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Development of Thermal-hydraulic Scaled-down Model of the Combined Heat Exchanger for Water Mock-up Hydraulic Performance Test

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1. Introduction

Designing a reliable decay heat removal (DHR) is essential for improving the safety of Sodium-cooled Fast Reactor (SFR). In the current SFR design, however, the internal flow path from the hot pool to the cold pool is somewhat ambiguous owing to the split flow ratio formed in a parallel path between the IHXs and DHXs. It may cause a large uncertainty in the DHX shell-side flowrate and corresponding heat transfer rate to the DRACS sodium loop [1].

For the purpose of an improving these large uncertainty, KAERI (Korea Atomic Energy Research Institute) proposed a new design concept with a simplified flow path from the hot pool to the cold pool through unified path passing both heat exchangers as shown in Fig.1 [1]. Furthermore, KAERI has developed the specific design of the combined IHX-DHX unit (hereafter called the CHX).

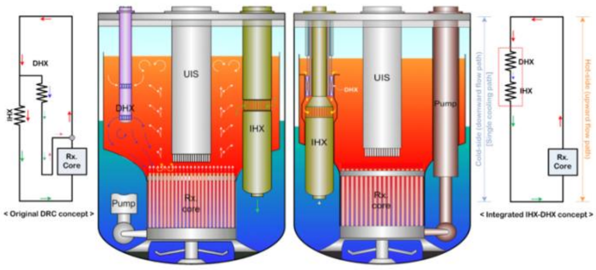

Fig. 1. Schematic diagram of reactor cooling in SFR [1]
(Typical configuration of HXs inside the RV (left) and New design and configuration of the CHX unit (right))

To demonstrate the applicability of the CHX design concept, POSTECH has been preparing for hydrodynamic experiment of the CHX unit collaborated with KAERI and KNU. The experiment will be conducted for investigating flow characteristics as well as synthetic pressure drop in the shell- and tube-side of the CHX unit. Since there are no thermal or heat transfer issues in this scope of experiment, water will be basically used as the working fluid of this experimental work [2].

In order to construct a lab-scale test facility, the 3-level scaling method was applied for designing the model CHX unit. In the present study, the appropriate scaling methods as well as the key design requirements for the model CHX unit are generally described. Specifications of the model CHX unit such as key design parameters, geometric features, and scaling distortions are discussed as well.

2. General scope and physical models of CHX

2.1 General scope and requirements

The main purpose of the CHX hydraulic performance test is to obtain the test database only for hydraulic behaviors in the CHX unit, which are suitable for verification of the physical models implemented in the computational code of CHXSA developed by KAERI. The scope of the CHX experiment basically aims at a measurement of flow characteristics in the shell- and tube-side of the unit and construction of pressure drop database for its specific tube configuration as shown in Fig.2.

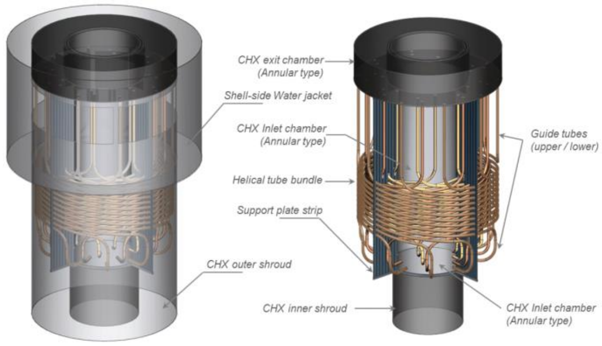

Fig. 2. Solid modeling of the model CHX unit

2.2 Physical models for flow analysis

The experiment for hydraulic performance test of the CHX unit would be made to investigate pressure loss characteristics in the whole section of the unit including the connecting parts to IHX. In this process, the detailed pressure drop models taken into account for experimental verifications are as follows.

- Frictional pressure drops for the peculiar tube configurations of the CHX unit, which are mainly for shell-side cross flow in a horizontal tube bank system (i.e. external flow) and coiling effect in tube-side flow (i.e. internal flow).
- Potential form losses at the connected parts with the multi-layered chambers, which are mainly for banding parts, sudden contraction/expansion to/from chambers, respectively.
- Pressure distributions in specified locations in the shell-side CHX unit installed in the space above the IHX unit.

3. Model CHX design for hydraulic performance test

3.1 Basic requirements

Basic requirements for the model CHX design are fundamentally chosen to investigate its pressure drop characteristics. All parameters are determined to meet the technical requirements listed below so that the data obtained from the experiment can be satisfactorily applied for the verification of the computational code for flow analysis.

- Maintaining the geometric similarity
- Maintaining the flow regime complying with the similarities of all anticipated operating conditions during the plant life-time, which cover the conditions at both the 100% normal (power) operation and at a decay heat removal mode.

Under various practical restrictions to the experiment, the global requirements cannot be exactly satisfied and there was some compromise between contradicting requirements and restrictions to produce the most optimum test conditions. In the process, the CHX conditions of the 100% power operation of KALIMER-600 [3] is the point of reference for the CHX operating condition, and all design parameters of the CHX unit described in reference [1] have been used as the reference geometry for the experiment.

Mainly the above two distinguished conditions of hydraulic tests are required for the peculiar tube arrangement of the CHX unit to figure out pressure drop characteristics both in the shell- and tube-side CHX tube bundle regions.

3.2 Scailing design criteria for the test section

Preservation of the multi-dimensional effect coming from helical-coil tube bundle geometries was also taken into account as the scaling design criteria. In order to meet the design characteristics of the combined heat exchanger unit with a complicated tube bundle configuration, such as a helically-coiled tube bundles, the well-established 3-level scaling law was basically implemented for the model CHX design [4]. Based on the 3-level scaling law, key dimensionless numbers were defined and used to obtain the global scaling criteria listed in Table 1.

Table.1. General Scaling Operators for the model CHX

Parameters	Scaling operators	3-level scaling law	
		Ratio (Model/Proto)	
Length (Height) Ratio	l_R	11/20	0.550
Diameter Ratio	d_R	29/50	0.580
Area Ratio	$a_R(=d_R^2)$	~ 8/25	0.336
Volume Ratio	$a_R \cdot l_R$	37/500	0.185
Aspect Ratio	$l_R / a_R^{1/2}$	~ 19/20	0.319
Power & Flow rate Ratio	$l_R \cdot a_R^{1/2}$	1/4	0.250
Velocity Ratio	$l_R^{1/2}$	37/50	0.740
Gravity Acceleration Ratio	1	1/1	1.0
Time	$l_R^{1/2}$	~ 37/50	0.742
Temp. distribution	1	1/1	1.0
Pressure Drop Ratio	l_R	11/20	0.550

With the cost factors including practical constraints of the scaled setup, the length scale of the model CHX unit was set to be 11/20 in height (or length) and 37/500 in volume, which results in the power and flowrate ratio of 1/4 complying with the global scaling criteria. Furthermore, key design parameters were also described as shown in Table 2.

Table.2. Key design parameters of the model CHX unit

Model CHX design parameters		Nominal Values
Thermal duty (MWt)		2.25
No. of unit		4
No. of tubes / tube rows		34 / 4
Tube ID/OD, Thickness (mm)		23.9/27.2, 1.65
Pitch to diameter ratio (PT/PL)		2.65/1.75
Tube material		STS304
Effective tube length (m)		4.272
Bundle height (m)		0.524
Heat transfer area (m^2)		12.41
Inner/Outer Shroud OD (m)		0.728 / 1.332
ΔT_{LMTD} (°C)		50.81
{UA}total (kW/°C)		44.4
Shell-side (Primary flow)	Flow rate (kg/sec)	9.45
	Inlet temp. (℃)	510.0
	Outlet temp. (℃)	324.0
	Pressure drop (Pa)	~ 100
Tube-side (DHRS flow)	Flow rate (kg/sec)	7.90
	Inlet temp. (℃)	254.3
	Outlet temp. (℃)	474.8
	Pressure drop (Pa)	~ 972

3.3 Configuration of the model CHX unit

The detailed geometry information on the helically-coiled tube bundle configurations of the model CHX unit are also provided in Table 3. The number of tubes maintaining the heat transfer area was determined. In addition, a detailed array of tubes that can be placed in the annular space of the shroud in the same number of tubes was optimized by the CONFHELI code developed by KAERI.

Table.3. Geometric information of the tube bundle configurations in the model CHX unit

Number of rows	1st Tube	2nd Tube	3rd Tube	4th Tube
i_{th} bundle ID (m)	0.800	0.944	1.088	1.233
i_{th} bundle OD (m)	0.854	0.999	1.143	1.287
Number of turns (turns)	1.631	1.389	1.210	1.071
Number of tubes (EA)	7	8	9	10

Number of stairs (layer)	11	11	11	11
Inclined tube angle (degree)	7.0	7.0	7.0	7.0
Tube bundle height (m)	0.524	0.524	0.524	0.524

In order to look over the feasibility of the scaled-down design of the model CHX unit, its key design parameters were compared over those of the prototype. Table 4 shows the scaling distortions of the model CHX design. Finally, the model CHX design has been well scaled from the prototype CHX unit complying with the specified scale ratios defined in Table 1.

Table.4. Scaling distortions of the model CHX design

CHX design parameters	Prototype CHX	Model CHX	Remarks
No. of CHX (Helical tube)	4	4	N/A
Thermal duty (MWt / each)	9.0	2.25	Ratio =1/4
Flowrate (shell / tube, kg/sec)	37.81/31.58	9.45 / 7.90	
No. of tubes	58	34	N/A
Heat transfer tube length (m)	7.766	4.272	11/20
Pitch to diameter (P_T/P_L)	2.65 / 1.75	2.65 / 1.75	Preserved
Tube ID/OD (mm)	23.9 / 27.2	23.9 / 27.2	Preserved
Tube thickness (mm)	1.65	1.65	Preserved
Tube material	Mod.9Cr -1Mo	STS304	For easier procurement
HX shell-side hydraulic dia. (m)	0.1334	0.1334	Preserved
Tube bundle height (m)	0.952	0.524	Ratio = 11/20
Avg. angle of inclined tubes (°)	6.94	7.0	Preserved
Helical-coil mean diameter (m)	1.796	1.030	Ratio = 29/50 (with~2% distortion)
ΔT_{LMTD} (℃)	50.74	50.81	Preserved
{UA} (kW/K)	177.9	44.4	Ratio=1/4
Average U (kW/m^2/K)	4.622	3.581	~22% distortion
Total heat transfer area (m^2)	38.49	12.41	
Inner/Outer Shroud OD (m)	1.494 / 2.098	0.728 / 1.332	Complying with tube arrangement

4. Conclusions

The general scope and basic requirements for evaluating pressure drop characteristics of the model CHX were developed in the present study. In order to satisfy the design characteristics of the prototype CHX, the well-known 3-level scaling law was implemented for the scaled-down model CHX design. Scaling design of the model CHX was completed in accordance with the specified scaling design criteria. Eventually, key design parameters of the model CHX were obtained and its scaling distortions were evaluated as well. The model CHX has been appropriately reduced with minor scaling distortions at the overall heat transfer coefficient and total heat transfer area when compared to those of the prototype. Based on this work, the model CHX will be manufactured for the purpose of the specified water mock-up hydraulic performance test.

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