Development of accelerated PCHE off-design performance model for optimizing power system control strategies in S-CO2 power conversion system of nuclear power plant applications

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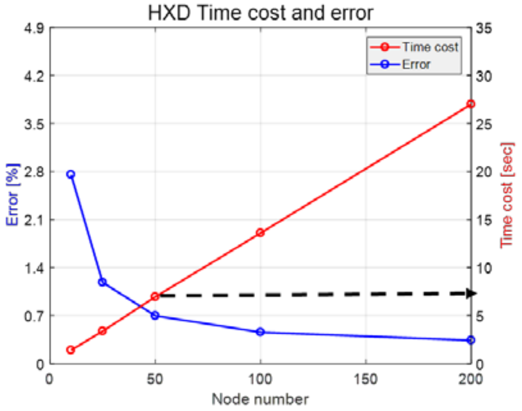
1. Introduction

The supercritical carbon dioxide (S-CO_2) Brayton cycle has been receiving a lot of attention due to many advantages as one of the promising power systems. That is because an S-CO_2 system is beneficial in several aspects like high thermal efficiency at a moderate turbine inlet temperature region (450°C – 750°C), compact power plant due to simple layout, small turbomachinery and compact heat exchanger technology, e.g. Printed Circuit Heat Exchanger (PCHE) technology [1]. PCHE has excellent structural rigidity and it can obtain high compactness due to large heat transfer area owing to a micro-sized channel. Therefore, many research works have been focused on to the application to a pre-cooler and a recuperator [2, 3].

However, the conventional heat exchanger analysis methods cannot be directly applied to heat exchangers of an S-CO_2 system since the specific heat is not constant in the pre-cooler due to substantial change of properties near the critical point. To solve non ideal gas property of CO_2 near the critical point, the PCHE analysis tool KAIST_HXD was developed and well validated with experimental data previously [4]. It uses finite element method with numerical method to find an adequate temperature and pressure profile. Since an iterative numerical calculation scheme is applied to the discretized channel system, KAIST_HXD requires significant amount of computational resource. The results show that the error is 0.7% when the calculation time is 7 seconds as shown in Figure 1.

A PCHE computation time problem becomes more pronounced if it is expanded to the system level analysis. To maximize the cycle efficiency, finding the optimum operating point is a key to the successful off-design operation. The optimum operating point can be obtained by repetitive quasi-steady state analysis under the change of control parameters (e.g. bypass valve fraction, throttle valve fraction and inventory of working fluid). Establishing the optimum control strategies demands significant amount of computational resources. To resolve an excessive time-consumption issue, reducing heat exchanger analysis time becomes imperative.

Therefore, the goal of this study is to develop a PCHE off-design performance model, which can accelerate the computation time while maintaining similar order of accuracy by modifying the existing LMTD method.



Hot side		Cold side	
CO_2		Water	
Temperature [°C]	[39] - 36.1	Temperature [°C]	37.2 – [15]
Pressure [Mpa]	[8.1] – 8.049	Pressure [Mpa]	0.42- [0.42]
Mass flow [kg/sec]	2	Mass flow [kg/sec]	0.5

Figure 1. Error and time cost depending on channel node numbers

2. Methods and Results

2.1 Recuperator off-design performance model

To develop the PCHE off-design performance for a recuperator, the Log Mean Temperature Difference (LMTD) method is introduced because the changes of specific heat is not significant inside the recuperator. LMTD method initially assumes hot side outlet temperature. Then, representative specific heat, viscosity, and thermal conductivity of the channel are obtained at mean enthalpy of inlet and outlet. With this, the heat transfer rate can be obtained from Equation 1. In the next step, hot side outlet enthalpy is calculated from the conservation of energy shown in Equation 2. This sequence is repeated until the difference between the previously calculated heat transfer rate and the present heat transfer rate is very small.

$$Q_{LMTD} = UA \times LMTD = \frac{1}{\frac{1}{h_{hot}} + \frac{t}{k_{conduction}} + \frac{1}{h_{cold}}} A \times LMTD \tag{1}$$

$$h_{hot,out} = h_{hot,in} - \frac{Q_{LMTD}}{\dot{m}_{hot}} \tag{2}$$

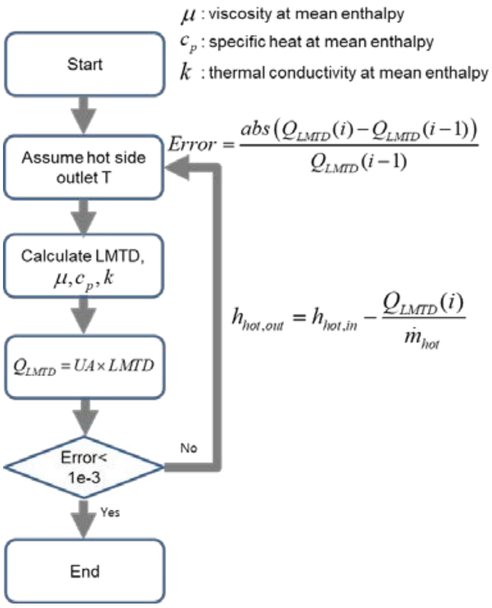


Figure 2. Flow chart of LMTD method

The reference is selected to be the recuperator in a simple recuperated cycle. It is widely used recuperator in an S-CO_2 system due to compactness. Off-design conditions for recuperator are studied and summarized in the following table.

Table I. The off-design condition for reference data at recuperator

Hot side		**Cold side**	
CO_2		CO_2	
Temperature [℃]	470 – 490 [10]	Temperature [℃]	60 – 80 [10]
Pressure [Mpa]	7.8 – 8.2 [0.2]	Pressure [Mpa]	19 – 21 [1]
Mass flow [kg/sec]	155 – 175 [20]	Mass flow [kg/sec]	155 – 175 [20]

The differences of heat transfer rate between LMTD method and reference data show constant difference of 7 %. LMTD method underestimates the heat transfer rate from the reference data. The reason is due to the underestimation of the representative overall heat transfer coefficient in a channel. Predicting low overall heat transfer coefficient is caused by using the mean enthalpy between inlet and outlet. In Figure 3, the circle black markers, which are the average enthalpy between inlet and outlet of LMTD method, have higher value than the mean enthalpy of the reference data. The obtained heat transfer coefficients of the LMTD method are also underestimated due to the higher mean enthalpy. Consequently, 7 % difference is caused by assuming the average enthalpy as the representative enthalpy of a channel. To remove the constant difference, a simple correction factor is introduced, which is the ratio of heat transfer rate with HXD under on-design point and heat transfer rate with LMTD method under on-design point as shown follow equation.

$$Q_{model,off} = \frac{(UA)_{off}\,(LMTD)_{off}}{(UA)_{on}\,(LMTD)_{on}} Q_{HXD,on} \qquad (3)$$

It can effectively eliminate the error caused by using the average enthalpy between inlet and outlet because the tendency of enthalpy change is the same when the recuperator is operating in off-design conditions. The corrected heat transfer rate agrees well with the reference data as shown in Figure 4.

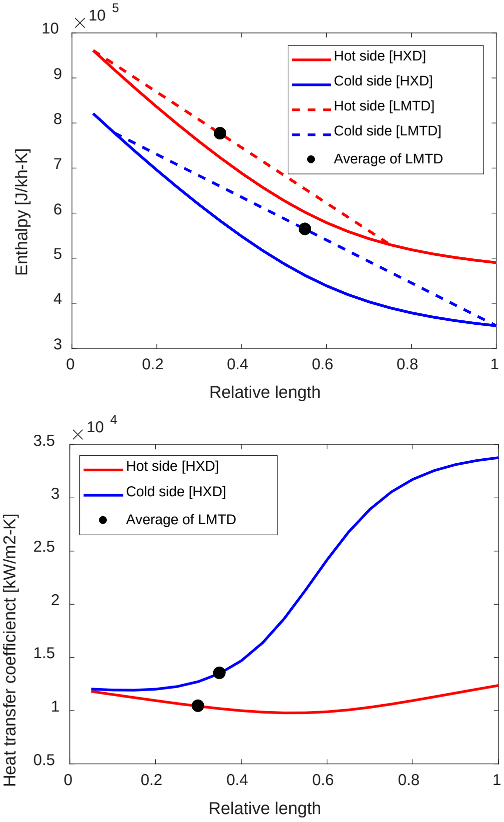


Figure 3. Enthalpy (up) and heat transfer coefficient (down) distribution along the flow channel at recuperator

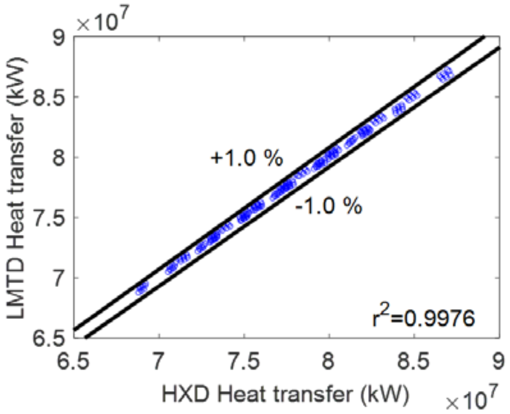


Figure 4. Comparison plot between LMTD method with correction factor and HXD in heat transfer rate at recuperator

2.2 Pre-cooler off-design performance model

The investigated off-design conditions for a pre-cooler are shown in Table.2, which are determined from the previous studies [1, 5, 6]. The total number of data is 945 including the on-design point. The reference heat exchanger is the water-cooled pre-cooler in the KAIST S-CO_2 experimental facility since the geometry of the pre-cooler is known.

Table II. The references of pre-cooler inlet point

Hot side		**Cold side**	
CO_2		Water	
Temperature [°C]	50 – 80 [5]	Temperature [°C]	18 – 26 [4]
Pressure [Mpa]	7.5 – 8.5 [0.25]	Pressure [Mpa]	0.5
Mass flow [kg/sec]	0.8 – 1.2 [0.2]	Mass flow [kg/sec]	1.2 – 2.0 [0.4]

When LMTD method with simple correction factor is applied to the assumed pre-cooler operating range, the maximum difference is around 20 %. It means LMTD method used to the recuperator is not suitable for pre-cooler due to substantial change of specific heat inside the heat exchanger. To modify LMTD method for the S-CO_2 pre-cooler, it is required to find the most influential parameter and it can be found through the derivation of LMTD method. The following equations can be obtained from the heat exchanger governing equation.

$$\ln\left(T_{hot}-T_{cold}\right)_x-\ln\left(T_{hot}-T_{cold}\right)_{x=0}= \int_{x'=0}^{x}\left[U\left(-\frac{1}{\left(\dot{m}c_p\right)_{hot}}+\frac{1}{\left(\dot{m}c_p\right)_{cold}}\right)\right]dA \qquad (4)$$

The left hand side of Equation 4 is the logarithmic function for the temperature difference, and the right hand side consists of the overall heat transfer coefficient and the heat capacity rate. Since the specific heat and the overall heat transfer coefficient are a constant in the LMTD derivation process, the right hand side of Equation 4 becomes a constant, and the logarithmic function of the temperature difference becomes a constant too. However, in the S-CO_2 pre-cooler that reflects the real gas properties, the logarithm of the temperature difference is not a fixed value. Therefore, the maximum variation of the right-hand side of Equation 4 is the key factor to determine the difference of the heat transfer rate of the KAIST_HXD with the LMTD method. The right-hand side in Equation 4 is denoted as ET, the abbreviation of Exponent of Temperature difference, and the maximum variation of the ET is denoted as Z in this paper, as in Equation 6.

$$ET=UA\left(-\frac{1}{\left(\dot{m}c_p\right)_{hot}}+\frac{1}{\left(\dot{m}c_p\right)_{cold}}\right) \qquad (5)$$

$$Z=ET_{MAX}-ET_{MIN} \qquad (6)$$

The flow chart of the conventional LMTD method was modified to reflect the newly introduced factor Z as shown in Figure 5. The LMTD method for the recuperator's performance prediction is first used to assume the outlet conditions of the pre-cooler. From this initial guess, additional parameters like the maximum specific heat and overall heat transfer coefficients can be obtained approximately under the off-design condition. These factors are used to acquire the maximum ET, which is proportional to the specific heat of CO_2, by determining whether CO_2 outlet temperature is higher than the pseudo-critical temperature that has the highest specific heat at the same pressure. The maximum ET can be obtained at the outlet of CO_2 when the outlet temperature of CO_2 is higher than the pseudo-critical temperature. For the other cases, the maximum ET exists inside the channel at the pseudo-critical temperature. Through the sequence of finding the maximum ET, the key parameter Z to remove the difference is easily calculated and implemented to the correction factor F. Then, the correction factor F, which is the function of Z as shown in Equation 8, is multiplied to the results of the LMTD method. Finally, off-design heat transfer rate is expressed with the ratio of heat transfer rate with KAIST-HXD under on-design point and heat transfer rate with the corrected LMTD method under on-design point as shown in Equation 7.

$$Q_{model,off}=\frac{\left(UA\right)_{off}\left(LMTD\right)_{off}F_{off}}{\left(UA\right)_{on}\left(LMTD\right)_{on}F_{on}}Q_{HXD,on} \qquad (7)$$

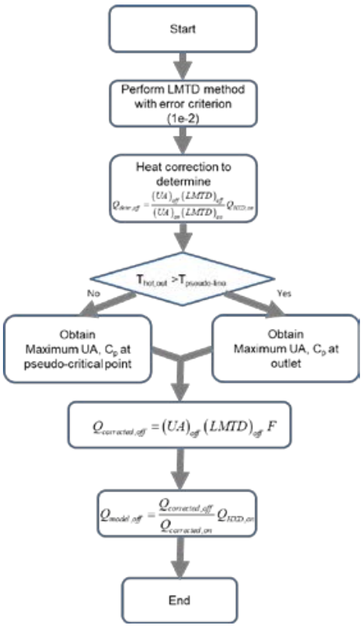


Figure 5. Flow chart of modified LMTD method reflecting a correction factor F

The heat transfer rate errors between the LMTD method and the reference data are plotted versus Z in Figure 6. The correction factor F is expressed as a linear function. The slope and y-intercept are obtained from a non-linear regression. The obtained correction factor F via regression is shown as follow equation.

$$F = -0.09Z + 1.21 \tag{8}$$

A comparison plot between heat transfer of newly developed off-design model and the KAIST_HXD is shown in Figure 7. The average absolute error with the correction factor F is 1.4% and the maximum error is 7.0%. Therefore, off-design model with correction factor F is suitable for evaluating heat transfer rate under off-design condition. The modified LMTD method and the iterative pressure drop model is 350 times faster than the reference code calculation to evaluate the off-design performance

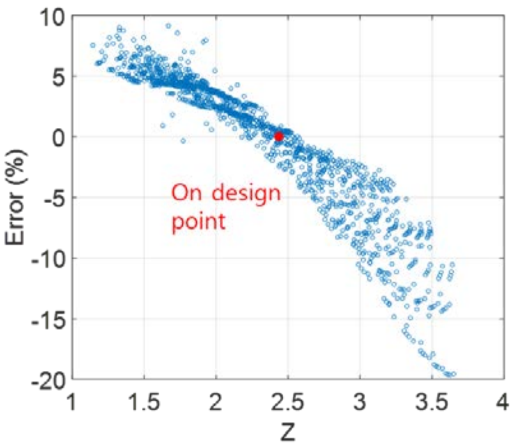


Figure 6. Heat transfer rate errors between modified LMTD method and reference data versus Z

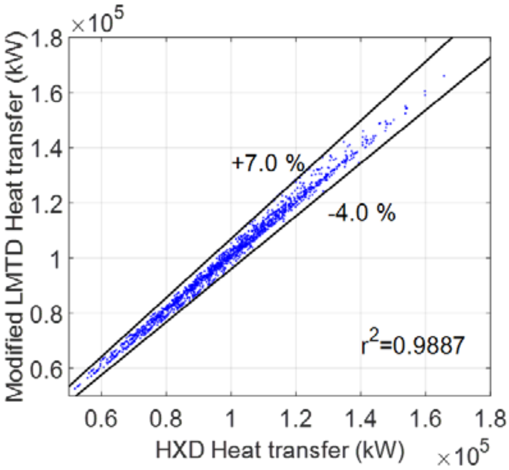


Figure 7. Comparison plot between LMTD method with correction factor F and HXD in heat transfer rate at pre-cooler

3. Conclusions

Establishing optimum power system control strategies is very important for various off-design conditions to operate the system in the best conditions. However, KAIST_HXD, which analyzes the heat exchanger with a fine discretization numerical method, requires significant amount of computational resource. Therefore, an accelerated PCHE off-design performance model is newly developed for both recuperator and pre-cooler. In the recuperator of an S-CO_2 cycle, the existing LMTD method and the pressure drop model have constant differences with the reference code calculations, which are due to the use of channel average enthalpy as a representative enthalpy of the channel. To resolve this problem, a simple correction factor is introduced.

In the pre-cooler for the S-CO_2 cycle, the abovementioned corrected LMTD method still shows high error due to large variation of specific heat inside the pre-cooler. For applying the LMTD method to the pre-cooler, a new parameter Z reflecting the variation of the specific heat and overall heat transfer coefficient in the channel is newly defined. The modified LMTD method can accelerate the calculation over 350 times faster to evaluate the off-design performance. Therefore, the developed off-design model can accelerate the heat exchanger analysis significantly while preserving the similar order of accuracy.

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