations becomes important. There are several thermal hydraulic system codes for nuclear reactor safety analysis, including MARS, RELAP5, and TRACE. Since these codes focus on the nuclear system safety analyses, each code needs to be improved in order to accurately analyze transient responses of the power conversion system as well. Although there were previous studies simulating the S-CO_2 cycle with the nuclear system analysis code, component design values and input modeling were independent due to limitations of realistic modeling of components applied to the S-CO_2 cycle in the conventional system codes [3].

In this paper, the MARS code, one of the nuclear system analysis codes, has been improved to accurately analyze the S-CO_2 cycle under the light water conditions. An option for calculating the properties of the fluid was added to precisely predict physical properties near the critical point. Modelling of main components such as heat exchangers and turbomachinery to be applied to S-CO_2 system has been added so that design values of each component can be reflected accordingly.

2. PWR + S-CO_2 System

In this section, the design results of PWR + SCO$_2$ system will be described. The authors previously performed the cycle optimization and design of main components for PWR + S-CO_2 system [4]. Since this paper focuses on the modifications of MARS code for the whole system analysis, the detailed design process and the description of design codes are omitted and only summarized the design results herein.

2.1 Cycle Design

The cycle design was performed with an in-house S-CO_2 cycle optimization code, namely KAIST-ESCA (Evaluator for S-CO_2 cycle based on Adjoint method) [5]. Table I and Fig. 1 show the cycle design results. The reference primary reactor system is System-integrated Modular Advanced ReacTor (SMART) which is a 330 MWt integral type reactor developed by KAERI (Korea Atomic Energy Research Institute). Cycle thermal efficiency was approximately 30% and the design conditions of the main components were obtained from the cycle design.

Table I: Cycle Design Variables

Core Thermal Power [MW]	330
Maximum Pressure [MPa]	20
Minimum Pressure [MPa]	7.8359
Maximum Temperature [°C]	310
Minimum Temperature [°C]	32
Turbine Efficiency [%]	90
Compressor Efficiency [%]	85

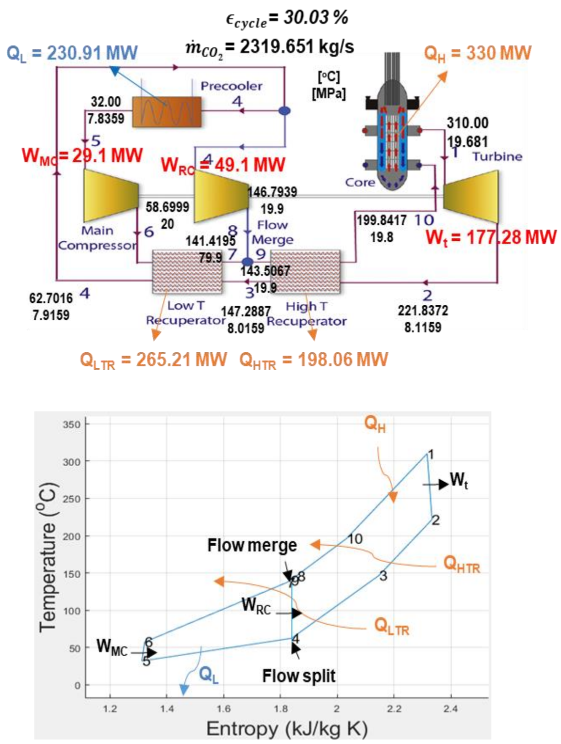

Fig. 1. The result of the S-CO_2 cycle design under the PWR type SMR conditions.

2.2 Component Design

The main components of S-CO_2 power conversion system are heat exchangers and turbomachinery. In case of heat exchangers, the proposed system has four sections of heat exchanger: the intermediate heat exchanger (IHX), the high temperature recuperator (HTR), the low temperature recuperator (LTR), and the precooler (PC). The type of all heat exchangers is Printed Circuit Hear Exchanger (PCHE). KAIST-HXD, a well validated in-house code, was used for designing each heat exchanger [6] and design parameters are summarized in Table II. The main design parameters for system analysis are hydraulic diameter, total flow area, active length, and heat transfer area.

For turbomachinery, there are three components: main compressor (MC), recompressing compressor (RC), and turbine. Each turbomachinery was designed with an in-house code, KAIST-TMD (TurboMachinery Design). Design outputs of KAIST-TMD code is the geometry and performance maps of each turbomachinery as shown in Fig. 2.

Table II: Design Parameters of Heat Exchangers

Parameters	IHX	HTR	LTR	PC
Heat Load [MW]	27.5	198.06	265.21	230.91
Effectiveness [%]	89.87	95.20	95.215	75.42
Hot Channels [#]	88600	1850000	2790000	1200000
Cold Channels [#]	88600	1850000	2790000	1200000
Total Flow Area [m^2]	**0.089**	**1.860**	**2.805**	**1.206**
Active Length [m]	**0.2337**	**0.398**	**0.8985**	**0.4695**
Heat Transfer Area [m^2]	**100.98**	**3591.02**	**12226.0**	**2748.06**
Total Active Volume [m^3]	0.21617	7.687	26.17	5.883

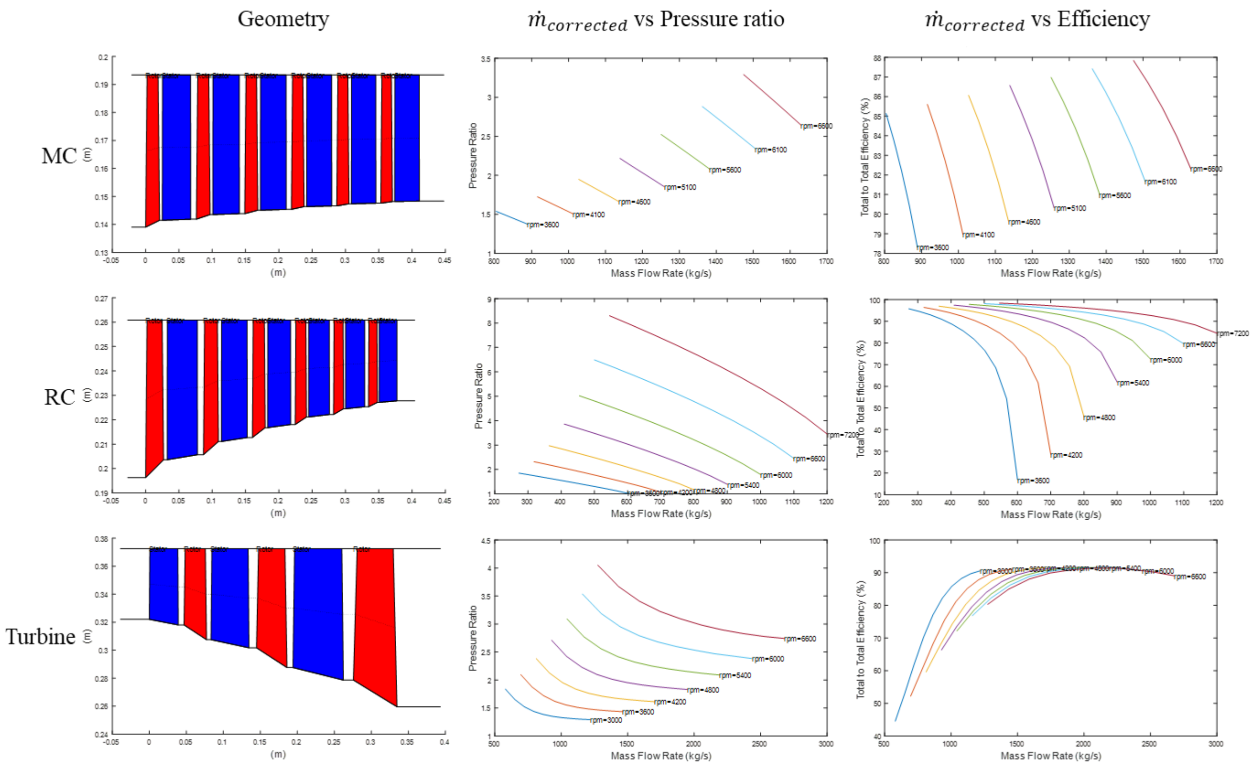

Fig. 2. Design results of turbomachinery.

3. Modifications of MARS Code

This section describes which models have been added to the original MARS code to better simulate the S-CO_2 cycle.

3.1 Physical Properties of Fluids

To maximize the efficiency of the S-CO_2 cycle, compressor inlet conditions should be maintained near the critical point. Since physical properties of the S-CO_2 change dramatically in the vicinity of the critical point, it is very important to accurately predict its properties in order to simulate the total system. The original MARS code calculate properties of fluids by linearly interpolating property table generated by NIST data points. However, as shown in Fig. 3, the lack of data points limits the inability to accurately calculate abrupt changes in physical properties near the critical point. Therefore, the authors added a property calculation option to directly import NIST data into MARS at every time step [7]. By activating newly added option, it is possible to accurately calculate the properties of CO_2 that exhibit nonlinear behavior near the critical point.

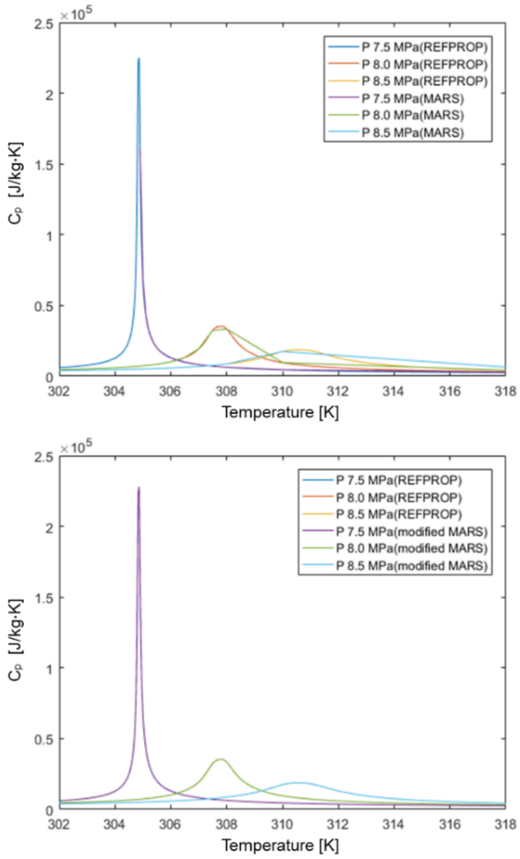

Fig. 3. An example of improvement in calculating properties near the critical point (specific heat).

3.2 PCHE Model

Typically, heat exchangers of the S-CO_2 cycle are designed as the PCHE type due to its high performance and compactness. However, since there is no heat structure model of PCHE in the original MARS code, there must be a gap between the design parameters and the system code input deck. Therefore, the authors added PCHE correlations to the heat structure sets of the MARS code so that design values such as heat transfer area and heat transfer length derived from the heat exchanger design code (KAIST-HXD) can be applied to input deck. As an example of four heat exchangers, Fig. 4 describes IHX test input with the modified MARS code reflecting design values summarized in section 2.2. Fig. 5. shows that the internal temperature distribution and heat transfer coefficients agree well with the design code.

- PCHE Correlations [6]

: CO_2 (15,000 < Re < 85,000, 2 < Pr < 33)

$$Nu = 0.08405Re^{0.5704}Pr^{1.08}, f = 0.0784Re^{-0.19} \cdots (1)$$

: Water (40 < Re 200)

$$Nu = 0.2829Re^{0.6686}, f = 6.9982Re^{-0.766} \cdots (2)$$

HXD Parameters	IHX
Hot side $\dot{m}$ [kg/sec]	129.5
Cold side $\dot{m}$ [kg/sec]	135.44
Hot side D_e [m]	9.7762e-4
Cold side D_e [m]	9.7762e-4
Heated length [m]	0.2771
Flow area [m^2]	0.08907
Total heated area [m^2]	100.98
Mesh [#]	10

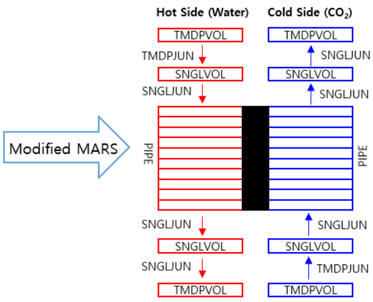

Fig. 4. Nodalization of test input for PCHE model in modified MARS code (IHX).

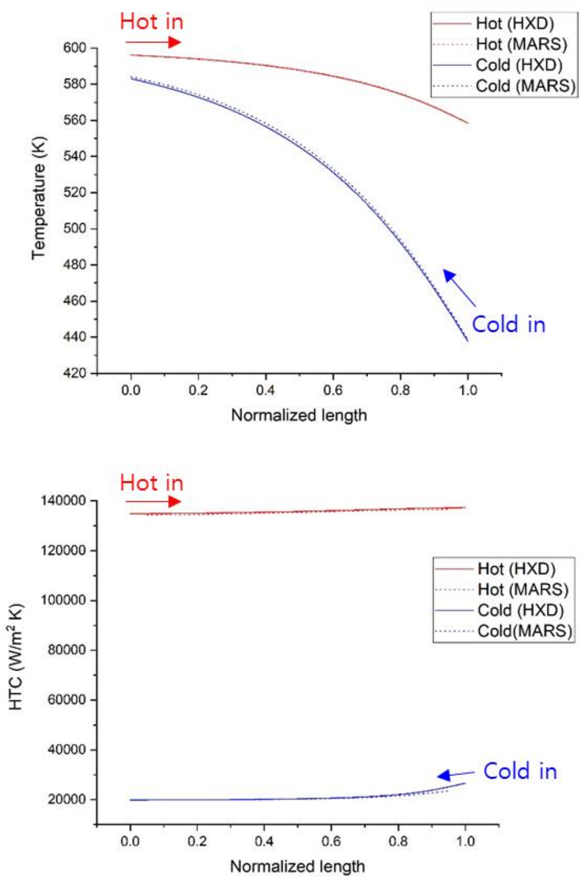

Fig. 5. Temperature and Heat transfer coefficient (HTC) profile in IHX.

3.3 Turbomachinery Model

Eqs. (3) and (4) are governing equations used in the calculation of turbine component in the original MARS code [8]. Only the momentum conservation equation uses a different equation generating larger pressure difference by multiplying pressure gradient by small coefficient using the efficiency of turbine. The original

MARS code has the gas turbine option and receive performance maps in the input deck [9]. However, only a performance map for a single RPM can be entered and the pressure ratio and turbine work are not properly calculated from the performance map. Fig. 5 shows that the existing turbine model have limitations in calculating the actual performance of the turbine, such as enthalpy error, when the pressure ratio is achieved using the loss coefficient.

- Turbine model of the original MARS code

: Momentum conservation equation

$$(\alpha_g \rho_g)\left(\frac{\partial v_g}{\partial t} + v_g \frac{\partial v_g}{\partial x}\right) = -\alpha_g (1-\eta) \frac{\partial P}{\partial x} - C_g \cdots (3)$$

$$(\alpha_f \rho_f)\left(\frac{\partial v_f}{\partial t} + v_f \frac{\partial v_f}{\partial x}\right) = -\alpha_f (1-\eta) \frac{\partial P}{\partial x} - C_f \cdots (4)$$

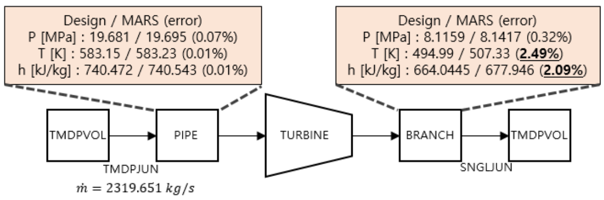

Fig. 6. Test results of S-CO_2 turbine in the original MARS code.

The authors added new options to accurately simulate the turbomachinery as shown in Fig. 7. When the newly added turbine or compressor option is on, code uses the new governing equations for turbomachinery reflecting additional pressure and enthalpy difference from performance maps. Fig. 8 shows that the results of testing each turbomachinery with the modified MARS code are well matched with the design values, when modeled based on the design results shown in section 2.2.

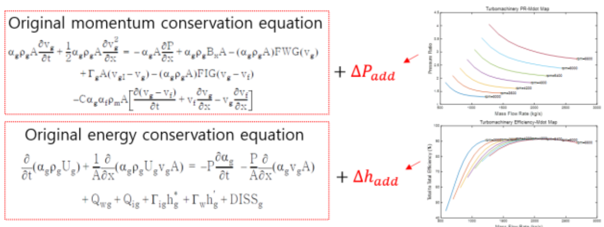

Fig. 7. Modified governing equations for turbomachinery.

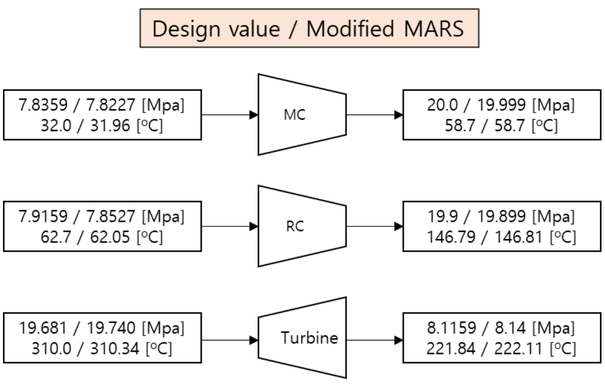

Fig. 8. Test results of designed turbomachinery in the modified MARS code.

4. Summary and Further Works

In this paper, the authors improved the MARS code to better simulate the S-CO_2 cycle under the PWR conditions. First, the option of interworking with NIST REFPROP was added to enable accurate calculation of physical properties of S-CO_2. Second, the heat structure model of PCHE was added so that the geometric parameters derived from the design code could be entered into the MARS code. Third, turbomachinery options was added to enable realistic simulation of turbine and compressor. The improved code will be used to perform steady-state and transient analysis of the entire system, including water-cooled reactor systems and S-CO_2 power cycle.

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