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Design and Performance Evaluation of a Combined DHX unit for SFR Design Application

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1. Introduction

A sodium-cooled fast reactor (SFR) has been considered as one of the most attractive future reactor systems from the aspect that it can achieve an efficient uranium resource utilization and substantial transuranics reduction. Based on the fundamentals, the Korea Atomic Energy Research Institute (KAERI) has been developing its own SFR design concept since 1992[1], and a recent exertion in this area has been focused on an enhancement of plant safety complying with the lessons learned from the Fukushima nuclear power plant accident.

Based on a higher operating temperature with excellent thermal conductivity and larger thermal inertia of liquid sodium coolant, the SFR system has employed passive safety systems to ensure reliable decay heat removal (DHR) and consequential plant safety enhancement. Although a passive type DHR system has many advantages over an active one, designing a well-coordinated passive system is usually more difficult than designing an effective active system. This is mainly because a cooling flow control is made directly by the system designer in an active system, while it is determined automatically by an intricate balance between the flow head loss and natural circulation head generation obtained from the density difference through the whole thermal flow system. To this end, securing a sufficient natural-circulation flow becomes one of the primary challenges for designing a reliable and successful DHR system in passive.

In a current pool-type SFR design [1][2], an internal cooling flow path from the hot sodium pool to the cold pool is somewhat ambiguous owing to the split flow ratio formed in parallel paths between the intermediate heat exchangers (IHXs) and decay heat exchangers (DHXs), which results in a large uncertainty in the DHX shell-side flowrate and corresponding heat transfer to the DHR sodium loops. To improve passive the DHR performance, we proposed a new design concept with a simplified flow path from the hot pool to the cold pool through a unified flow path serially passing the DHX and IHX units.

To materialize this concept successfully we have devised an innovative design concept of the combined IHX-DHX unit (hereafter called CHX), and its thermal sizing and feasibility evaluation have been made. This study introduces an innovative design concept of the helical-coil CHX unit, and provides the CFD analysis results to confirm a multi-dimensional flow effect coming from the complicated heat transfer tube arrangement.

2. Methods and Results

2.1 Combined IHX-DHX unit (CHX)

The CHX unit is a shell-and-tube type counter-current flow heat exchanger with a helically-coiled tube arrangement. **Figure 1** shows the CHX configuration with the IHX coaxial pipe arrangement inside the reactor vessel.

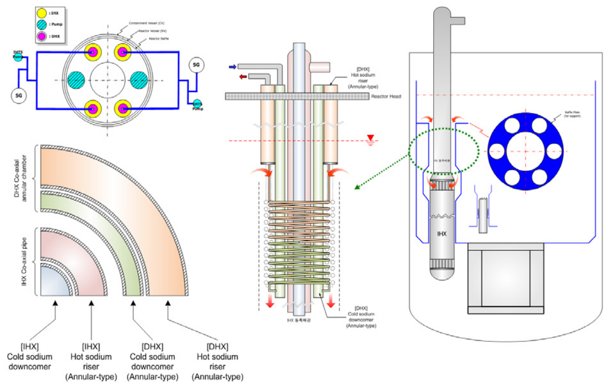

Fig.1 Configuration of the CHX unit

The 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 an 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 in the proposed CHX configuration.

The vertical cylinder welded on the separation plate (hereafter, called a flow guide barrel) is installed to surround the DHX tube bundle. Therefore, the flow guide barrel provides a unified single flow path from the hot sodium pool to the cold pool through 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 CFD analysis for the CHX unit

From the thermal sizing data of the CHX unit including the heat transfer tube arrangement, its solid modeling was completed and its nominal design parameters for the DSFR-600 design are summarized in **Table 1** [3]. The solid modeling of the CHX unit with the arrangement of other reactor internals is also shown in **Figure 2**. Since the CHX unit is designed by using a one-dimensional design approach based on several empirical correlations, the multi-dimensional effect of the shell-side sodium flow passing the helical-coil tube bundle region should be evaluated to confirm the design method [3].

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} (°C)		50.74	UA total (kW/°C)		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. (°C)	510.0		Inlet temp. (°C)	474.3
	Outlet temp. (°C)	324.4		Outlet temp. (°C)	254.3
	Pressure drop (kPa)	7.826		Pressure drop (kPa)	6.249

Fig.2 Configuration of the CHX unit with 3D modeling

To assess the detailed flow patterns inside the CHX unit and its heat transfer performance, a computational fluid dynamics (CFD) analysis was carried out for the full-shape geometries of the CHX unit in the DSFR-600, which are explicitly modeled. The commercial code, STAR-CCM+[4], a general-purpose CFD and multi-physics code based on the finite volume method was employed in this work.

A geometric representation of the problem is created through CAD software, which is then divided into computational cells. The CAD modeling data including all tube arrangement surrounding the IHX coaxial pipe and the quadruple-layered sodium chamber structures are used for the analysis. Unstructured polyhedral meshes are independently generated in the computation domains and these meshes are attached with each other to build a complete calculation domain.

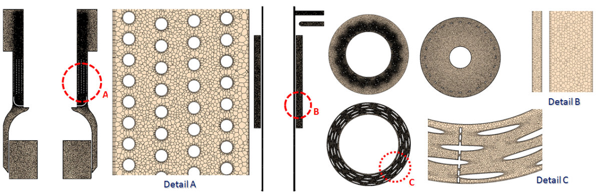

Fig.3 Fine mesh planar views at each calculation domain

Figure 3 shows the mesh distributions at each calculation domain. The total number of volume cells is around 77 million and the standard k-ε Reynolds model is employed as a turbulent model. The CFD code then solves the flow fields and conjugated heat transfer (CHT) with the relevant physics equations on this grid, and these results are post-processed in order to provide better insight into the physical behavior of the system. The total elapsed CPU time was around 310 hours using a 2.67 GHz Intel Zeon X32 CPU based parallel processing machine.

Table 2 shows the boundary conditions at each position of the domain. The inlet boundaries are located at each entrance of the shell- and tube-side CHX unit which connect a sodium pools. The mass flowrates are specified at each inlet boundary, and temperatures of the sodium coolant are also specified at these locations complying with the prototype design conditions [2]. The outlet boundary conditions are specified at the outlet of each heat exchanger flow circuit and a slip wall boundary condition is set on the pool surface where the liquid sodium contacts with Argon gas.

Table 2. BCs at each position of calculation domain

Specified Boundary Conditions at each position		
Tube-side inlet (sodium)	31.58 kg/s	254.3 °C
Shell-side inlet (sodium)	37.81 kg/s	510.0 °C
Outlet (Tube- & shell-side)	Pressure outlet	
Wall	No-slip, Adiabatic	

The CFD analysis results for the multi-dimensional flow and temperature fields of the CHX unit are shown in **Figures 4** and **5**.

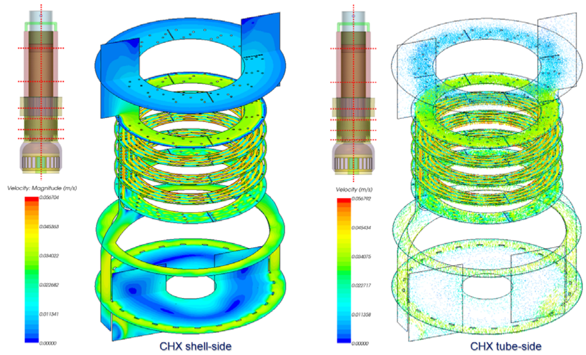

Fig.4 CHX velocity (flow) distributions

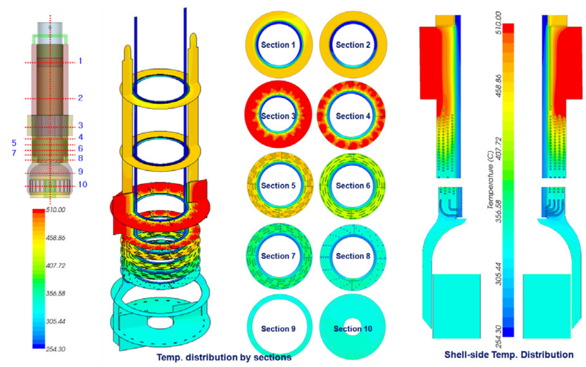

Fig.5 CHX temperature distributions

A comparison of the CHX performance calculated by a 1-D design approach with that made by a CFD analysis was carried out, and the quantitative results of the heat transfer rate for both cases are provided in **Table 3**.

Table 3. Comparison of Heat transfer performance

	Exit Temperature		Heat Transfer Rate (MWt)
	Shell-side	Tube-side	
1-D approach [3]	324.4	474.3	9.0
CFD Results	334.3	461.1	8.49 (*7.35)
% difference	~3.0%	~2.8%	~ 5.7%

*: Helical tube bundle region only

3. Conclusions

The present study aims at introducing the innovative design concept of the combined IHX-DHX unit and evaluating its design features in view of the heat transfer capability. From a comparison of the CHX performance designed by a one-dimensional approach with that made by a CFD analysis, it was quantitatively obtained that the difference in heat transfer rate is about 5.7%. It was also found that unexpected bypass flow in the shell-side CHX unit gave rise to a discrepancy. Since this feature cannot be fully considered in any one-dimensional design approach, we need to improve the physical models for CHX thermal sizing to get a more reasonable design. Finally, the conventional CHX design is feasible and the present study paves the way for a better understanding of the desirable DHR system design.

ACKNOWLEDGEMENT

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