2.5 MWT Heat Exchanger Designs for Passive DHRS in PGSFR

Dehee Kim*, Jaehyuk Eoh, Tae-Ho Lee
Korea Atomic Energy Research Institute, 989-111 Daedeok-daero, Yuseong-gu, Daejeon, Korea
**Corresponding author: dehee@kaeri.re.kr*

1. Introduction

Decay Heat Removal System (DHRS) of PGSFR consists of two passive DHRS (PDHRS) trains and two active DHRS (ADHRS) trains. Recently, total heat removal capacity of the DHRS in the PGSFR has increased to 10 MWT from 4 MWT reflecting safety analysis results. Consequently, DHRS components including heat exchangers, dampers, electro-magnetic pump, fan, piping, expansion tank and stack have been newly designed.

In this work, physical models and correlations to design two main components of the PDHRS, decay heat exchanger (DHX) and natural-draft sodium-to-air heat exchanger (AHX), are introduced and designed data are presented.

2. Methods and Results

2.1 Physical modeling of the heat exchangers

DHX and AHX are designed utilizing SHXSA and AHXSA codes, respectively. Those design codes have capability of thermal sizing and performance analysis for the shell-and-tube type and counter-current flow heat exchanger unit. Since both SHXSA and AHXSA codes are similar, following description is focused on the SHXSA code.

A single flow channel associated with an individual heat transfer tube is basically considered for thermal sizing and then the calculation results and design variables regarding heat transfer and pressure drop, etc. are extended to whole tubes. Various correlations of heat transfer and pressure loss for the shell- and tube-side flows were implemented in the computer codes. The analysis domain is discretized into several control volumes and heat transfer and pressure losses are calculated in each control volume.

Conservation equations for the mass, momentum, and energy balance for both shell- and tube-sides fluid flow are solved. Constant mass flow rate is set for continuity equation and acceleration, friction and gravitation terms are included for momentum conservation.

A schematic diagram of heat transfer in each control volume is illustrated in Fig. 1. Heat transfer rates through the tube wall, from the shell-side flow, and to the tube-side flow are written as Eqs. (1) to (3). The terms ΔQ, U, $\Delta A_{o,w}$, T, w, H are heat transfer rate, overall heat transfer coefficient, heat transfer area of tube outer surface, temperature, mass flow rate, and enthalpy, respectively.

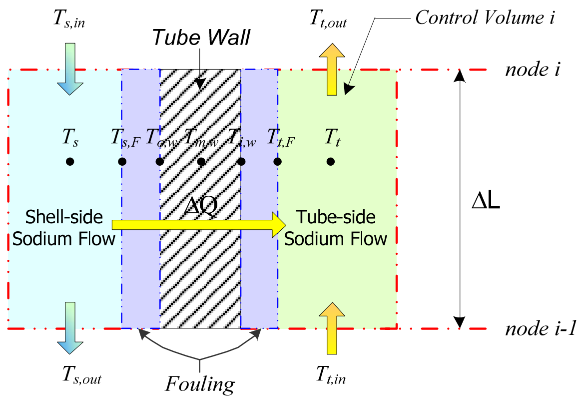

Fig. 1 Schematic diagram of heat transfer in each control volume

Subscripts *t, s, in, out* describe the tube side, the shell side, incoming flow, and outgoing flow, respectively. The terms ΔT_{LMTD} and $d_{o,w}$ mean the log-mean temperature difference (LMTD) and outer diameter of each heat transfer tube for corresponding control volume, respectively.

$$\Delta Q = U \Delta A_{o,w} \Delta T_{LMTD} \tag{1}$$

$$\Delta Q = w_t (H_{t,out} - H_{t,in}) \tag{2}$$

$$\Delta Q = w_s (H_{s,in} - H_{s,out}) \tag{3}$$

$$\Delta T_{LMTD} = \frac{(T_{s,in} - T_{t,out}) - (T_{s,out} - T_{t,in})}{\ln\left(\dfrac{T_{s,in} - T_{t,out}}{T_{s,out} - T_{t,in}}\right)} \tag{4}$$

$$\Delta A_{o,w} = \pi d_{o,w} \Delta L \tag{5}$$

Overall heat transfer coefficient, U, is determined by considering the thermal resistances in the heat transfer path, which are the convection resistances both on the shell- and tube-side fluid flows, the conduction resistance in the tube wall thickness, and fouling resistances on the inner/outer surfaces. Using Eqs. (1) to (5), U is derived as Eq. (6).

$$U = \left[\frac{d_{o,w}}{d_{i,w}} \left(\frac{1}{h_t} + \frac{1}{h_{t,F}} \right) \frac{1}{h_t} + \frac{d_{o,w}}{2k} \ln\left(\frac{d_{o,w}}{d_{i,w}} \right) + \frac{1}{h_s} + \frac{1}{h_{s,F}} \right]^{-1} \tag{6}$$

where, $d_{i,w}$, h, k are tube inner diameter, convective heat transfer coefficient and thermal conductivity, respectively.

2.2 Correlations for the DHX design

To calculate heat transfer and pressure loss in the SHXSA code, several correlations were implemented. Fluid flow inside the tube is assumed to be fully turbulent and the forced convection heat transfer coefficients on the tube-side are calculated using the Lyon-Martinelli correlation [1].

$$Nu = 4.0 + 0.025 \cdot Pe^{0.8} \tag{1}$$

Schad-modified correlation is applied for the shell-side sodium flow [2].

$$\begin{aligned} &Nu = [-16.15 + 24.96(P/d) - 8.55(P/d)^{2.0}] \cdot Pe^{0.3} \\ &\text{for } 1.1 \le P/d \le 1.5 \text{ and } 150 \le Pe \le 1000 \\ &Nu = 4.496[-16.15 + 24.96(P/d) - 8.55(P/d)^{2.0}] \\ &\text{for } Pe \le 150 \end{aligned} \tag{2}$$

To calculate pressure loss, Darcy friction factor is used and appropriate form loss coefficients are applied considering the flow geometries [3].

2.3 Correlations for the AHX design

For the tube-side sodium path, fluid flow inside the tube is assumed to be fully turbulent and the forced convection heat transfer coefficients on the tube-side are calculated using the Lubarski-Kaufman [4].

$$Nu = 0.624 \cdot Pe^{0.4} \tag{3}$$

Zhukauskas correlations have been implemented for the cross flow over the heat transfer tubes of the AHX [5].

$$\begin{aligned} &Nu = \xi \cdot \mathrm{Re}_{D,\max}^{m} \cdot \mathrm{Pr}^{0.36} \cdot (\mathrm{Pr}/\mathrm{Pr}_s)^{0.25} \\ &\text{for } N_L \ge 20,\ 0.7 < \mathrm{Pr} < 500,\ 10^3 < \mathrm{Re}_{D,\max} < 2\times10^6 \\ &\text{where, } \mathrm{Re}_{D,\max} = f(V_{\max}),\ V_{\max} = \frac{P_T}{P_T - d_o} \cdot V \end{aligned} \tag{4}$$

Subscript s denotes the wall surface and N_L is the number of the accumulated tubes in the flow direction of air. ξ and m are functions of P_T and P_L [6]. Re_D is defined by the maximum velocity of the flow passing the tube bank and the maximum velocity, $V_{\max}$ is a function of P_T and P_L. $V_{\max}$ is determined from the mass conservation and means the frontal velocity before entering the tube bank. d_o is an outer diameter of the heat transfer tube. All the constants used in the correlations are obtained reflecting the characteristics of the staggered and aligned grid arrangements [5, 6].

Tube-side pressure loss is calculated using Mori-Nakayama friction factor [7] and shell-side pressure loss is obtained from Zhukauskas correlation [5].

2.4 DHX designed data

Using the SHXSA code, DHX with 2.5 MWT capacity was designed and designed data are summarized in Table 1. Active tube length was unchanged from previous design but number of tubes was increased.

Table 1. Designed data of DHX

Design parameter		Design value
Thermal duty (MWT)		2.5
Number of tubes		114
Pitch to diameter ratio (P/D)		1.5
Tube arrangement		Equilateral triangle
Heat transfer surface area (m^2)		13.44
ΔT_{LMTD} (℃)		29.67
UA total (kW/℃)		83.9
Shell side	Flow rate (kg/s)	12.76
	Inlet / outlet temp. (℃)	390.0 / 239.9
	Pressure drop (Pa)	242
Tube side	Flow rate (kg/s)	17.54
	Inlet / outlet temp. (℃)	226.2 / 334.6
	Pressure drop (Pa)	798

2.5 AHX designed data

Using the AHXSA code, AHX with 2.5 MWT capacity was designed and designed data are summarized in Table 2. Same as the DHX, active tube length was unchanged from previous design but number of tubes and tube rows were increased.

Table 2. Designed data of AHX

Design parameter		Design value
Thermal duty (MWT)		2.5
Number of tube rows		6
Number of tubes		190
Pitch to diameter ratio (P_T / P_L)		2.5 / 1.71
Tube arrangement		Helical type
Heat transfer surface area (m^2)		482.2
ΔT_{LMTD} (℃)		106.17
UA total (kW/℃)		23.28
Shell side	Flow rate (kg/s)	10.65
	Inlet / outlet temp. (℃)	40.0 / 279.0
	Pressure drop (Pa)	140
Tube side	Flow rate (kg/s)	17.54
	Inlet / outlet temp. (℃)	334.6 / 226.2
	Pressure drop (Pa)	466

3. Conclusions

Physical models and correlations applied for heat exchangers in the PDHRS design were introduced and design works using the SHXSA and AHXSA codes has been completed for 2.5 MWT decay heat removal capability.

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