A Decay Heat Removal System Design of the Prototype Sodium-cooled Fast Reactor

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1. Introduction

Decay Heat Removal System (DHRS) shall be able to remove total decay and sensible heat from the reactor coolant system without exceeding temperature limits of the reactor core, structures, and relevant system components at any design basis accident during the plant life. The direct reactor auxiliary cooling system (DRACS) concept is employed for the 150MWe prototype SFR [1]. The decay heat exchangers (DHXs) are located in the cold pool and 4MWt (1% of the rated core thermal power) has been decided as the decay heat removal capacity [1]. There are 4 DHRS loops composed of 2 Active DHRS (ADHRS) loops and 2 Passive DHRS (PDHRS) loops. Each loop has 1MWt heat removal capacity.

There are three heat transport paths in the DHRS, i.e., a Primary Heat Transport System (PHTS) path including the DHX shell-side sodium flow, a DHRS sodium loop path through the piping, an air flow path through the sodium-to-air heat exchanger shell-side. To design the components of the DHRS and to determine its arrangement, key design parameters such as mass flow rates of the three paths, inlet/outlet temperatures of primary and secondary flow sides of each heat exchanger have to be determined reflecting the coupled heat transfer mechanism over the heat transfer paths.

As a preliminary design work, design parameters of the DHRS have been calculated and thermal sizing of the DHRS components has been conducted.

2. Methods and Results

2.1 Physical Modeling of the DHRS

Since the heat transport paths in the DHRS are strongly coupled with each other, the system modeling is very complicated and thus iterative methodologies are required to solve the equations. Accordingly, the design parameters such as inlet/outlet temperatures, mass flow rates, overall heat transfer coefficients should be calculated by coupling with the system geometries affecting the natural circulation flow rate in each heat transport path. Only inlet temperatures of the DHX and the AHX shell-sides are given as 390℃ and 40℃, respectively, and other design parameters are obtained by solving the non-linear equations [2].

A typical heat removal concept and temperature distributions 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).

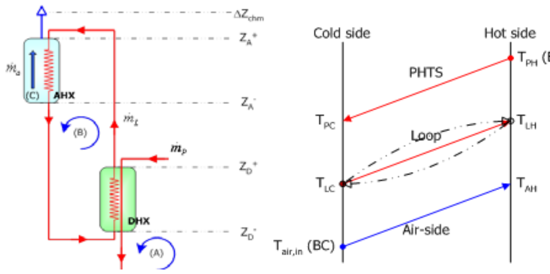

Fig. 1. DHRS heat removal paths (left) and temperature distribution concept (right).

In common, subscripts *P*, *L* and *A* mean the PHTS side, the DHRS sodium 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.

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

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

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

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

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

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

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

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

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

Equations (1) and (2) are for the heat transfer rates through the DHX and the AHX, 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 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, 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, chimney, and *C*, ΔH, β_T denote the flow resistance, the natural circulation head difference, and the adjustment factor to reflect the temperature change in each calculation step for iteration. 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_{AC} are given values.

2.2 Computer code for designing the DHRS

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

2.3 DHRS design point and its arrangement

Design parameters at the design point have been calculated by the POSPA code and are summarized in Table I. In Table I, FHX means Finned-tube Sodium-to-Air Heat Exchanger. Design parameters obtained by thermal sizing of heat exchangers are listed in Table II. Layouts of the PDHRS and the ADHRS are illustrated in Figs 2 and 3, respectively.

Table I: Key design parameters of the DHRS

Key design parameters		Design value
Mass flow rate (kg/s)	DHX shell-/tube-sides	6.22 / 4.38
	AHX, FHX shell-sides	4.09 / 4.93
Temperature (°C)	DHX shell inlet/outlet	390.0 / 265.8
	AHX shell inlet /outlet	40.0 / 289.7
	FHX shell inlet /outlet	40.0 / 249.0
	DHRS hot-/cold-legs	370.2 / 195.6
Elevation difference between thermal centers of DHX and AHX (m)		~21
Required chimney height and ID (m)		20 / 1.8

Table II: Design parameters of the HXs

Components	Design parameters	Design value
DHX	No. of DHX	4
	No. of tubes	42
	Pitch to Diameter ratio (P/D)	1.50
	Tube OD/ID (mm)	21.7 / 18.4
	Active tube length (m)	1.73
AHX	No. of unit	2
	No. of tube rows	5
	No. of tubes	68
	Pitch to Dia. (P_T/P_L)	2.5 / 1.71
	Tube OD/ID (mm)	34.0 / 30.7
	Effective tube length (m)	23.76
	Bundle height (m)	4.19
	Tube inclined angle (degree)	9.9
FHX	No. of unit	2
	No. of tubes	84
	Pitch to Dia. (P_T/P_L)	2.5 / 2.05
	Bare tube OD/ID (mm)	34.0 / 30.7
	Finned tube length (Total, m)	8.978
	Fin height (mm)	15.0
	Fin thickness(width, mm)	1.5
	Tube inclined angle (degree)	8.7
	No. of fin (per unit length, m)	152
	Spacing between Fins (mm)	5.08

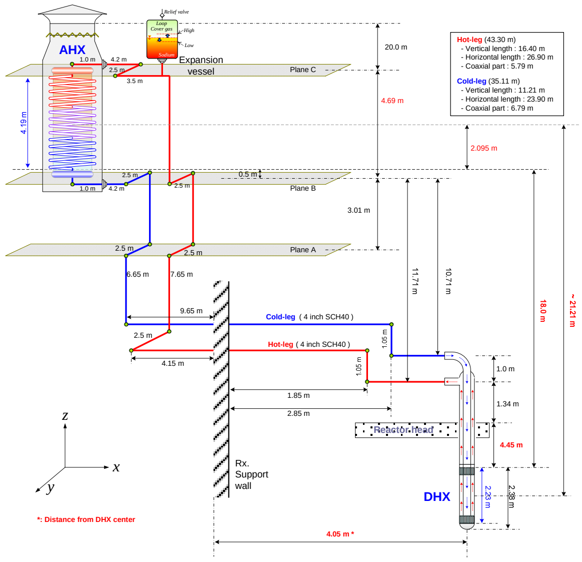

Fig. 2. PDHRS layout

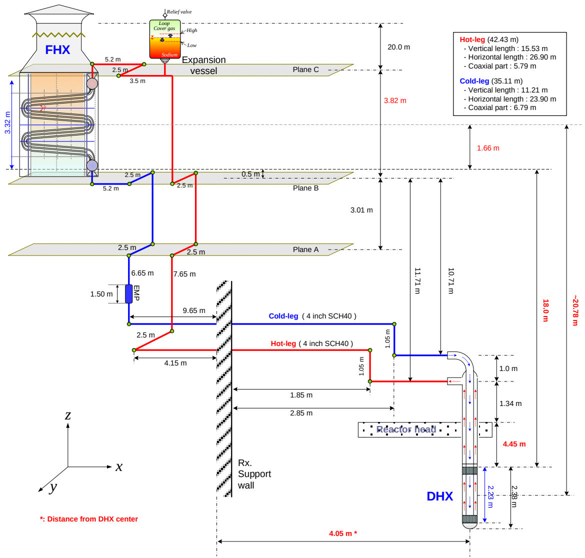

Fig. 3. ADHRS layout

3. Conclusions

A design point has been calculated for the DHRS design of 150MWe prototype SFR. Based on the design point, thermal sizing of the DHRS components and the DHRS arrangement has been carried out.

REFERENCES

[1] D. Kim, Decay Heat Removal System (DHRS) Conceptual Design Report, SFR-510-DF-462-001Rev.01, KAERI, 2013.

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[3] http://www.hao.ucar.edu/modeling/pikaia/pikaia.php