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Design and Evaluation of the Helical-coil Sodium-to-Air Heat Exchanger of STELLA-1

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1. INTRODUCTION

The conceptual design of a 600MWe demonstration SFR (Sodium-cooled Fast Reactor) has been performed by the Korea Atomic Energy Research Institute (KAERI). In order to enhance plant safety, reliable decay heat removal (DHR) systems with natural circulation flow have been considered, and a few types of sodium-to-air heat exchanger (AHX) have been employed as an ultimate heat sink for this type of DHR system.

The DHR system comprises two diverse heat removal loops [1], and the heat load imposed on the primary sodium pool is safely rejected into the environment through different kinds of sodium-to-air heat exchangers. Serpentine-type and helical-coil sodium-to-air heat exchangers have been considered for air-coolers. The former is called as an FDHX (Forced-draft sodium-to-air HX) and the latter is simply called as an AHX.

For a general AHX design, convection resistance in the shell-side air flow path becomes the dominant factor affecting the mechanism of the conjugate heat transfer from the sodium flow inside the tube to the air path across the sodium tube wall. To this end, verification of the AHX performance is one of the most important tasks to secure the overall performance of a DHR system.

In order to assess the performance of the sodium-to-air heat exchanger, KAERI is now constructing a large-scale sodium thermal-hydraulic test facility, STELLA-1 (Sodium Integral Effect Test Loop for Safety Simulation and Assessment)[2]. The helical-coil AHX is to be installed at this facility, which is designed so that the local phenomena occurring at the sodium-to-air heat exchanger of the prototype is well preserved. Various scaling methodologies aimed at providing a suitable simulation for single-phase heat transfer with natural circulation of sodium and air have also been applied to obtain proper scaled design parameters [2].

This study introduces the one-dimensional design approaches of the helical-coil AHX using reasonable heat transfer and pressure drop models, and provides the CFD analysis results to confirm the multi-dimensional flow effect coming from the complicated heat transfer tube arrangement. The feasibility of the helical-coil AHX design and some design features regarding the helical tube arrangement are discussed as well.

2. METHODS AND RESULTS

2.1 Sodium-to-air heat exchanger (AHX)

The AHX is a counter-current flow shell-and-tube type heat exchanger with a helical-coil tube arrangement. Atmospheric air enters the air inlet duct at the lower part of the unit and flows upward across the helical-coil tube bundle located in the shell-side AHX. The air is heated as it passes the bundle region and the heated air is collected at the top of the unit; and then discharged through a sufficiently high air chimney. The end of the air chimney is designed to have rain protectors to limit an unexpected inflow of rain water or harmful obstacles.

The typical AHX design features are preserved in the scaled AHX unit of STELLA-1, but the heat capacity is reduced to 1/9 corresponding to the scaling criteria [2]. The typical shape and tube configuration of the AHX unit of STELLA-1 are shown in Figure 1.

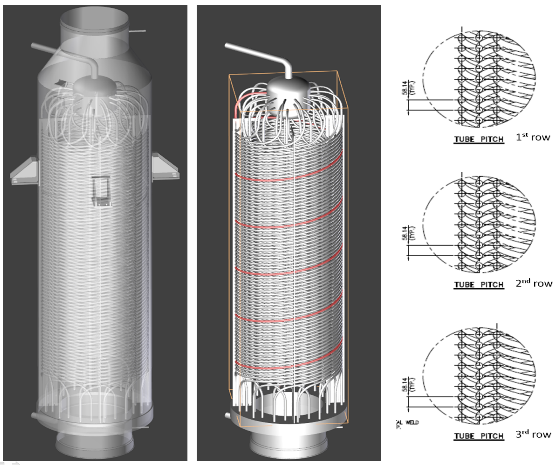

Fig. 1 Configuration of STELLA-1 AHX unit

2.2 Physical model for AHX thermal sizing

The physical models for the heat exchanger 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 depicted in Figure 2.

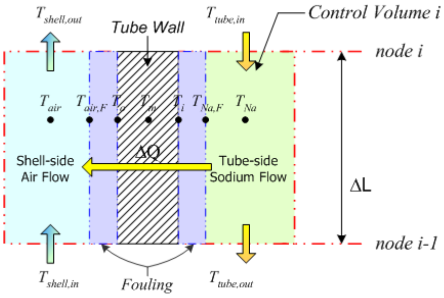

Fig. 2 AHX control volume model

On the shell-side AHX, the air flow is assumed as a cross flow across a tube bank as shown in Figure 3.

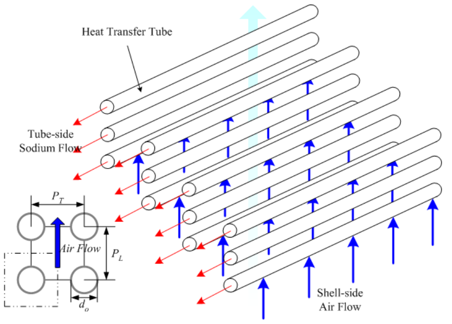

Fig. 3 Schematic of a tube bank in cross flow

To obtain the sodium- and air-side heat transfer coefficients, the following correlations for each flow medium are employed.

$$Nu_{Na} = 0.625 \cdot Pe^{0.4} \tag{1}$$

$$Nu_{air} = C \cdot \mathrm{Re}_{D,\max}^{m} \cdot \mathrm{Pr}^{0.36} \cdot \left(\frac{\mathrm{Pr}}{\mathrm{Pr}_s}\right)^{0.25} \tag{2}$$

$$for\ N_L \geq 20,\ 0.7 < \mathrm{Pr} < 500,\ 10^3 < \mathrm{Re}_{D,\max} < 2\times10^6$$

Eqs. (1) and (2) are the heat transfer correlations for the tube-side sodium flow [3] and the shell-side air flow across a tube bundle [4], respectively. Appropriate pressure drop correlations for the internal flow of sodium and the external air flow across a tube bank are also used as a function of Reynolds number [2][5]. Based on the above correlations, the thermal sizing of the scaled AHX was completed by preserving the typical design features of the prototype AHX. Table 1 shows the scaled AHX design parameters of STELLA-1.

Table 1. STELLA-1 AHX design parameters

Parameters	unit	Design value
No. of tubes / rows	ea	36 / 3
Tube O.D / I.D	mm	34.0 / 30.7
Tube thickness	mm	1.65
Heat transfer tube length	m	23.76
Tube material	-	STS316
Shroud size (ID/Length)	m	1.53 / 5.60

2.3 CFD analysis for the scaled AHX unit

Since the AHX design is basically performed by using a one-dimensional design approach based on several empirical correlations, the multi-dimensional effect of the air-side flow passing the helical-coil tube bundle region should be evaluated to confirm the design method mentioned previously. To assess the AHX performance, a CFD analysis for the full-shape AHX unit of STELLA-1 was performed by using STAR-CD.

Based on the results of the AHX thermal design, two kinds of tube arrangements distinguished by the winding method of helical tubes were obtained. One is based on the winding with an aligned direction for all tube rows, and the other is with alternating directions for every other tube row.

Figure 4 shows a comparison of the air-side velocity field and stream line for the aligned winding model and alternate winding model. The results show that the air flow of the aligned winding model swirls over the helical tube bundle, and there is a rare turbulence effect caused by a cross flow passing the horizontal tube bank.

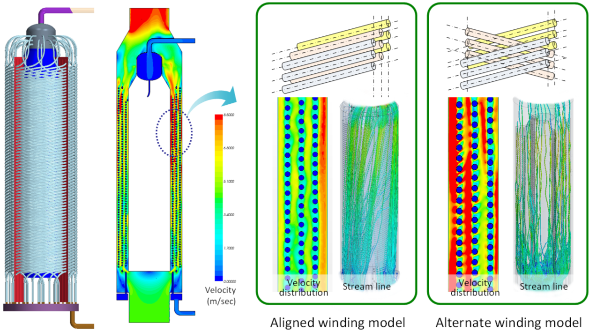

Fig. 4 Comparison of velocity distributions

Hence the alternate tube row arrangement contributes to mitigating the flow separation around the rear surface of the heat transfer tubes across the flow direction. This feature results in an enhancement of the heat transfer rate of the AHX when compared to the aligned winding model. A comparison of the AHX performance calculated by a conventional design approach with that made by CFD analysis was carried out, and the quantitative results of heat transfer rate for both cases are provided in Table 2.

Table 2. Comparison of Heat transfer performance

		Heat Transfer rate (MWt)
Result of Thermal sizing (1-D)		1.0
CFD Results	Aligned winding model	0.76 (24% difference)
	Alternate winding model	0.95 (5% difference)

3. CONCLUSIONS

This study aims to introduce the design method of a helical-coil AHX and to evaluate its design features in view of heat transfer capability. From a comparison of the AHX performance designed by a one-dimensional approach with that made by CFD analysis, it was found that the conventional AHX design is feasible and the alternate winding method has better performance than the aligned one in the aspect of heat transfer characteristics.

ACKNOWLEDGEMENT

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