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Thermal-hydraulic Design of 9.5 MWT Decay Heat Removal System in SFR

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1. Introduction

SFR (Sodium-cooled Fast Reactor) is one of a next-generation nuclear power reactor. Since the SFR uses liquid sodium as a coolant, high operating pressure is not required and thermal efficiency is excellent. KAERI (Korea Atomic Energy Research Institute) has performed a conceptual design of the PGSFR (Prototype Gen-IV Sodium-cooled Fast Reactor) [1]. KAERI has also performed a preliminary design of a pool-type SFR which consists of PHTS (Primary Heat Transport System), IHTS (Intermediate Heat Transport System) and DHRS (Decay Heat Removal System). This SFR has TRU core and the capacity of 3800 MWt.

In this study, a thermal-hydraulic design of 9.5 MWt decay heat removal system is presented. A methodology of determining the geometric parameter and design conditions of heat exchangers is addressed.

2. System Descriptions

The DHRS removes the decay heat of the core and the sensible heat of the primary heat transport system transferred through the decay heat exchanger (DHX) when it is impossible to cool the primary heat transport system using the main steam and feedwater system. It performs the safety function by cooling the primary transport system to the safe shutdown temperature after the reactor is stopped. The DHRS consists of a total of six loops which are grouped into three passive decay heat removal system (PDHRS) and three active decay heat removal system (ADHRS) loops to satisfy diversity and redundancy requirements, and each loop is arranged and operated independently. In the PDHRS, natural convection is formed by the density difference of air, whereas in the ADHRS, air flow is formed by using a blower, which is an active device. The total heat removal capacity of the DHRS is 57 MWt which is 1.5% of nominal reactor thermal power, and The DHRS is designed to cool the core in the case of a design basis accident with only 38MWt, which is 2/3 of the design capacity.

3. Methods and Results

3.1 Modeling of the DHRS

Figure 1 shows the process of the DHRS heat transfer. The decay heat of the core is removed to the atmosphere through three heat transfer paths of the DHRS. There are three coupled heat transfer paths in the DHRS, i.e., the DHX shell side path, the loop path, the natural-draft sodium-to-air heat exchanger (AHX) shell side path. The operating conditions in the three heat transfer paths depend on the cold pool temperature, inlet air temperature of the AHX, heat transfer performance of the heat exchangers, and the piping arrangement.

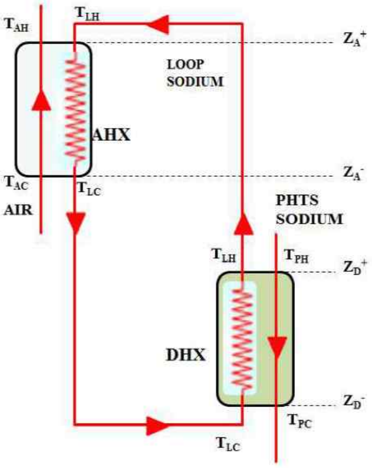

Fig. 1 Schematic of DHRS heat transfer

The governing equation for energy conservation along the heat transport paths is defined as follows.

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

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

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

$$Q_{Loop}^{rej} = \dot{m}_L \cdot (c_p(T_{LH}) \cdot T_{LH} - c_p(T_{LC}) \cdot T_{LC}) \quad (4)$$

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

where subscripts P, L, A, H, C represent the PHTS side, loop side, AHX shell side, hot fluid temperature, and cold fluid temperature, respectively. Q, U, A, T, $\dot{m}_A$, c_p represent the heat transfer rates, overall heat transfer coefficient, heat transfer area, temperature, mass flow rate, and specific heat, respectively. Superscript rej represents heat rejection and subscript $LMTD$ means a log mean temperature difference. Equations (1) and (2) mean heat transfer rates through the DHX and AHX, respectively. Equations (3) to (5) mean heat transfer rates in the DHX shell side path, loop path, and the AHX shell side path, respectively. All the heat transfer rates in Equations (1) to (5) should be same in the steady state condition.

The governing equation for momentum conservation of the DHRS can be represented as the correlations between developing head and pressure loss. The developing head is formed by the height and density difference between the DHX and AHX, and the pressure loss is influenced by geometries and arrangements of the components. The driving forces of sodium and air in the three heat transfer paths are the head due to the density difference. The relationship between the head, the flow resistance and the mass flow rate of the heat transfer path can be represented by the following equations.

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

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

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

where C, ΔH, Z, subscript chm represent the flow resistance, head, elevation, and chimney, respectively.

Since the size of the DHX and AHX should be appropriately designed for the nuclear reactor, the UA value must be adjusted. Therefore, the UA ratio of the DHX and AHX can be defined as follows.

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

To calculate the mass flow rate in each heat transfer path, it is necessary to calculate the head and flow resistance. The head is calculated using density difference and height, and the flow resistance is calculated using friction loss and form loss. Schematic of the flow resistances in the three heat transfer paths is shown in Fig. 2.

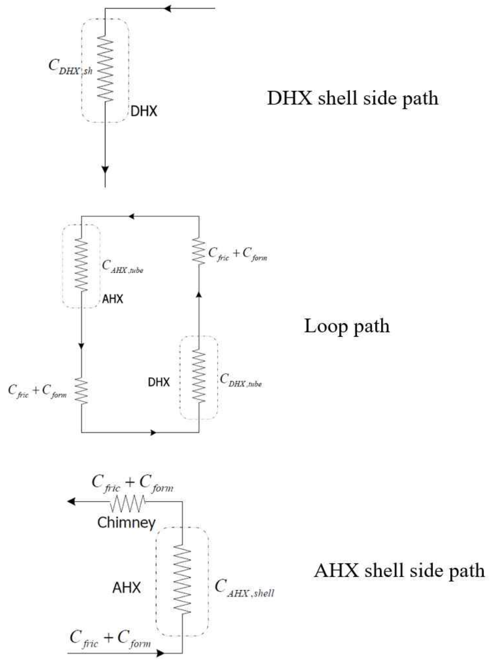

Fig. 2 Schematic of the flow resistances in the three heat transfer paths

The design point of the DHRS was calculated using POSPA-GA code [2], which solves above 9 equations to get temperature, mass flow rates, and heat transfer performance. This code contains a genetic algorithm which can decide design parameters optimally and solve the nonlinear equations. The object function of this code is the heat transfer rate that satisfies above 9 equations, and this code optimizes the design variables used in the above 9 equations.

3.2 Design parameters of the PDHRS

The PDHRS consists of three independent loops, and each loop has one DHX and one AHX. Thermal-hydraulic and geometrical design parameters have been calculated using the POSPA-GA code. In this code, modules of the SHXSA and AHXSA code are utilized, which are the code for thermal design and analysis of the DHX and AHX, respectively. PDHRS design parameters are summarized in Table 1.

Table 1. Main design parameters of the PDHRS

Design parameter	Value
Loop (ea)	3
DHX unit (ea)	1
AHX unit (ea)	1
DHX/AHX heat transfer rate (MWt)	9.5
DHX shell mass flow rate (kg/s)	54.8
Loop mass flow rate (kg/s)	59.9
AHX shell mass flow rate (kg/s)	38.3
DHX shell inlet/outlet temperature (°C)	360.0/227.5
AHX shell inlet/outlet temperature (°C)	40.0/292.6
Loop hot/cold temperature (°C)	335.8/215.1

3.3 Design parameters of the ADHRS

The ADHRS was designed through the same methodology as the PDHRS. The ADHRS consists of three independent loops, and each loop has one DHX and one forced-draft sodium-to-air heat exchanger (FHX). In the design of the ADHRS, modules of the SHXSA and FHXSA code are utilized, which are the code for thermal design and analysis of the DHX and FHX, respectively. ADHRS design parameters are summarized in Table 1.

Table 2. Main design parameters of the ADHRS

Design parameter	Value
Loop (ea)	3
DHX unit (ea)	1
FHX unit (ea)	1
DHX/FHX heat transfer rate (MWt)	9.5
DHX shell mass flow rate (kg/s)	54.8

Loop mass flow rate (kg/s)	56.5
FHX shell mass flow rate (kg/s)	47.6
DHX shell inlet/outlet temperature (°C)	360.0/227.5
FHX shell inlet/outlet temperature (°C)	40.0/245.1
Loop hot/cold temperature (°C)	340.0/212.0

4. Conclusions

A preliminary design of the DHRS in SFR with the capacity of 3800 MWt was performed. The DHRS was designed to consist of the PDHRS and ADHRS to satisfy diversity and redundancy requirements. A methodology of determining the design parameters of the DHRS was presented. Thermal-hydraulic and geometrical design parameters for 9.5MWt PDHRS and ADHRS have been calculated using the POSPA-GA code.

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