Preliminary study for the development of PCHE off-design performance model for S-CO$_2$ power conversion cycle of nuclear power plant applications

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1. Introduction

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 thermal efficiency at a modest turbine inlet temperature region (450°C – 750°C) with simple layout and compact power plant due to small turbomachinery and compact heat exchanger technology like a Printed Circuit Heat exchanger (PCHE). PCHE, developed by Heatric of Meggitt (UK), is a rising heat exchanger owing to excellent structural rigidity, which can 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. In addition, 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]

However, the conventional heat exchanger analysis methods (LMTD, ε -NTU) cannot be applied to a precooler of S-CO$_2$ system due to substantial change of properties near the critical point. To solve the property problem, the PCHE analysis tool KAIST_HXD was developed and well validated with experimental data in KAIST [2]. The energy equation and momentum equation are solved for each node by dividing the flow channel into several nodes. Moreover, iteration scheme is applied to KAIST_HXD to analyze the counter-current case by assuming the temperature and pressure at cold side outlet. With discretized channel calculation and iteration scheme, KAIST_HXD requires significant amount of computational resource.

A PCHE computation time problem becomes more pronounced if it is expanded to the level of power system analysis from component level analysis. Since the iteration scheme of KAIST_HXD is sensitive to initial value, more computational time is needed if the change in heat exchanger inlet conditions is large during the cycle iteration process. When finding the optimum operating condition of the power system under the off-design condition, a myriad of PCHE analysis are carried out depending on the combination of cycle variables.

Therefore, the goal of this study is to develop a PCHE off-design performance model, which can accelerate the computation time by using non-dimensional parameters while preserving similar accuracy. The reference PCHE is the water-cooled precooler in an S-CO$_2$ Brayton cycle, which is operating very close to the critical point of CO$_2$. This new model will be compared with the results of the analysis with the existing discretized method.

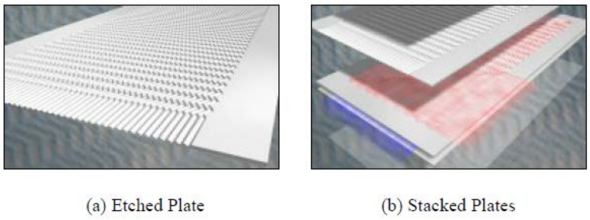
(a) Etched Plate (b) Stacked Plates

Fig. 1. PCHE Plates and Diffusion Bond [1]

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

2. Methods and Results

2.1 Selecting the parameters and establishing the heat transfer correlation

It is important to find influential parameters for heat transfer between hot and cold fluid. Following equations are governing equation of heat transfer inside a heat exchanger.

$$dQ_{hot} = \dot{m}_{hot}\left(C_p dT + \frac{\delta h}{\delta P}dP\right)_{hot}$$

$$dQ_{cold} = \dot{m}_{cold}\left(C_p dT + \frac{\delta h}{\delta P} dP\right)_{cold}$$

$$dQ_{transferred} = U(T_{hot} - T_{cold})dA$$

It can be seen that U and $T_{hot} - T_{cold}$ are the key parameters in heat transfer. Temperature difference between hot and cold fluid changes similar to the log function [3] along the heat exchanger flow channel because specific heat of water does not change much, but the specific heat of CO_2 changes sharply as it approaches the critical point [4]. However, U has a little difference along the heat exchanger flow channel. The reason is overall heat transfer coefficient is governed by low heat transfer coefficient due to its form which is a harmonic mean. The form of UA is shown below equation. Overall heat transfer coefficient is greatly affected by water side heat transfer coefficient which is almost constant in precooler region when heat transfer coefficient of CO_2 side rapidly increases as it approaches to critical point,

$$\frac{1}{UA} = \frac{1}{hA} + \frac{1}{hA} + \frac{x}{kA}$$

To reflect a temperature difference between hot side and cold side, heat capacity rate ratio, which is closely related to temperature change, is considered in the off-design performance model. The below equation presents the influential parameters for heat transfer.

$$Q = f\left(T_{hot,in} - T_{cold,in}, \frac{\dot{m}c_{p,cold}}{\dot{m}c_{p,hot}}, UA\right)$$

The new variable R is introduced to reflect the properties of CO_2 near the critical point, which is defined as the temperature difference inlet temperature of CO_2 side and pseudo-critical line with assuming same inlet pressure. To prevent representative CO_2 property from overestimation, the property of CO_2 on the pseudo-critical line is obtained at the pseudo-temperature minus one. The variable R is used to evaluate the specific heat of CO_2. UA is obtained from properties at inlet condition.

$$R = T_{hot,in}(P_{hot,in}) - T_{hot,pseudo-line}(P_{hot,in}) - 1$$

$$\frac{\dot{m}c_{p,cold}}{\dot{m}c_{p,hot}} = \frac{\dot{m}c_{p,cold}}{\dot{m}_h\left[\frac{a(2)}{R}c_{p,hot,pseudo-line} + \left(1 - \frac{a(2)}{R}\right)c_{p,hot,in}\right]}$$

The heat transfer at the off-design condition can be obtained by the following scaling law by using on-design data. The parameters like a(1), a(2), a(3) and a(4) are coefficients which can be obtained from a regression technique.

$$\frac{Q_{off}}{Q_{on}} = \left[\frac{(T_{hot,in} - T_{cold,in})_{off}}{(T_{hot,in} - T_{cold,in})_{on}}\right]^{a(1)} \left[\frac{(\dot{m}c_p)_{hot,on}}{(\dot{m}c_p)_{hot,off}}\right]^{a(3)} \left[\frac{U_{off}}{U_{on}}\right]^{a(4)}$$

$$\frac{(\dot{m}c_p)_{hot,on}}{(\dot{m}c_p)_{hot,off}} = \frac{m_{hot,on}\left[\frac{a(2)}{R}c_{p,hot,pseudo-line} + \left(1 - \frac{a(2)}{R}\right)c_{p,hot,in}\right]_{on}}{\dot{m}_{hot,off}\left[\frac{a(2)}{R}c_{p,hot,pseudo-line} + \left(1 - \frac{a(2)}{R}\right)c_{p,hot,in}\right]_{off}}$$

2.2 Off-design condition of the PCHE precooler

The off-design condition of the PCHE precooler is shown in Fig. 3 and Table.1. Fig. 3 contains the on-design point of S-CO_2 precooler of experimental facility of SNL[5] and other power system design studies[6, 7]. From these reference data, the off-design conditions of temperature and pressure for this study can be decided by checking the CO_2 behavior in a precooler.

The rate of water side mass flow rate and CO_2 side mass flow rate range is chosen to be from 1 to 1.3 times of the nominal condition in this study because there is a possibility to lose generality due to the tendency of changing only the temperature of one side fluid significantly. For example, Knoll Atomic Power Laboratory (KAPL) set the CO_2 mass flow rate as 5.46 (kg/sec) and water mass flow rate as 8.83 (kg/sec) when they designed the experimental facility [5]. The off-design parameters are hot side inlet temperature, inlet pressure and mass flow rate. The on-design point of this study is at 46 (°C), 8 (MPa), 0.4 (kg/sec). The number of data set is 104.

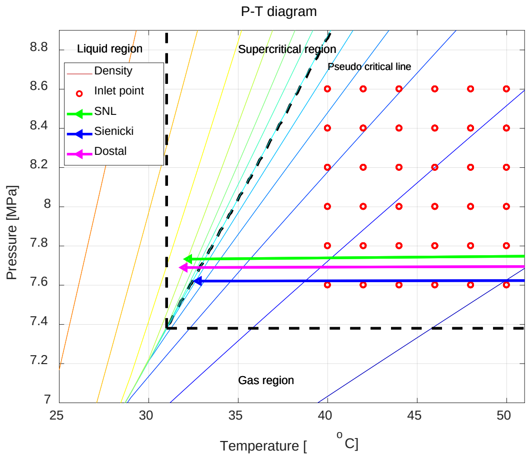

Fig. 3. CO_2 inlet points under off-design condition

Table 1. Precooler inlet points

Hot side		Cold side	
CO_2		Water	
Temperature [°C]	40 – 50 [2]	Temperature [°C]	16.5

Pressure [Mpa]	7.6 – 8.6 [0.2]	Pressure [Mpa]	0.42
Mass flow [kg/sec]	0.35 – 0.45 [0.05]	Mass flow [kg/sec]	0.35

2.3 Regression and result

The regression process was performed using MATLAB's “fminsearch” function, which was implemented by simplex algorithm by Nelder-Mead. It has excellent performance to find the optimum point in a nonlinear multidimensional space. With this method, the coefficients, which makes the optimum values, are obtained. The correlation of this study is presented below equation. The comparison heat transfer by correlation of this study with HXD heat transfer are presented in Fig.3.

$$\frac{Q_{off}}{Q_{on}} = \left[\frac{\left(T_{hot,in}-T_{cold,in}\right)_{off}}{\left(T_{hot,in}-T_{cold,in}\right)_{on}}\right]^{1.09}\left[\frac{(\dot{m}c_p)_{hot,on}}{(\dot{m}c_p)_{hot,off}}\right]^{0.02}\left[\frac{U_{off}}{U_{on}}\right]^{0.49}$$

$$c_{p,hot} = \frac{-1.56}{R}c_{p,pseudo} + \left(1+\frac{1.56}{R}\right)c_{p,hot,in}$$

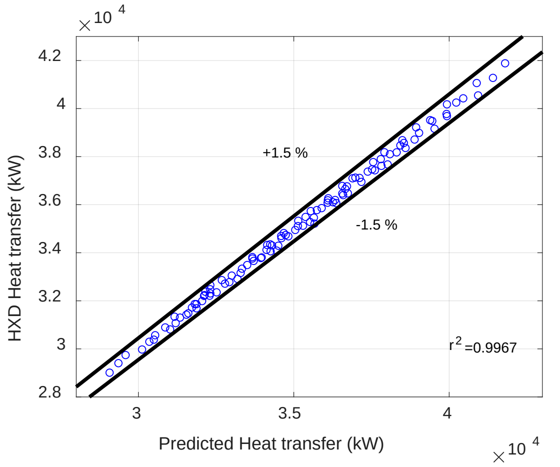

Fig. 4. Comparison between predicted heat transfer and HXD heat transfer

The heat transfer rate predicted by the correlations was within 1.5% of the error range when compared to the heat transfer of HXD. It means off-design performance model of this study well predicts the PCHE precooler heat transfer.

3. Summary and Conclusions

PCHE off-design modeling was performed for the reference of water-cooled precooler in an S-CO_2 Brayton cycle. The results show that the correlation that is presented in this study matches well with the PCHE design code under off-design condition. The off-design performance can be easily obtained by using this model. Further study will be conducted by applying this method to the cycle off-design analysis and difference of the results will be compared.

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