Scaled Heat Exchanger Design of the Sodium Thermal-Hydraulic Experimental Facility; STELLA-1

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1. Introduction

The demonstration of safe and reliable decay heat removal (DHR) is one of the most important tasks in the successful design of a sodium-cooled fast reactor (SFR). The Korea Atomic Energy Research Institute (KAERI) has performed conceptual design studies of the pool-type sodium-cooled fast reactors, which were developed to satisfy the design targets of proliferation resistance, enhanced safety, economic competitiveness and environmental friendliness [1][2]. As a next step in that progress, advanced design concept of the demonstration SFR is currently being developed along with basic key technologies at KAERI. According to the long-term SFR development plan of the Korean government, it will be constructed by 2028.

The passive decay heat removal circuits (PDRC) are employed as a safety-grade DHR system in the demonstration SFR design, which are operated by a passive mechanism with natural circulation flow. The PDRC system consists of four independent loops, and each loop is equipped with a sodium-to-sodium decay heat exchanger (DHX), a sodium-to-air heat exchanger (AHX), and an intermediate sodium loop connecting the DHX with the AHX [1][2].

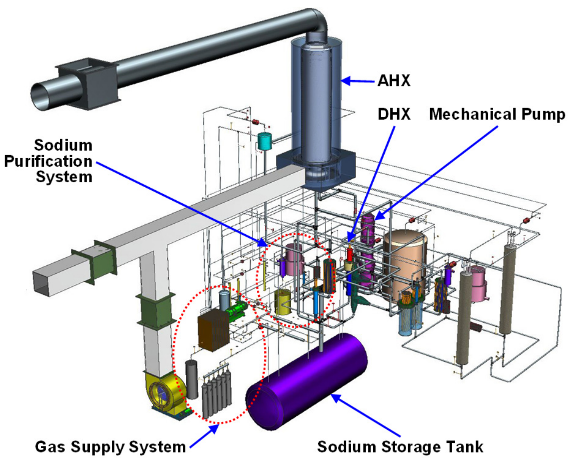

Fig.1 Overall layout of STELLA-1

A kind of separate effect test for assessing the performances of the sodium heat exchangers has been put in progress in order to demonstrate the design characteristics and verify the component design codes. On the basis of the preliminary test facility design, the basic and detailed designs of STELLA-1 (Sodium Integral Effect Test Loop for Safety Simulation and Assessment) are being carried out for the new demonstration SFR, and the installation of the experimental facility is scheduled to be completed by the middle of 2011. The main experiments will start from 2012 after the startup test in 2011. **Figure 1** shows the overall layout of STELLA-1.

2. Methods and Results

In order to model the local phenomena occurring at each heat exchanger unit employed in the PDRC system, various scaling methodologies aimed at providing a suitable simulation for single-phase heat transfer with sodium natural circulation have been considered. Detailed methodologies implemented in the scaling analysis are provided in the following sections.

2.1 General scaling approaches

For the local scaling approach, major concerns have been focused on the two kinds of scaling methods, i.e. the linear and the volume scaling method. Regarding the linear scaling method, the aspect ratio and the velocity term can be preserved, while a time reduction and a gravity increase are expected. This feature results in a large distortion of the acceleration term, and thus the linear scaling method is not suitable for simulating gravitation-related phenomena in scaling approaches. In contrast, in the volume scaling method, the height (or length), velocity, and gravity can be preserved, and thus real time simulation is possible. This method is also suitable for simulating the conditions that the gravitation effect is weaker than the pressure difference of the concerning system, and thus a one-dimensional flow system with a natural circulation flow can be appropriately simulated by using this method. Hence, the volume scaling methods were implemented basically to preserve the major design parameters of heat exchangers working with natural-draft flow mechanism.

2.2 Scaled heat exchanger design and evaluation

The scaling approach implemented in this study is based on the mathematical identity of analogous physical systems, and the specific dimensionless variables and parameters used in the similarity study were derived from the dimensionless conservation equations of the system [3]. The overall scale ratio of the test components of heat exchanger units was selected to be unity for height and 1/9 for volume on the basis of the scaling criteria. Hence, the designed capacities of the DHX and AHX become 1.0 MWt, respectively. Sodium was selected as the working fluid of the component test loop and the operating temperatures and the pressures of the whole system were preserved to properly simulate the realistic conditions of the reference plant.

In a scaled heat exchanger design process, the major distortions coming from gravity acceleration and time reduction are not of importance but the preservation of the characteristic parameters (U, ΔT_{LMTD}) for each heat exchanger becomes a major factor to be considered.

The scaling work for each heat exchanger was conducted based on the knowledge of the scaling method, and the appropriateness of the scaled design parameters was evaluated. **Figure 2(a)** shows the scaled design parameters of the DHX depending on the number change of the DHX heat transfer tubes, and all the parameters were normalized to the nominal design data.

When the number of heat transfer tubes becomes 28, the terms, ΔT_{LMTD} and U were kept at unity and the heat transfer surface area agreed to the ideal scaling ratio of 1/9 within 1%. The length of DHX heat transfer tube was identical to the prototype, and thus the pressure drops of shell- and tube-side were well preserved.

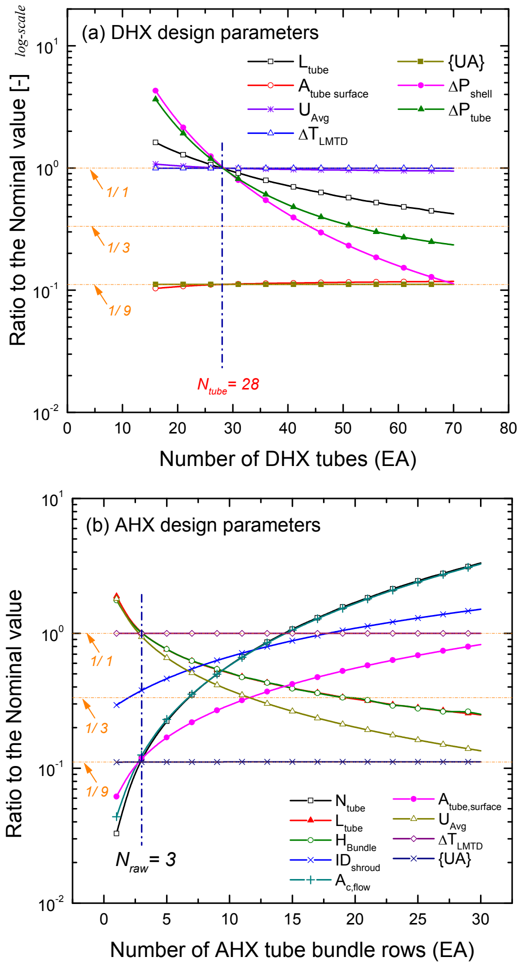

Fig.2 Distortions of the scaled design parameters

Similar trends were observed in the scaling process of the AHX. **Figure 2(b)** shows the scaled design parameters of the AHX depending on the number change of the AHX tube bundle rows, and all the parameters were also normalized to the nominal design data. As the number of AHX tube bundle rows increases, the bundle height or tube length has large discrepancy from the theoretical scaling criteria at the scaled length ratio of 1.0. Therefore, the number of AHX tube bundle rows was determined to be 3, and the terms (U, ΔT_{LMTD}) were well preserved only when the ratio of the tube bundle height was kept at unity.

This means that a one-dimensional flow system with the convection-dominated natural circulation flow can be appropriately simulated by using the volume scaling ratio, which well preserves the height scale at unity. This is mainly because the flow resistance of the AHX air path is highly dominant in the overall heat transfer mechanism, but relatively large uncertainties have been encountered in determining the hydraulic diameter of the AHX air path in this regard. In order to preserve the overall heat transfer coefficient (U) and the log-mean temperature differences (ΔT_{LMTD}), the characteristics of the air flow based on the relationship of the developing head and the flow resistance should be suitably considered in the scaling process.

3. Conclusions

The STELLA-1 heat exchangers were appropriately scaled and designed to preserve the overall heat transfer coefficient (U), the log-mean temperature differences (ΔT_{LMTD}). The scaling ratio of the pressure drop (ΔP), flow rate and heat capacity are also maintained as the given similarity criteria. All the scaled heat exchangers of the sodium test loop have the identical tube materials, tube pitches, and diameters (ID/OD) with the prototype in order to preserve the characteristics of heat transfer and pressure drop. The scaling distortions with respect to the heat exchanger characteristics were quantitatively discussed. It was found that a full-height scaling method (volume scaling method) needs to be considered in order to overcome a large scaling distortion coming from the balance between buoyancy and inertia in the heat exchanger flow paths.

ACKNOWLEDGEMENT

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