Development of Design method for a Finned-tube Sodium-to-Air Heat Exchanger in 600MWe demonstration SFR

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1. Introduction

The conceptual design of a 600MWe demonstration sodium-cooled fast reactor (hereafter called DSFR-600) has been performed by the Korea Atomic Energy Research Institute (KAERI). In order to enhance plant safety, reliable decay heat removal (DHR) systems with natural circulation flow have been considered, and different kinds of sodium-to-air heat exchangers were employed as an ultimate heat sink for this type of DHR system.

The DHR system comprises two diverse heat removal loops [1], and the heat load imposed on the primary sodium pool is safely rejected into the environment through different shapes of final air-coolers. Serpentine- and helical-coil type sodium-to-air heat exchangers have been considered for the purpose. The former is called FDHX (Forced-draft sodium-to-air heat exchanger) and the latter is simply called AHX [1].

For a general sodium-to-air heat exchanger design, convection resistance at shell-side air flow path becomes a dominant factor affecting the mechanism of conjugate heat transfer from the sodium flow inside the tube to the air path across the sodium tube wall. To this end, performance evaluation of a sodium-to-air heat exchanger is one of the most important tasks to secure the overall performance of a DHR system.

This study introduces one-dimensional design approach of a finned-tube sodium-to-air heat exchanger using reasonable heat transfer and pressure drop models, and provides detailed design parameters with heat transfer tube arrangement including the factors of fin-effect. The operational strategy regarding sodium freezing protection of the FDHX unit was briefly discussed as well.

2. Methods and Results

2.1 Finned tube sodium-to-air heat exchanger

FDHX is a shell-and-tube type counter-current flow heat exchanger with serpentine finned-tube arrangement. Liquid sodium flows inside the heat transfer tubes and atmospheric air flows over the finned tubes. Each unit is designed to have heat removal capability of 9.0MWt corresponding to the design capacity of the DHR system of DSFR-600 [1].

Cold atmospheric air is introduced into the air inlet duct at the lower part of the unit by using an electrically driven air blower. The air flows across the finned tube bank rising upward direction to make uniform air flow with perfect mixing across the tubes. The finned tube bundle is placed inside a well-insulated casing. The air heated at the tube bank region is collected at the top of the unit and then is discharged through the air stack above the unit. The configuration and overall shape of the unit are shown in Figure 1.

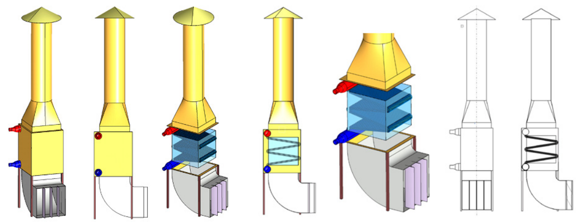

Fig.1 Configuration of the FDHX unit

2.2 Physical model for FDHX thermal sizing

The physical models for the heat exchanger design and performance analysis are based on the relations of mass conservation and energy balance for the system of a single heat transfer tube and a postulated single flow channel, which is based on the node and control volume system depicted in Figure 2. The schematic of the fin geometry is shown in Figure 3, and the air flow on the shell-side FDHX is assumed as a cross flow across a finned-tube bank.

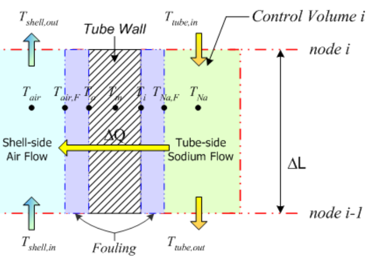

Fig. 2 FDHX control volume model

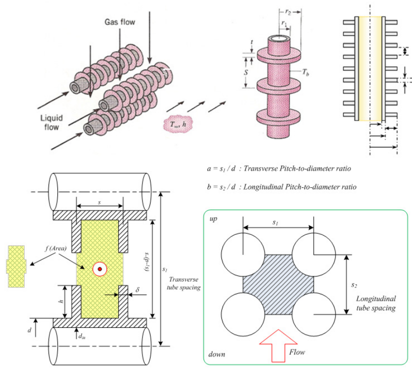

Fig. 3 Schematic of a finned-tube bank in cross flow

In regard to the thermal sizing of shell-and-tube type finned-tube heat exchangers, the overall heat transfer coefficient (U) from the hot-side to the cold-side can be obtained from Eq.(1), where the subscripts *s*, *t*, and *F* mean the shell-side, tube-side and fouling factor, respectively. If the heat transfer medium is sodium, the fouling factor can be assumed to be an infinite value to neglect its effect. The term, η_s means a fin-effect for this finned tubing system [2][3].

$$U_{HX} = \left[\frac{1}{\eta_s \cdot h_s} + \frac{1}{\eta_s \cdot h_{s,F}} + \frac{d_o}{2k} \ln\left(\frac{d_o}{d_i}\right) + \frac{d_o}{d_i}\frac{1}{h_{t,F}} + \frac{d_o}{d_i}\frac{1}{h_t} \right]^{-1} \qquad (1)$$

To obtain the sodium- and air-side heat transfer coefficients, the following correlations for each flow medium are employed.

$$Nu_{Na} = 0.625 \cdot Pe^{0.4} \qquad \text{(for sodium)} \qquad (2)$$

$$Nu_f = 0.192(a/b)^{0.2}(s/d)^{0.18}(h/d)^{-0.14} Re_f^{0.65} Pr_f^{0.36}(Pr_f/Pr_w)^{0.25}$$
$$\text{for } 1\times 10^2 \le Re_f \le 2\times 10^4 \quad \text{(for air)} \qquad (3)$$

$$Nu_f = 0.0507(a/b)^{0.2}(s/d)^{0.18}(h/d)^{-0.14} Re_f^{0.8} Pr_f^{0.4}(Pr_f/Pr_w)^{0.25}$$
$$\text{for } 2\times 10^4 \le Re_f \le 2\times 10^5 \quad \text{(for air)} \qquad (4)$$

$$Nu_f = 0.0081(a/b)^{0.2}(s/d)^{0.18}(h/d)^{-0.14} Re_f^{0.95} Pr_f^{0.4}(Pr_f/Pr_w)^{0.25}$$
$$\text{for } 2\times 10^5 \le Re_f \le 1.4\times 10^6 \quad \text{(for air)} \qquad (5)$$

Eqs. (2)-(5) are the heat transfer correlations for the tube-side sodium flow [4] and the shell-side air flow across a tube bundle [2], respectively. A typical pressure drop correlation for sodium flow inside tubes are employed, and appropriate pressure drop correlations for an external air flow across a finned-tube bank are also used as a function of Reynolds number as shown in Eqs.(6) and (7) [2][3][5].

$$K_{Drag} = f(Re, h/d, s/d, s_1/d, s_2/d, etc.) \qquad (6)$$

$$\Delta P = K_{Drag} \cdot \left(\frac{1}{2} \cdot \rho v^2\right) \cdot N_L \cdot c_z \qquad (7)$$

Based on the above correlations, the thermal sizing of the FDHX was completed and the detailed design parameters were obtained. The overall size of the FDHX unit is 4.413 by 3.849 by 4.701 meters for its width, length and height, respectively. In order to make a difference from the passive AHX layout, the FDHX unit consists of four-pass serpentine tube banks. There are total 46 exclusive serpentine tube rows, and each tube row consists of three independent sodium tubes arranged on the specific pitches. Hence, total 138 single-wall finned-tubes are employed, and the dimension of each heat transfer tube is 34.0 mm in OD and 1.65 mm in wall thickness. The length of a single heat transfer tube is 14.013m, and the total heat transfer tube surface area including all fin surfaces is 2185.47 m^2. The main material for tubing, internal structures and other structures of the unit is STS316 stainless steel, which has a reasonable resistance to corrosion under humid environmental condition. The nominal design data and performance specifications of the FDHX unit at the design point of the DHR system are summarized in Table 1.

A special sodium freezing protection of the FDHX unit is activated if the sodium exit temperature in individual tubes falls below 140°C [1]. This temperature is controlled by an adequate damper throttling of the FDHX air path, and the protection is totally based on multiple temperature measurements at selected positions with an automatic damper closure.

Table 1. FDHX design and performance data

Design parameters		Design value
	No. of unit	2
	Thermal duty (MWt)	9.0
	No. of tubes	138
	Tube arrangement with pitch data	4 passes serpentine tubes [P_L =2.05]&[P_T =2.5]
	Tube material	STS316
	Bare tube OD/ID (mm)	34.0 / 30.7
	Thickness (mm)	1.65
	Finned tube length (Total, m)	14.013
	Fin height (mm)	15.0
	Fin thickness(width, mm)	1.5
	Tube inclined angle (degree)	14.2
	No. of fin (per unit length, m)	208
	Spacing between Fins (mm)	3.31
	Tube outside fouling (W/m/K)	2841
	Total heat transfer area including Fin surface (m^2)	2185.47
	Total number of Fins per each tube row (ea)	2914
	Surface area of single Bare tube (m^2)	15.84
	Fin surface area on single tube (m^2)	14.34
	Ratio of Finned surface (AFin/Atot) (-)	0.905
	Surface extension ratio (-)	10.580
	Overall surface efficiency (-)	0.873
	Overall unit aize (WxDxH, m)	4.413 x 3.849 x 4.701
	LMTD (°C)	170.3
	UA total (MW/°C)	53.14
Shell-side (Air)	Flow rate (kg/sec)	30.7
	Inlet temp. (°C)	40
	Outlet temp. (°C)	335
	Pressure drop (kPa)	1.278
Tube-side (Sodium)	Flow rate (kg/sec)	31.6
	Inlet temp. (°C)	474
	Outlet temp. (°C)	254
	Pressure drop (kPa)	1.348

3. Conclusions

This study aims to develop the design method of a finned-tube sodium-to-air heat exchanger and to provide detailed design parameters for the 9MWt FDHX design of 600MWe demonstration SFR developed at KAERI. The operational strategies regarding sodium freezing protection of FDHX during the standby and scheduled shutdown operation modes were also discussed.

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