Preliminary Design of PCHE in S-CO_2 Brayton Cycle Coupled to KALIMER-600

Tae-Ho Lee [a*], Jae-Eun Cha [a], Jae-Hyuk Eoh [a], Seong-O Kim [a], Do-Hee Hahn [a]
[a] *Korea Atomic Energy Research Institute, Fast Reactor Development Group, 1045 Daedeokdaero, Yuseong, Daejeon, 305-353*
[*] *Corresponding author: thlee@kaeri.re.kr*

1. Introduction

A Supercritical CO_2 Brayton cycle is a promising alternative as the energy conversion system for sodium-cooled fast reactor. Higher cycle efficiency can be achieved when compared with a Rankine steam cycle, and also the safety is improved due to the exclusion of the possibility of sodium-water reaction. Among the various components in the cycle, the heat exchangers such as Na-CO_2 heat exchanger, recuperator and cooler are the essential components. In the S-CO_2 Brayton cycle coupled to sodium-cooled fast reactor KALIMER-600, Printed Circuit Heat Exchangers (PCHE)[1] are adopted as those heat exchangers from the consideration of the operability at very high pressure and temperature conditions and the good heat transfer efficiency. In this study, a simple design methodology is presented to satisfy the design requirements of PCHE, and the preliminary design parameters are produced.

2. Design Method

Analytical model to produce the design data such as the heat transfer area and the flow channel configuration for the specified inlet and outlet conditions was developed under the following assumptions.

- semi-circular cross section of the flow channel
- zig-zag flow path along the flow direction
- single-banking type
- considering only the enthalpy change between the inlet and outlet for the energy balance
- manufacturing limit of 0.6 m (width) x 1.5 (length) for the PCHE plate

The balance equations for the fluid mass, momentum and energy are given as follows.

$$\dot{m}_i = \sum_k \dot{m}_{i,k} \qquad i = hot\ or\ cold\ channel \tag{1}$$

$$\Delta P_{i,k} = \left(\frac{f\,L_{i,k}}{D_{e,i,k}} + K_{form,i,k}\right)\left(\frac{\dot{m}_{i,k}}{A_{i,k}}\right)^2\left(\frac{1}{2\rho_{avg,i,k}}\right) + \left(\frac{\dot{m}_{i,k}}{A_{i,k}}\right)^2\left(\frac{1}{\rho_{out,i,k}} - \frac{1}{\rho_{in,i,k}}\right) \tag{2}$$

$$Q_i = \dot{m}_i\,(h_{out,i} - h_{in,i}) = U\,A_h\,\Delta T_{LMTD} \tag{3}$$

In Eq. (1), $\dot{m}$ is the mass flow rate, and the subscripts i and k mean the hot or cold channels and the total number of channels, respectively. In Eq. (2), ΔP, f, D_e, K_{form}, A, ρ are the pressure drop, the friction factor, the hydraulic diameter, the form loss factor, the flow area and the density, respectively. Also, the subscripts avg, in and out indicate the average value, the inlet and the outlet, respectively. In Eq. (3), Q_i , h , U, A_h and ΔT_{LMTD} are the heat transfer rate, the fluid enthalpy, the overall heat transfer coefficient, the heat transfer area and the log-mean temperature difference. The overall heat transfer coefficient is approximated by using the plate thickness as follows.

$$U = 1/\left(1/H_h + t/k_w + 1/H_c\right) \tag{4}$$

In Eq. (4), H_h, t, k_w and H_c indicate the heat transfer coefficient for the hot channel, the plate thickness, the thermal conductivity of the wall and the heat transfer coefficient for the cold channel, respectively.

In addition to the balance equations for the fluid, several geometrical relations for the PCHE channels are used to produce the flow channel configuration. The geometrical parameters related with the channel configuration are shown in Fig. 1. In the developed method, if the channel diameter (D), the bending angle of the hot channel (θ_{hot}), the pitch of the cold channel (P_{cold}), the width of the PCHE plate (Y) and L in Fig. 1 are given, then the geometrical parameters such as the bending angle of the cold channel (θ_{cold}), the number of bendings along the flow path for the hot and cold channels, the total number of PCHE plate, the number of channels on each the PCHE plate and the length of PCHE plate (X) are calculated.

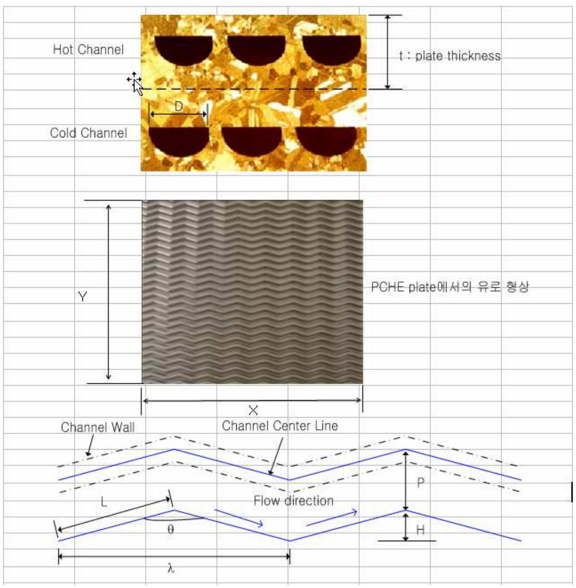

Fig. 1. Channel configuration and geometrical parameters

4. Results

Using the developed method, the preliminary design parameters for the PCHEs in the S-CO_2 Brayton cycle of KALIMER-600 were produced. The input parameters used in the design are indicated in Table 1. Among the input parameters, the geometrical input parameters such as D_{cold}, D_{hot}, t, P_{cold} and θ_{hot} were assumed, and the width of the PCHE plate (Y) was set to be 0.6 which corresponds to the manufacturing limit.

Table 1. Design input parameters

Parameter	Na-CO_2 HX	HTR	LTR	Cooler
D [mm]	2.0	1.5	1.5	2.0
θ_h [deg]	180	170	170	100
P_c [mm]	3.0	2.5	2.5	2.5
t [mm]	2.0	2.0	2.0	1.66
L [mm]	5.0	5.0	5.0	5.0
Y [m]	0.6	0.6	0.6	0.6
Hot fluid	Sodium	CO_2	CO_2	CO_2
Cold fluid	CO_2	CO_2	CO_2	Water
$T_{hot,in}$ [^oC]	526.0	394.2	203.1	91.2
$T_{hot,out}$ [^oC]	364.0	203.1	91.2	31.25
$T_{cold,in}$ [^oC]	353.9	185.8	84.8	30.0
$T_{cold,out}$ [^oC]	508.0	353.9	184.2	46.0
$P_{hot,in}$ [MPa]	0.1094	7.60	7.53	7.46
$P_{hot,out}$ [MPa]	0.1014	7.53	7.46	7.40
$P_{cold,in}$ [MPa]	19.94	19.98	20.0	0.147
$P_{cold,out}$ [MPa]	19.74	19.94	19.98	0.101
$\dot{m}_{hot}$ [kg/s]	7400.2	8076.6	8076.6	5734.4
$\dot{m}_{cold}$ [kg/s]	8076.6	8076.6	5734.4	13076.4

For the heat transfer coefficient, the model of Hesselgreaves[2] was used except for the Sodium flow in the Na-CO_2 heat exchanger, and the model of Seban and Shimazaki[3] was applied to the Sodium flow in the Na-CO_2 heat exchanger. The model of Idelchik[4] was adopted as a friction factor since this model is widely used over the entire Reynolds number range. For the form loss factor (K_{form}), by considering the zig-zag flow path as a series of elbows, the model proposed by Ishizuka et al.[5] was used.

Table 2 shows the calculated design parameters for the PCHEs. The heat transfer area of the LTR is larger than that of the HTR in spite of its smaller heat transfer capacity than the heat transfer capacity of the HTR. This is due to the fact that the ratio of the heat transfer capacity to the log-mean temperature difference for the LTR is larger that that for the HTR ($(Q/\ T_{LMTD})_{LTR} > (Q/\ T_{LMTD})_{HTR}$). The design data shown in Table 2 should be considered preliminary because the data were calculated by assuming some geometrical parameters and the applicability of the used models for heat transfer coefficient and friction factor to the corrugated flow path of PCHE is still uncertain. More studies on the heat transfer and pressure drop characteristics by considering a variation of the flow path configuration should be performed to produce the optimized design parameters.

Table 2. Preliminary design parameters for the PCHEs

HX		Na-CO_2 HX	HTR	LTR	Cooler
Heat transfer capacity [MW_t]		1528.7	1746.6	1070.3	873.7
Diameter [mm]	Hot	2.0	1.5	1.5	2.0
	Cold	2.0	1.5	1.5	2.0
No. of flow channels	Hot	7917247	16929875	17213028	7478706
	Cold	6605593	15836829	15673301	8174331
Single channel length [mm]	Hot	1046.6	790.6	1235.7	1271.7
	Cold	1254.5	845.2	1357.1	1163.5
Plate dimension (X [m] * Y [m])		1.05*0.60	0.79*0.60	1.23*0.60	0.97*0.60
No. of plate (Hot or Cold)		44092	66076	65425	34186
No. of channels on each plate	Hot	179	256	263	218
	Cold	149	239	239	239
Bending angle [deg]	Hot	180	170	170	100
	Cold	113	137	130	114
Heat transfer area [m^2]	Hot	42607.4	51615.2	82023.6	48900.4

4. Conclusion

The design method for producing the preliminary design parameters for the PCHEs in the S-CO_2 Brayton cycle of KALIMER-600 was developed based on the balance equations for the fluid and the geometrical relations for the channels. Although the produced design data is not considered to be optimized due to the uncertainties in the used correlations and some geometrical parameters, the developed methodology could be used as one of the useful tools for developing the S-CO_2 Brayton cycle energy conversion system.

REFERENCES

[1] Heatric^{TM}, hppt://www.heatric.com/.

[2] J.E. Hesselgreaves, "Compact Heat Exchangers, Selection, Design and operation", 1st edition, Pergamon, 2001.

[3] R.A. Seban and T. Shimazaki, "Heat Transfer to a fluid flowing turbulently in a smooth pipe with wall at constant temperature", ASME Paper 50-A-128, 1950.

[4] I.E. Idelchik, "Handbook of Hydraulic Resistance", 2nd edition, Hemisphere Publishing Co., 1986.

[5] T. Ishizuka et al., Thermal-Hydraulic Characteristics of a Printed Circuit Heat Exchanger in a Supercritical CO_2 Loop, Proceedings of 11th Int. Topical Conf. on Nuclear Reactor Thermal-Hydraulics, Avignon, France, Oct. 2-6, 2005.