Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 25-26, 2012

Development of a Combined Heat Exchanger Design Concept for an SFR Decay Heat Removal System

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1. Introduction

A fast neutron spectrum reactor is one of the most promising options for efficient uranium resources utilization and a substantial reduction of radioactive waste to be disposed. To this end, the Korea Atomic Energy Research Institute (KAERI) has developed the own sodium-cooled fast reactor(SFR) design concept since 1992[1], and recent efforts putting into this area have been focused on enhancement of plant safety complying with the lessons learned from the Fukushima nuclear power plant accident.

In particular, a reliable decay heat removal (DHR) becomes one of the most important tasks in successful SFR design. Therefore, to achieve more reliable DHR performance, KAERI has developed the innovative design concept called the PDRC [1][2], which is similar to conventional DRACS[3] but its detailed flow path inside the reactor vessel is very creative. The schematic of the heat transport system in DSFR-600[2] is depicted in Figure 1 as an example.

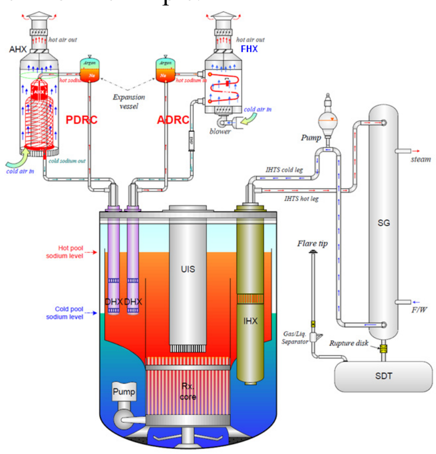

Fig.1 Main heat transport system in DSFR-600[2]

In regard to the DHR operation, the internal flow path passing through the reactor core should be maintained at all time but, in accident conditions, converted from the normal heat transport mode using the intermediate heat transport system (IHTS) to the alternate path with the DRACS loops. If the normal heat transport path via the IHTS is not available, the DRACS shall substitute the normal path and remove total heat load including core decay and sensible heat from the primary sodium pool. Since heat rejection from the intermediate heat exchanger (IHX) is not guaranteed in this situation, the decay heat exchanger (DHX) becomes the only heat sink and thus its arrangement inside the reactor vessel plays an important role in determining DHR capability.

In the current SFR design, however, the internal flow path from the hot pool to the cold pool is somewhat ambiguous due to the split flow ratio formed in a parallel path between IHXs and DHXs. This ambiguity results in a large uncertainty in DHX shell-side flowrate and corresponding heat transfer rate to the DRACS sodium loop. In order to improve heat transfer performance of the DHX unit, we proposed the new design concept with simplified flow path from the hot pool to the cold pool via a unified path passing the DHX and IHX. Hence we developed the creative design concept of the combined IHX-DHX unit (hereafter called the CHX), and its thermal sizing and 3D modeling works have been carried out.

This paper introduces one-dimensional design approach for the CHX unit using reasonable heat transfer and pressure drop models, and provides detailed shape and design parameters with sophisticated heat transfer tube arrangement. The structural design issues for the CHX unit regarding its installation methods are briefly discussed as well.

2. Methods and Results

2.1 Combined IHX-DHX unit (CHX)

The CHX is a shell-and-tube type counter-current flow heat exchanger with helically-coiled tube arrangement. Figure 2 shows the CHX configuration with the IHX coaxial pipe arrangement inside the reactor vessel.

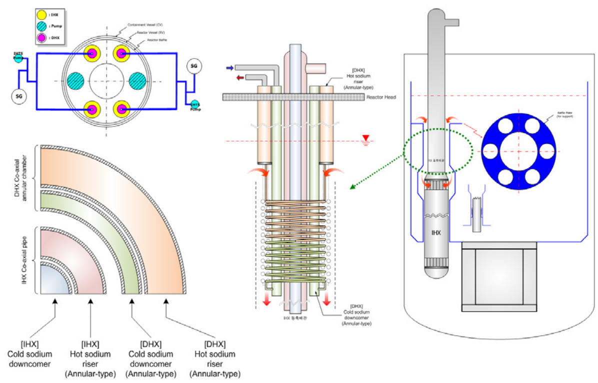

Fig.2 Configuration of the CHX unit

Total 4-row heat transfer tube bundle of the DHX surrounds the coaxial part of the IHX unit, and its lower end is vertically placed above the IHX inlet nozzle. The annular-type sodium downcomer chamber surrounds the IHX coaxial pipe and annular-type hot sodium riser chamber also surrounds it. As a result, the quadruple sodium chambers form the segregated sodium flow paths of the DHX and IHX unit regarding the CHX configuration.

The vertical cylinder welded on the separation plate (hereafter called the flow guide barrel) is installed to surround the DHX tube bundle. Therefore the flow guide barrel provides the unified single flow path from hot sodium pool to the cold pool via the CHX shell path, which is composed of a serial flow path of the DHX tube bundle and IHX shell region. The top end of the flow guide barrel is vertically positioned sufficiently below the sodium free surface to avoid unexpected gas entrainment [1]. This feature makes a transient sodium flow path very simple and improves the DHR capability.

2.2 Physical models for CHX thermal sizing

The physical models for the CHX 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 the postulated single flow channel, which is based on the node and control volume system. On the shell-side CHX, sodium flow is assumed as a cross flow across a tube bank. In order to obtain the shell- and tube-side sodium heat transfer coefficients, the following Kalish-Dwyer and Lubarsky-Kaufmann correlations were employed to a cross flow mode and an in-line flow situation, respectively[4];

Kalish-Dwyer correlation:

$$Nu=\left(\frac{\phi}{D}\right)^{0.5}\left(\frac{P-D}{P}\right)^{0.5}\left[\frac{\sin\beta+\sin^2\beta}{1+\sin^2\beta}\right]^{0.5}\left(5.44+0.228[Pe_{v,\max}]^{0.614}\right) \quad (1)$$

Lubarsky-Kaufmann correlation:

$$Nu_t=0.625\cdot Pe^{0.4} \quad (2)$$

For the shell- and tube-side pressure drop calculations of the CHX sodium flow paths, the following Gunter-Shaw's and Darcy's formula were applied for a cross- and an internal-flow conditions, respectively. The appropriate friction factors for the specific geometries were also employed. In particular, Mori-Nakayama's friction factor correlation was used to implement a coiling effect inside helical tubes.

Gunter-Shaw's formula:

$$\Delta P=\frac{f_c}{2}\frac{G^2L}{\rho_b D}\left(\frac{\mu_b}{\mu_\infty}\right)^{-0.14}\left(\frac{D_v}{s_T}\right)^{0.4}\left(\frac{s_L}{s_T}\right)^{0.6},\quad \frac{f_c}{2}=0.96\left(\frac{D_v G}{\mu_b}\right)^{-0.145} \quad (3)$$

Darcy's formula with Mori-Nakayama's friction factor:

$$\Delta P=\frac{f_m}{2}\frac{G^2L}{\rho_b D},\quad f=\left(\frac{d_i}{D_c}\right)^{0.5}\cdot\frac{0.192}{\left[\mathrm{Re}(d_i/D_c)^{2.5}\right]^{1/6}}\cdot\left(1+\frac{0.068}{\left[\mathrm{Re}(d_i/D_c)^{2.5}\right]^{1/6}}\right) \quad (4)$$

Based on the physical models, the thermal sizing computer code, named as CHXSA, was developed for a helically-coiled sodium-to-sodium heat exchanger. The nominal design data of the CHX unit in DSFR-600 at the design point are summarized in Table 1.

2.3 Solid modeling of the CHX unit

From the thermal sizing data of the CHX unit including heat transfer tube arrangement, its solid modeling was carried out to investigate the feasibility of the developed CHX design concept. Figure 3 shows the results of the 3D modeling for the CHX unit with the arrangement of other reactor internals. The solid modeling well showed that the tube arrangement surrounding the IHX coaxial pipe and the quadruple sodium chamber structures are very feasible to be installed. However, high-temperature thermal stress analysis for the sophisticated structures should be investigated to confirm their fabrication. It was also found that the support of the entire chamber structures including IHX unit becomes an important issues to materialize this innovative design concept.

Table 1. CHX design parameters for DSFR-600

CHX Design parameters		Design value	CHX Design parameters		Design value
Thermal duty (MWt)		9.0	No. of unit		4
No. of tubes / tube rows		58 / 4	Pitch to Dia. (P_T/P_L)		2.65/1.75
Tube OD/ID, Thickness (mm)		27.2/23.9, 1.65	Tube material		Mod.9Cr-1Mo
Effective tube length (m)		7.767	Bundle height (m)		0.952
Inner/outer shroud ID (m)		1.494 / 2.098	Heat transfer area (m^2)		38.493
ΔT_{LMTD} (ºC)		50.74	UA total (kW/ºC)		177.93
Shell-side (Primary sodium)	Flow rate (kg/sec)	37.8	Tube-side (DHR loop sodium)	Flow rate (kg/sec)	31.6
	Inlet temp. (ºC)	510.0		Inlet temp. (ºC)	474.3
	Outlet temp. (ºC)	324.4		Outlet temp. (ºC)	254.3
	Pressure drop (kPa)	7.826		Pressure drop (kPa)	6.249

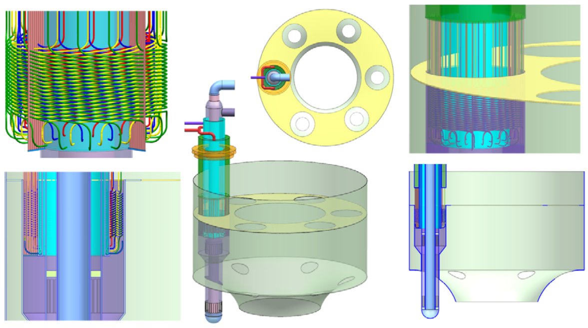

Fig.3 Configuration of the CHX unit with 3D modeling

3. Conclusions

This study aims to develop the new design method of a combined IHX-DHX unit and to provide detailed design parameters for the 9MWt capacity CHX design for DSFR-600. Based on the results of solid modeling, the general arrangement and the support issues of the CHX unit were discussed.

ACKNOWLEDGEMENT

This study was performed under the Creative Nuclear R&D Program sponsored by the Korea Atomic Energy Research Institute.

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