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A 2.5 MWT Passive Decay Heat Removal System Design for PGSFR

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1. Introduction

Decay Heat Removal System (DHRS) of the PGSFR is a safety-grade system to remove decay heat from the reactor coolant system. The DHRS is composed of four independent trains which are grouped into two passive and two active DHRS trains depending on coolant driving mechanisms. Each passive DHRS (PDHRS) train has a decay heat exchanger (DHX), a natural-draft sodium-to-air heat exchanger (AHX), piping, an expansion tank, a stack, air ducts and dampers. The PDHRS works by naturally developing head through three heat transfer paths of the DHX shell side, the PDHRS cold- and hot-legs and the AHX shell side connecting to the air stack. Previously, all the components of the PDHRS were designed to meet the heat removal requirement of 1 MWT per train. Recently, total heat removal capacity of the DHRS has changed to 10 MWT from 4 MWT reflecting safety analysis results and thus each DHRS train should have 2.5 MWT heat removal capability.

For design and arrangement of the DHRS components, geometrical dimensions of piping, stack and heat exchangers and thermal-hydraulic design conditions such as mass flow rates of the three flow paths, inlet/outlet temperatures of primary and secondary flow sides of each heat exchanger were determined considering system performance and overall structure. After determination of these parameters, all the components have been designed newly.

In this work, a methodology of determining the geometrical dimensions and the design conditions is addressed and its results are presented.

2. Methods and Results

2.1 Physical modeling of the PDHRS

There are three coupled natural circulating heat transport paths in the PDHRS, i.e., the PHTS path comprising the cold sodium pool and the DHX shell side, the PDHRS heat removing sodium loop (PDHRS loop) including the DHX tube side, the PDHRS hot- and cold-legs, and the AHX tube side, and finally the AHX shell-side air path including the chimney (stack). A typical heat removal concept and temperature distributions in the three-path heat transport system with two heat exchangers are illustrated in Fig. 1.

To model the heat transport system through the coupled heat transport paths, the thermal-hydraulic models were developed.

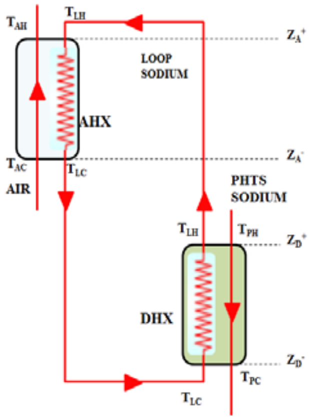

Fig. 1 PDHRS heat removal concept and temperature distributions

Heat balance in each path has a physical relation expressed by the following equations. In common, subscripts *P*, *L* and *A* denote the PHTS side, the PDHRS loop side, and the AHX shell side, respectively.

Also, subscripts *H* and *C* combined with any path denote the hot and cold fluid temperatures in each path.

$$Q^{rej}_{DHX} = \{UA\}_{DHX} \cdot \Delta T_{LMTD}(T_{PH}, T_{PC}, T_{LH}, T_{LC}) \quad (1)$$

$$Q^{rej}_{AHX} = \{UA\}_{AHX} \cdot \Delta T_{LMTD}(T_{LH}, T_{LC}, T_{AH}, T_{AC}) \quad (2)$$

Eqs. (1) and (2) are for the heat transfer rates through the DHX and the AHX, respectively, and *UA* is multiplication of an overall heat transfer coefficient and a heat transfer area. Superscript *rej* means heat rejection and subscript *LMTD* denotes a log mean temperature difference. Heat transfer rates, Q^{rej} in heat transfer paths can also be expressed by the following Eqs. (3) to (5), where $\dot{m}$ and c_p are the mass flow rate and the specific heat, respectively. $\bar{T}$ denotes an averaged value over the region for the heat transfer calculation.

$$Q^{rej}_{DHX} = \dot{m}_P \cdot c_p(\bar{T}_P) \cdot (T_{PH} - T_{PC}) \quad (3)$$

$$Q^{rej}_{LOOP} = \dot{m}_L \cdot c_p(\bar{T}_L) \cdot (T_{LH} - T_{LC}) \quad (4)$$

$$Q^{rej}_{AHX} = \dot{m}_A \cdot c_p(\bar{T}_A) \cdot (T_{AH} - T_{AC}) \quad (5)$$

All the heat transfer rates in the heat transport paths should be same for the steady state condition. Mass flow rates are governed by developing heads and flow resistances which are influenced by geometries and arrangements of the PDHRS components and the loop piping. The three flow paths and the elevations of the components are described in Fig. 1. The terms, *Z*, *A*, *D*, +, −, *chm* mean the elevation from the bottom of the reactor vessel, the AHX, the DHX, top of a heat exchanger, bottom of a heat exchanger, and chimney respectively.

Correlations between flow resistance, mass flow rate, and developing head can be written as Eqs. (6) to (8).

$$C^P \cdot \dot{m}_P^2 = \Delta H(T_{PH}, T_{PC}, Z_D^+, Z_D^-, \beta_{TP}) \quad (6)$$

$$C^L \cdot \dot{m}_L^2 = \Delta H(T_{LH}, T_{LC}, Z_D^+, Z_D^-, Z_A^+, Z_A^-, \beta_{TL}) \quad (7)$$

$$C^A \cdot \dot{m}_A^2 = \Delta H(T_{AH}, T_{AC}, Z_A^+, Z_A^-, Z_{chmr}^+, Z_{chmr}^-, \beta_{TA}) \quad (8)$$

In Eqs. (6) to (8), the term C is the flow resistance and ΔH means the developing head. β_T is an error term.

Additionally, the UA ratio of the DHX and the AHX can be included for a governing equation as Eq. (9). The UA ratio can be determined optionally by a system designer with the considerations of the economics or the system arrangement referring to other reactors employing similar DHRS concept.

$$R_{UA} = \{UA\}_{DHX} / \{UA\}_{AHX} \quad (9)$$

Among variables, Q^{rej}, T_{PH}, T_{AC} are given. Then number of unknown variables is equal to number of equations.

2.2 Heat transfer modeling through heat exchangers

To calculate the temperatures of Eqs. (1) to (5), heat transfer in heat exchangers needs to be analyzed. For this purpose, modules of the SHXSA and the AHXSA code are utilized, which are the computer codes for thermal design and analysis of the DHX and the AHX, respectively.

2.3 Developing head and flow resistance models

The developing head, ΔH in each heat transport path is calculated using density difference and height of flow path. Flow resistance, C, is calculated by two methods. For the DHX/AHX shell- and tube-sides flow resistance values are obtained from the SHXSA/AHXSA modules, respectively, and for the other flow regions inside sodium piping and air ducts following equation is applied.

$$C = \sum_i \frac{1}{2\rho_i A_i^2}\left[K_i + f_i\left(\frac{L_i}{D_i}\right)\right] \quad (10)$$

where, i, ρ, A, K, f, L, D are flow segment, density, flow area, form loss coefficient, friction coefficient, flow segment length, hydraulic diameter, respectively.

Then, mass flow rate in each flow path can be obtained by $\dot{m} = \sqrt{\Delta H / C}$.

2.4 Computer code for the DHRS design

The physical models and correlations were incorporated into a one-dimensional system design code, POSPA [1]. This code solves above 9 equations to get temperatures, mass flow rates, UA values. Originally, Newton-Raphson method was employed to solve the nonlinear equations [1]. Finite difference type solver can solve the equations fast if initial conditions are well given, but all the parameters except unknown variables (9 variables in our case) have to be pre-defined. Namely, design parameters such as number of tubes, active tube length, pipe diameter and length, component arrangement, stack diameter and height, etc. have to be known. It requires engineering experience and trial-and-error. To reduce these demerits, a genetic algorithm was implemented. Genetic algorithm can decide design parameters such as geometrical dimensions optimally and solve the nonlinear equations. In this work, some parameters such as thickness and pitches of tubes are pre-defined but these also can be set to unknown variables.

As a global optimization method, genetic algorithms are robust numerical optimization techniques which mimic the biological evolution process by natural selection [2]. Although genetic algorithms are computationally expensive due to the excessive number of objective function calculations, genetic algorithms are fit to our case because the POSPA code is a simple system code and thus can calculate the objective function very quickly. Design parameters are converted to genetic population and evolved over given generations in which process Selection, Crossover, and Mutation are carried sequentially. We utilized the code, PIKAIA, which is a well-built genetic algorithm program [2]. From the Eqs. (1) to (9), the residuals are calculated and summed as in Eq. (11) using weighting functions, W_i. Optimization is proceeded to maximize the objective function f.

$$RES = \sum_{i=1}^{9} W_i \times |RES_i| \quad (11)$$

$$f = 1/RES \quad (12)$$

2.4 DHRS design parameters using POSPA-GA

Using the genetic algorithm version of POSPA (POSPA-GA) [3], thermal-hydraulic and geometrical design parameters have been produced successfully. PDHRS design parameters are summarized in Table 1. Mass flow rates for the three flow paths and temperatures at inlets/outlets of heat exchangers were obtained and geometrical data were also produced.

Table 1. Design parameters of the PDHRS

Design parameter		Design value
Mass flow rate (kg/s)	DHX shell-/tube-side	12.76 / 17.54
	AHX shell-side	10.65
Temperature (°C)	DHX shell inlet/outlet	390.0 / 239.9
	AHX shell inlet /outlet	40.0 / 279.0
	DHRS hot-/cold-leg	334.6 / 226.2
Number of DHX tubes		114
Number of AHX tubes		190
Elevation difference between thermal centers of DHX and AHX (m)		~21
Sodium loop pipe ID (m)		~0.21
Sodium loop length of hot-/cold-leg		~43 / ~33
Chimney height and ID (m)		30 / 2.5

3. Conclusions

Physical models for the PDHRS design were addressed and an optimal approach with a genetic algorithm was applied to determine design parameters of the PDHRS in the PGSFR. Using the POSPA-GA code thermal-hydraulic design conditions and geometrical design parameters for 2.5 MWT decay heat removal capability per DHRS train have been calculated optimally.

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