Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 17-19, 2017

PCHE off-design performance model for S-CO_2 power cycle under SMART condition

Jinsu Kwon, Jeong Ik Lee*
Department of Nuclear and Quantum Engineering, Korea Advanced Institute of Science and Technology, 373-1 Guseong-dong Yuseong-gu,Daejeon 305-701, Republic of Korea
**Corresponding author: jeongiklee@kaist.ac.kr*

1. Introduction

SMART (System-integrated Modular Advanced ReacTor) is a promising advanced small nuclear power reactor. It is a 330 MW_{th} integral type reactor developed by KAERI (Korea Atomic Energy Institute) for multipurpose utilization, which incorporated inherent safety systems, system simplification and component modularization.

The steam-Rankine cycle was the most widely used power conversion system for a nuclear power plant. Recently, there has been a growing interest in the supercritical carbon dioxide (S-CO_2) Brayton cycle as the most promising power conversion system. The reason is high efficiency with simple layout and compact power plant due to small turbomachinery and compact heat exchanger technology like Printed Circuit Heat exchanger (PCHE). That is why the S-CO_2 Brayton cycle can enhance the existing advantages of Small Modular Reactor (SMR) like SMART, such as reduction in size, capital cost, and construction period.

It is important to predict an off-design performance of the equipment because it generally does not operate only under the design conditions. The equipment should be operated efficiently as the external conditions change. To operate the equipment efficiently, it is necessary to find the optimum point of the cycle operating condition. Moreover, in order to find the optimum point of the cycle operating condition in real time in the field, the calculation speed of the code must be fast. During the cycle off-design analysis, the S-CO_2 PCHE component usually performs analysis in a discretized way, which will take a long computer time. Therefore, there is a need for a method for quickly predicting the off-design performance of the heat exchanger component.

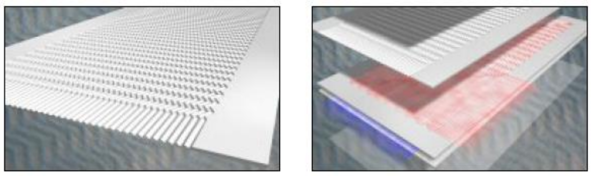
A similar study was performed by Kevin Hoopes et al [1], which evaluated the off-design performance using scaling law. However, since it is evaluated using the discretized method, it can be inferred that the calculation speed is not fast.

Therefore, the goal of this study is to develop the PCHE off-design performance model by modifying the existing Log-Mean Temperature Difference (LMTD) method. This new method will be compared with the results of the analysis with the existing discretized method by applying to the SMART operating condition. Moreover, with this method, the cycle off-design point will be analyzed.

2. Methods and Results

2.1 PCHE

PCHE(Printed Circuit Heat Exchanger), developed by Heatric Division of Meggitt (UK), is a promising heat exchanger because it is able to withstand pressures up to 50 MPa and temperatures from cryogenic condition to 700 °C. It is extremely compact and has high efficiency. Fluid flow channels are etched chemically on metal plates. The channels are semicircular with 1-2mm diameter. Etched plates are stacked and diffusion bonded together to fabricate as a block. These processes are shown in Fig. 1. Also, for the same thermal duty and pressure drop, a PCHE is up to 85% smaller than an equivalent shell and tube heat exchanger. A relative size comparison is shown in Fig. 2. [1]



(a) Etched Plate (b) Stacked Plates

Figure 1. PCHE Plates and Diffusion Bond [1]

Figure 2. Size comparison of PCHE and shell and tube heat exchanger [1]

2.2 Modified LMTD method

When designing the power cycle, a LMTD method or ε-NTU methodology is mainly used in heat exchanger design. These two methods need to assume that the specific heat of the fluid inside the heat exchanger is a constant. Accordingly, these methods are suitable for fluids such as water in which the specific heat is not greatly changed by the temperature. However, carbon dioxide is unlike water since rapid change of properties near the critical point and pseudo critical point occur in the power cycle. As a result, modified LMTD method needs to be developed.

In order to begin the off-design performance calculation, the information from the on-design point is needed. PCHE on-design point can be found by using an in-house code of which the name is KAIST_HXD. It is well validated with experimental data from KAIST S-CO_2 pressurizing experiment (S-CO_2PE) facility [2]. The LMTD method can be described by the following equation.

$$Q = UA_{on}\Delta LMTD \tag{1}$$

$$\Delta LMTD = \frac{(T_{Hot,in} - T_{\mathrm{Cold,out}}) - (T_{Hot,\mathrm{out}} - T_{\mathrm{Cold},in})}{\ln(T_{Hot,in} - T_{\mathrm{Cold,out}}) - \ln(T_{Hot,\mathrm{out}} - T_{\mathrm{Cold},in})} \tag{2}$$

$$\frac{1}{UA_{on}^{mean}} = \frac{1}{hA_{on}^{hot}} + \frac{1}{hA_{on}^{cold}} + \frac{x}{kA_{material}} \tag{3}$$

The off-design performance can be estimated by scaling the on-design hA terms for both the hot and cold sides using the following scaling law.

$$Q_{off} = UA_{off}\Delta LMTD_{off} \tag{4}$$

$$hA_{off} = hA_{on} \times [\frac{k_{off}}{k_{on}}] \times [\frac{\mathrm{Re}_{off}}{\mathrm{Re}_{on}}]^{x} \times [\frac{\mathrm{Pr}_{off}}{\mathrm{Pr}_{on}}]^{y} \tag{5}$$

$$\frac{1}{UA_{off}^{mean}} = \frac{1}{hA_{off}^{hot}} + \frac{1}{hA_{off}^{cold}} + \frac{x}{kA_{material}} \tag{6}$$

This equation can be used when the heat transfer correlation in the heat exchanger is a function of Re and Pr. Also, the values of x and y may be different depending on the correlation of the Cold side and Hot side.

The pressure drop at the off-design condition can be obtained by the following scaling law.

$$\Delta p_{off}^{mean} = \Delta p_{on}^{mean} \times \frac{\dot{m}_{off}^{2}}{\dot{m}_{on}^{2}} \times \frac{\rho_{on}}{\rho_{off}} \tag{7}$$

The major difference between the modified LMTD method and the LMTD method is the overall heat transfer coefficient UA. In the LMTD method, the representative physical properties of the fluid are used as the average value of the inlet temperature and the outlet temperature. The modified LMTD method takes one more step. The UA value obtained by the conventional LMTD method is set as UA_{on}^{mean} at the mean fluid temperature. To find the UA_{off}^{mean}, the outlet temperature should be assumed at first and second. Then, by using the below equation, UA_{off} can be found.

$$UA_{on}^{lmtd} = \frac{Q}{\Delta LMTD} \tag{8}$$

$$UA_{off} = UA_{off}^{mean} \times \frac{UA_{on}^{lmtd}}{UA_{on}^{mean}} \tag{9}$$

After that, the results between Q_{off} and $Q_{channel}$ are compared. If the difference error is higher than 1E-4, the iteration scheme is applied to match the heat balance. Linear interpolation scheme is used at the iteration step.

$$difference\ error = \frac{|Q_{\mathrm{off}} - Q_{channel}|}{Q_{off}} \tag{10}$$

$$Q_{channel} = \dot{m}(h_{Hot,out,assumed} - h_{Hot,\mathrm{in}}) \tag{11}$$

In a similar way as above, the off-design pressure drop term can also be expressed as below.

$$\Delta p_{off} = \Delta p_{off}^{mean} \times \frac{\Delta p_{on}}{\Delta p_{on}^{mean}} \tag{12}$$

Δp_{on} : On-design pressure drop. Δp_{on}^{mean} : On-design pressure drop when the representative physical properties of the fluid are used as the average value of the inlet temperature and the outlet temperature.

2.3 Design condition of the S-CO_2 Brayton cycle

The design condition of the S-CO_2 recompression Brayton cycle is shown in Fig. 3 [3]. Originally the heat capacity of steam generator is 330MW_{th}. However, this steam generator heat duty is 27.5MW_{th} because when the number of PCHE steam generators is increased, the size of the nuclear reactor becomes smaller and the pressure drop on PCHE becomes smaller. The primary mass flow rate and inlet temperature was set to 174 kg/sec and 323 °C respectively. The same inlet pressure was assumed.

For the secondary side (CO_2 side), the design parameters were obtained through an in-house cycle design code. The mass flow rate is 199.056 kg/sec and flow split ratio which is defined as ratio of the flow into main compressor to the total cycle mass flow rate. The value is 0.62.

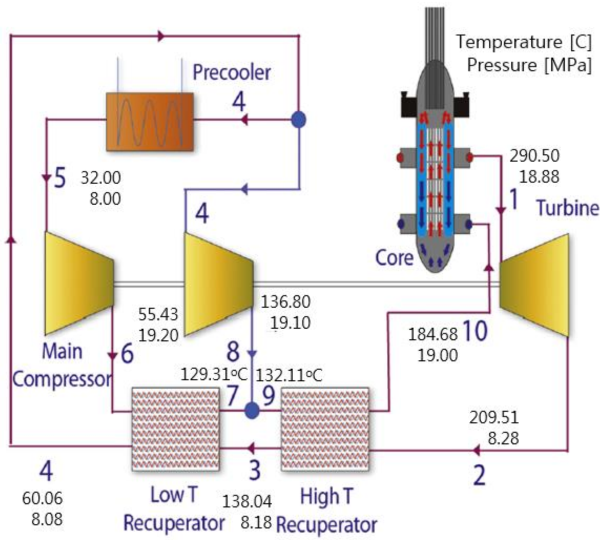


Figure 3. S-CO_2 Brayton cycle design point [3]

2.4 Comparison of PCHE design code and modified LMTD method

The target model is Low Temperature Recuperator because the change of the property value is large in this region. The off-design parameter is cold side inlet temperature from 45 degree Celsius to 65 degree Celsius and the other conditions are the same. The on-design point is shown in Table.1. The differences of transferred heat and pressure drop between PCHE design code and modified LMTD method are presented in Fig.4 and Fig.5.

$$dQ\ error\ [\%] = \frac{\left|Q_{\text{PCHE Design Code}} - Q_{off}\right|}{Q_{\text{PCHE Design Code}}} \times 100 \quad (13)$$

$$dP\ error\ [\%] = \frac{\left|P_{\text{PCHE Design Code}} - P_{off}\right|}{P_{\text{PCHE Design Code}}} \times 100 \quad (14)$$

Table 1. Low Temperature recuperator operating condition

	Hot side	Cold side
T_{in} [C]	138.04	55.43
T_{out} [C]	59.85	129.92
P_{in} [MPa]	8.18	19.2
P_{out} [MPa]	8.08	19.15
Mass flow rate[kg/sec]	199.06	123.41

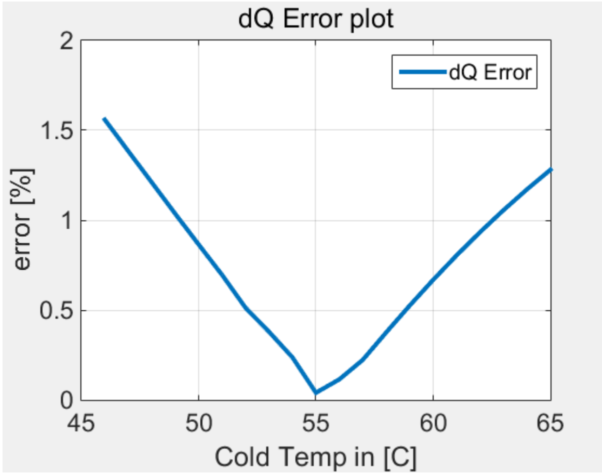


Figure 4. Heat error versus cold side inlet temperature

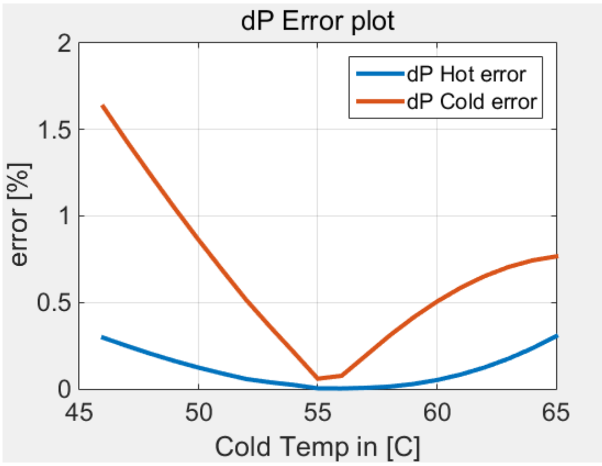


Figure 5. Pressure drop error versus cold side inlet temperature

3. Summary and Conclusions

PCHE off-design modeling was performed with the target of low temperature recuperator modeling in S-CO_2 Brayton cycle under the SMART operating conditions. The results show that the modified LMTD method works well with the PCHE design code near the design point, but the heat transfer error and pressure drop error increase with distance from the design point. However, since the influence on the temperature is not large when the heat transfer error is 1 to 2%, this method can be used usefully within an appropriate range. In addition, since the absolute value of the pressure drop is about 100 kPa, an error of 1 to 2% is almost no influence. Further study will be conducted by applying this method to the cycle off-design analysis and difference of the results will be compared.

REFERENCES

[1] Kevin Hoopes, et al. "A NEW METHOD FOR MODELLING OFF-DESIGN PERFORMANCE OF sCO2 HEAT EXCHANGERS WITHOUT SPECIFYING DETAILED GEOMETRY", The 5thInternational Symposium - Supercritical CO2 Power Cycles, 2016
[2] www.heatric.com, 2008.
[3] Baik, Seungjoon, et al. "Study on CO2 – Water Printed Circuit Heat Exchanger Performance Operating under Various CO_2 phases for S-CO_2 Power Cycle Application." Applied Thermal Engineering 2017
[4] Kwon, Jinsu, et al. "Comparison the steam Rankine cycle with the supercritical CO2 Brayton cycle as a power conversion system for water-cooled SMR." America Nuclear Society, 2016