A Finned-tube Sodium-to-Air Heat Exchanger Design for a Passive Plant Concept of the PGSFR

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1. Introduction

In the Prototype Gen-IV Sodium-cooled Fast Reactor (PGSFR), the Decay Heat Removal System (DHRS) is employed to remove the decay and sensible heat from the primary heat transport system (PHTS) without exceeding temperature limits of the reactor core, structures, and components at any design basis accident during the plant life. The DHRS of the PGSFR is one of the direct reactor auxiliary cooling system concept in which a decay heat exchanger (DHX) is located in the cold pool region inside the reactor vessel and the decay heat is removed from the PHTS via the DHX to the sodium-to-air heat exchanger of the upper region of the auxiliary building. The DHRS consists of 2 Active DHRS (ADHRS) trains and 2 Passive DHRS (PDHRS) trains. Each train has 2.5MWt heat removal capacity.

Active and passive trains are adopted for the purpose of diversity in the safety-related system. If the PGSFR pursues a passive plant in the future, the safety-related systems have to be designed without AC power supply. In this paper, the ADHRS is re-designed into another passive DHRS for which the blower is removed and the finned-tube sodium-to-air heat exchanger (FHX) is resized. Before the FHX sizing, a new mixed heat transfer correlation appropriate for the present FHX tube arrangement is also presented.

2. Methods and Results

2.1 Physical Modeling of the DHRS

In order to design the DHRS components, governing equations of three heat and mass flow paths have to be solved simultaneously. Three paths are the PHTS flow path including the DHX shell-side sodium flow, the DHRS sodium loop path through the piping, an air flow path through the FHX shell side. Key design parameters for the DHRS arrangement and components design are mass flow rates of the three paths, inlet and outlet temperatures of primary and secondary flow sides of each heat exchanger.

A typical heat removal concept in the three-path heat transport system with two heat exchangers are shown in Fig. 1. Equations modeling the heat transport system through the coupled heat transport paths are written as Eqs. (1) to (9).

Only inlet temperatures of the DHX and the FHX shell side are given as 390℃ and 40℃, respectively, and other design parameters are obtained by solving the non-linear equations [1].

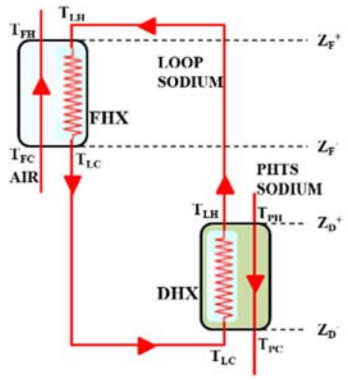

Fig. 1. DHRS heat removal paths.

In common, subscripts *P*, *L* and *F* mean the PHTS side, the DHRS sodium loop side, and the FHX shell side, respectively. Also, subscripts *H* and *C* combined with any path denote the hot and cold fluid temperatures in each path.

$$Q_{DHX}^{rej} = \{UA\}_{DHX}\Delta T_{LMTD}(T_{PH}, T_{PC}, T_{LH}, T_{LC}) \quad (1)$$
$$Q_{FHX}^{rej} = \{UA\}_{FHX}\Delta T_{LMTD}(T_{LH}, T_{LC}, T_{FH}, T_{FC}) \quad (2)$$
$$Q_{DHX}^{rej} = \dot{m}_P c_p(\bar{T}_P)(T_{PH} - T_{PC}) \quad (3)$$
$$Q_{LOOP}^{rej} = \dot{m}_L c_p(\bar{T}_L)(T_{LH} - T_{LC}) \quad (4)$$
$$Q_{FHX}^{rej} = \dot{m}_F c_p(\bar{T}_F)(T_{FH} - T_{FC}) \quad (5)$$
$$C^P \dot{m}_P^2 = \Delta H(T_{PH}, T_{PC}, Z_D^+, Z_D^-) \quad (6)$$
$$C^L \dot{m}_L^2 = \Delta H(T_{LH}, T_{LC}, Z_D^+, Z_D^-, Z_F^+, Z_F^-) \quad (7)$$
$$C^F \dot{m}_F^2 = \Delta H(T_{FH}, T_{FC}, Z_F^+, Z_F^-, Z_{CHM}^+, Z_{CHM}^-) \quad (8)$$
$$R_{UA} = \{UA\}_{DHX}/\{UA\}_{FHX} \quad (9)$$

Equations (1) and (2) are for the heat transfer rates through the DHX and the FHX, respectively, and *UA* means an overall heat transfer coefficient multiplied by a heat transfer area. Superscript rej means heat rejection and subscript $LMTD$ denotes a log mean temperature difference. Heat transfer rates in the heat transfer paths can also be expressed by Eqs. (3) to (5), where, $\dot{m}, c_p, \bar{T}$ are the mass flow rate, the specific heat, the average temperature, respectively. Correlations between flow resistance, mass flow rate, and developing head can be written in Eqs. (6) to (8), where $Z, F, D, +, -, CHM$ mean the elevation from the bottom of the reactor vessel, the FHX, the DHX, top of a heat exchanger, bottom of a heat exchanger, chimney, and $C, \Delta H$ denote the flow resistance, the natural circulation head difference. The UA ratio (R_{UA}) can be determined optionally by a system designer with the considerations of the economics or the system arrangement. Q^{rej}, T_{PH}, T_{FC} are given values.

2.2 Computer code for calculating the DHRS design point

A one-dimensional system design code, POSPA, had been developed to determine the steady-state system design parameters [1]. To get the solutions such as temperatures, mass flow rates, *UA* values, the nine nonlinear equations are solved simultaneously [1]. Pressure losses and the heat transfer rates in heat exchangers are also calculated via modules developed for those components [1,2]. A genetic algorithm had been implemented to decide proper ranges of the design parameters and it is found robust for convergence [2,3].

2.3 Computer code for designing the FHX

The FHXSA computer code was utilized for the thermal sizing of the FHX. Heat transfer coefficients inside the tubes are obtained using the Lubarski-Kaufman [4].

$$Nu = 0.625\,Pe^{0.4} \tag{10}$$

Zhukauskas correlations have been implemented for the cross flow over the finned tubes of the FHX [5]. The fin shape and tube arrangement can be found in Fig. 2.

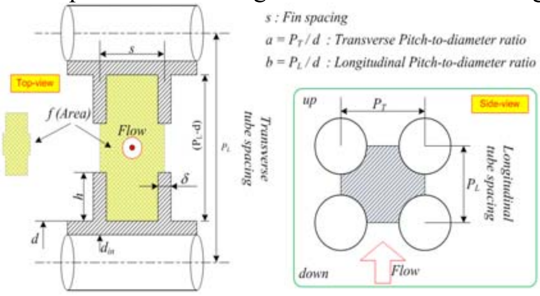

Fig. 2. Fin shape and tube arrangement.

Eqs. (11) to (14) are heat transfer correlations for the staggered tube arrangement.

$$Nu_f = 0.192\left(\frac{a}{b}\right)^{0.2}\left(\frac{s}{d}\right)^{0.18}\left(\frac{h}{d}\right)^{-0.14} Re_f^{0.65} Pr_f^{0.36}\left(\frac{Pr_f}{Pr_w}\right)^{0.25} \tag{11}$$

for $1 \times 10^2 \le Re_f \le 2 \times 10^4, 1.1 < a < 4.0, 1.03 < b < 2.5,$
$0.07 < h/d < 0.715, 0.06 < s/d < 0.36$

$$Nu_f = 0.0507\left(\frac{a}{b}\right)^{0.2}\left(\frac{s}{d}\right)^{0.18}\left(\frac{h}{d}\right)^{-0.14} Re_f^{0.8} Pr_f^{0.4}\left(\frac{Pr_f}{Pr_w}\right)^{0.25} \tag{12}$$

for $2 \times 10^4 \le Re_f \le 2 \times 10^5, 1.1 < a < 4.0, 1.03 < b < 2.5,$
$0.07 < h/d < 0.715, 0.06 < s/d < 0.36$

$$Nu_f = 0.0081\left(\frac{a}{b}\right)^{0.2}\left(\frac{s}{d}\right)^{0.18}\left(\frac{h}{d}\right)^{-0.14} Re_f^{0.95} Pr_f^{0.4}\left(\frac{Pr_f}{Pr_w}\right)^{0.25} \tag{13}$$

for $2 \times 10^5 \le Re_f \le 1.4 \times 10^6, 2.2 < a < 4.2, 1.27 < b < 2.2,$
$0.125 < h/d < 0.6, 0.125 < s/d < 0.28$

where, $Re_f = f(V_{max}), V_{max} = \frac{P_T V}{(P_T - d_o) R_{A,flow}}, R_{A,flow} = 1 - \frac{2h\delta}{s(P_T - d)}$

For the aligned tube arrangement, following correlation was applied.

$$Nu_f = 0.303 Re_f^{0.625} \varepsilon^{-0.375} Pr_f^{0.36}\left(\frac{Pr_f}{Pr_w}\right)^{0.25} \tag{14}$$

for $5 \times 10^3 \le Re_f \le 1 \times 10^5, 1.72 < a < 3.0, 1.8 < b < 4.0,$
$5 < \varepsilon < 12$

where, ε is a surface extension ratio. FHX tubes are arranged in a mixed form of staggered and aligned arrays. Thus, weighting factors 1/3 and 2/3 were multiplied to the Nusselt numbers for staggered and aligned arrays, respectively and the Nusselt numbers were added together to get a Nusselt number for the mixed arrangement. Above Nusselt number correlations for the staggered arrangement are for fully developed flow but the staggered tubes of the FHX are not in the fully developed region. Therefore, correction factor 0.87 from Fig. 14.22 in [5] was multiplied additionally to the Nusselt number correlations for the staggered arrangement.

2.4 DHRS design point and its arrangement

DHRS design point has been calculated by the POSPA code and are summarized in Table 1. To calculate the design point the DHX configuration and piping arrangement remained unchanged from [6] and the FHX was only re-sized. The FHXSA code was validated using CFD data [7] and showed excellent agreement within 3%. Table 2 shows the designed data using the FHXSA code. For passive decay heat removal, number of tubes and finned-tube length were increased by 12 and 1.2 m, respectively, from original FHX of the ADHRS.

Table 1. DHRS design point by the POSPA

Design parameter		Design value
Mass flow rate (kg/s)	DHX shell-/tube-side	12.76 / 17.54
	FHX shell-side	12.42
Temperature (°C)	DHX shell inlet/outlet	390.0 / 239.9
	FHX shell inlet /outlet	40.0 / 246.3
	DHRS hot-/cold-leg	334.6 / 226.2
Number of DHX tubes		114
Number of FHX tubes		108
Elevation difference between thermal centers of DHX and FHX (m)		~21
Sodium loop pipe ID (m)		~0.21
Chimney height and ID (m)		30 / 2.5

Table 2. Designed data of the FHX

Design parameter		Design value
Thermal duty (MWT)		2.5
Number of tubes		108
Pitch to diameter ratio (P_T / P_L)		2.5 / 2.05
Tube arrangement		4-pass serpentine
Finned-tube length (m)		9.2
Heat transfer surface area (m²)		824.95
ΔT_{LMTD} (℃)		130.14
UA total (kW/℃)		18.99
Shell side	Flow rate (kg/s)	12.42
	Inlet / outlet temp. (℃)	40.0 / 246.3
	Pressure drop (Pa)	152
Tube side	Flow rate (kg/s)	17.54
	Inlet / outlet temp. (℃)	334.6 / 226.2
	Pressure drop (Pa)	622

3. Conclusion

A mixed heat transfer correlation for the FHX tube arrangement of the PGSFR has been presented and the FHX of the ADHRS has been re-sized for the passive plant concept of the DHRS in the PGSFR.

ACKNOWLEDGEMENT

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