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Design Evaluation of Thermal-hydraulic Test Facility for a Finned-tube Sodium-to-Air Heat Exchanger

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1. Introduction

For more reliable design of the safety-grade decay heat removal system (DHRS) in PGSFR (Prototype Gen-IV Sodium-cooled Fast Reactor), two kinds of sodium-to-air heat exchangers have been employed in the system as an ultimate heat sink [1]. One is a natural-draft sodium-to-air heat exchanger (AHX) with helically-coiled sodium tubes, and the other is a forced-draft sodium-to-air heat exchanger (FHX) with finned-tubes with a straight-type arranged. Since the FHX is normally operated in an active mode with a forced air draft conditions, its performance should be verified for any anticipated operating conditions [2,3]. For this reason, we have designed a kind of separate effect test facility called SELFA (Sodium thermal-hydraulic Experiment Loop for Finned-tube sodium-to-Air heat exchanger) and its construction has been recently completed. This paper introduces the recent progress of overall design phase for the SELFA facility and deals with basic thermal-hydraulic design parameters and its design validation as well.

2. Design and Evaluation of SELFA

2.1 Experimental setup

The SELFA consists of the main test loop, sodium purification system, gas supply system, and related auxiliary systems. The schematic of the SELFA is shown in Fig.1.

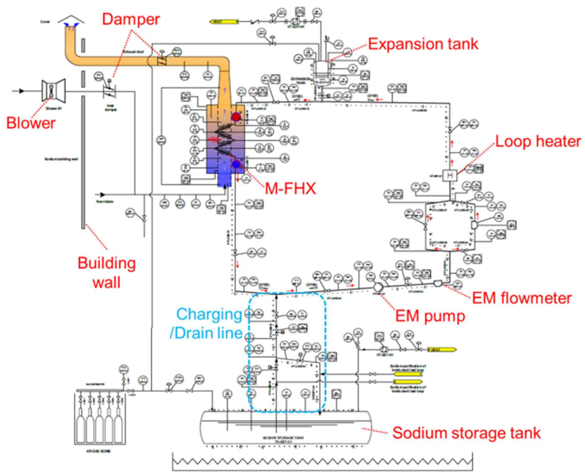

Fig. 1. P&ID of the SELFA test section.

Main components of the test section are the model FHX (hereafter called M-FHX), an electromagnetic pump, an electric loop heater, sodium valves, an expansion tank, and a sodium storage tank. An EMP (electromagnetic pump) and an air blower are equipped to provide controllable liquid sodium and air flow into the tube- and shell-side M-FHX, respectively. Fig. 2 shows images of the key components installed in the SELFA facility.

Fig. 2. Images of key components.

2.2 Descriptions of the Model FHX (M-FHX)

The prototype FHX has been designed to be four-pass serpentine shape (M-shape) with staggered tube arrangement to enhance its heat transfer performance [1]. Each heat transfer tube has several helical-fins with narrow pitch to extend effective heat transfer surface area contacting air flow.

The main objectives of experiments using the SELFA facility are i) to construct test database for verification and validation of the computer code, FHXSA [2] developed for thermal sizing of the FHX unit and ii) to investigate its thermal-hydraulic performance. For this reason, scaling design of the model heat exchanger has been carefully conducted complying with the general design criteria established for the SELFA design [3-5]. The fabrication of the M-FHX has been also completed to preserve overall design requirements for the M-FHX.

Basically the overall length scale of the M-FHX has been preserved to minimize any distortions coming from the power scale reduction. To make this feature possible, the number of tube columns has been reduced in accordance with the power scale of 1/8. The specific design parameters of the M-FHX are shown in Table I.

Table I. Comparison of design parameters of the model FHX

Design parameters	FHX (PGSFR)	M-FHX (SELFA)	Ratio
Thermal duty (MWt)	2.5	0.3125	1/8
No. of tube columns	32	7	1/8
No. of tubes	96	21	1/8
Tube pitch, P_L/D & P_T/D	2.05&2.5	2.05&2.5	1/1
Tube material	Gr.91	STS304	-
Tube OD/ID (mm)	34.0/30.7	34.0/30.7	1/1
Thickness (mm)	1.65	1.65	1/1
Finned-tube length (m)	8.000	7.722	0.965
Fin height (mm)	15.0	15.0	1/1
Fin thickness (mm)	1.5	1.5	1/1
Tube inclined angle (°)	7.2	7.2	1/1
No. of fins (per unit length, m)	152	157.48	0.965
Spacing between fins (mm)	5.08	4.85	0.955
Total fin surface area (m^2)	656.34	82.04	1/8
Total No. of fins per tube (ea)	1216	1216	1/1
Frontal Area (~ W x D, m)	1.98× 2.76	1.98×0.38	1/8

To validate the model heat exchanger design, flow and temperature distributions of liquid sodium and air flow of the M-FHX have been carried out using commercial CFD tools, such as ANSYS CFX V16.1 and STAR-CCM+. For more uniform supply of liquid sodium and air flow into the test section, particularly heat transfer region, a cross-baffle plate inside the upper sodium chamber and vane structures inside the air intake section were introduced as shown in Fig. 3. Based on the analysis results, we could figure out that unexpected flow distributions coming from a scaling effect with the column number reduction can be minimized.

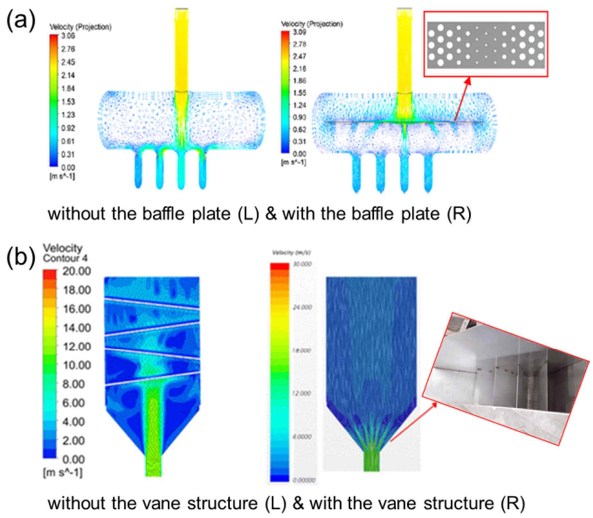

Fig. 3. CFD analysis results for the inlet guide structures with (a) cross-baffle and (b) vane structure.

2.3 Instrumentation

The main parameters to be measured in the experiment are flow rates and temperatures. Both an electromagnetic flowmeter (EMF) and a Coriolis mass flowmeter were employed to measure liquid sodium flow rate, of which specifications were chosen in accordance with the test conditions [4]. In regard to the temperature measurement, total 100 points at the air-side and total 66 points with thermo-wells at the sodium-side will be measured by using multipoint thermocouple (T/C). Fig. 4 shows the concept and images of the multipoint thermocouples, and Fig. 5 shows sodium-side thermocouples installed with thermo-wells.

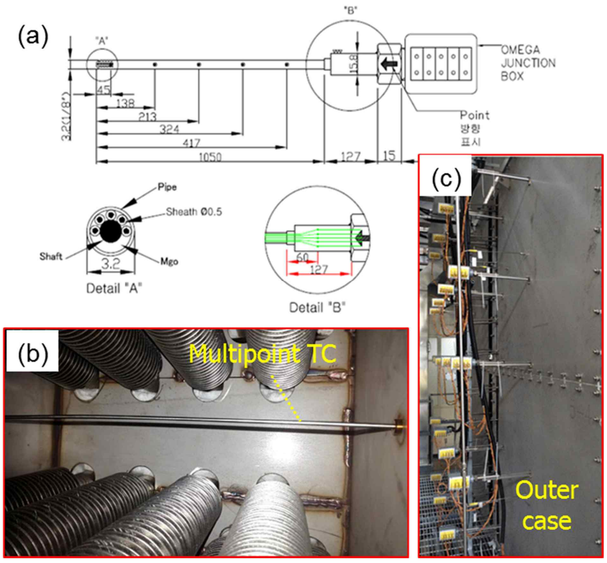

Fig. 4. Multipoint thermocouple at the M-FHX air-side: (a) drawing and (b, c) installed images.

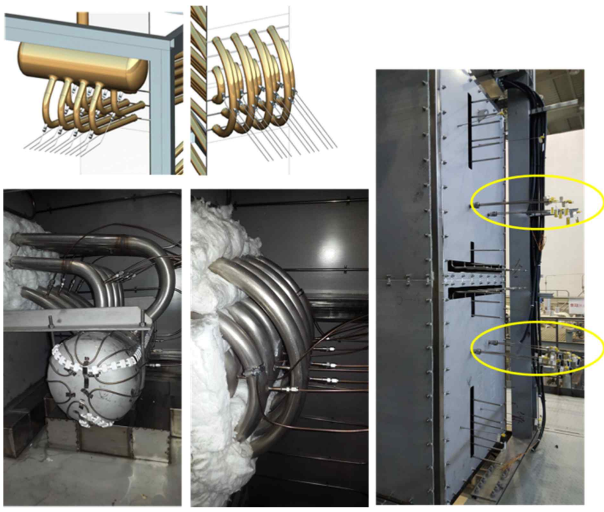

Fig. 5. Concept of thermo-wells for T/C installation at the M-FHX sodium-side.

For the measurement of sodium-side pressure drop, NaK-filled pressure transducers (PTs) have been employed. Since it has been usually used in the pressure range over several hundred kilo-pascal range, we also conducted additional calibrations for the PTs under 200 kPa.

2.4 Mechanical design and integrity evaluation

Detail design and integrity evaluation on the mechanical components and piping systems in the SELFA were conducted. The design evaluation has been conducted according to ASME Section VIII Div.2, ASME Subsection NH (ASME-NH) and RCC-MRx for the heat exchanger of FHX and pressure vessels, and according to ASME B31.1 and RCC-MRx RD-3600 for piping systems. The profiles of temperature and stress intensity in FHX test section are shown in Fig. 6. The design evaluation results of the test section (heat exchanger and frames) showed that all results were well within the design limits of ASME Section VIII, (ASME-NH and RCC-MRx for hot spot). In addition, the evaluation results in Fig. 7 for the SELFA piping system were also within the design limits of ASME B31.1 and RD-3600. Therefore, integrity of M-FHX and piping systems were confirmed.

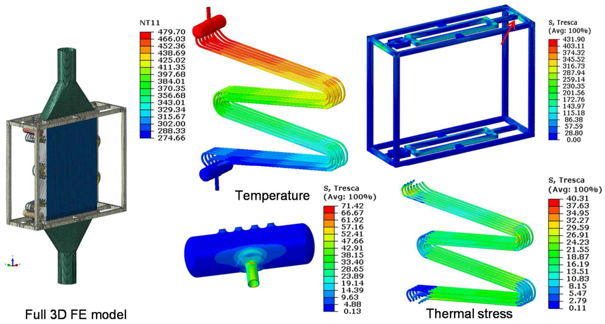

Fig. 6. Finite element model and analysis results of the M-FHX including the frame structure.

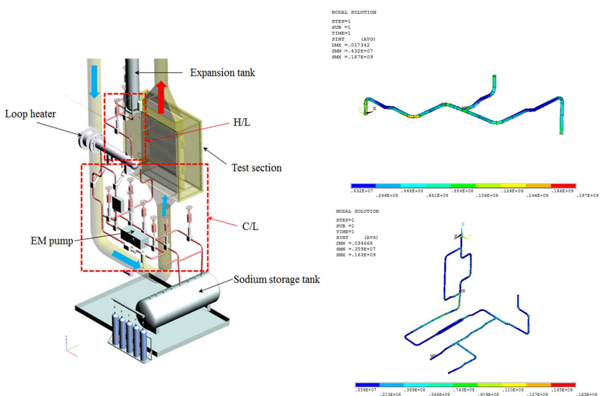

Fig. 7. Schematic of the SELFA and analysis results of sodium piping system.

2.5 Preliminary CFD evaluation

The preliminary CFD analysis is in progress by using the commercial code of ANSYS CFX V16.2. Total 95,896,560 hybrid meshes (hexa + tetra/prism) were generated as shown in Fig. 8.

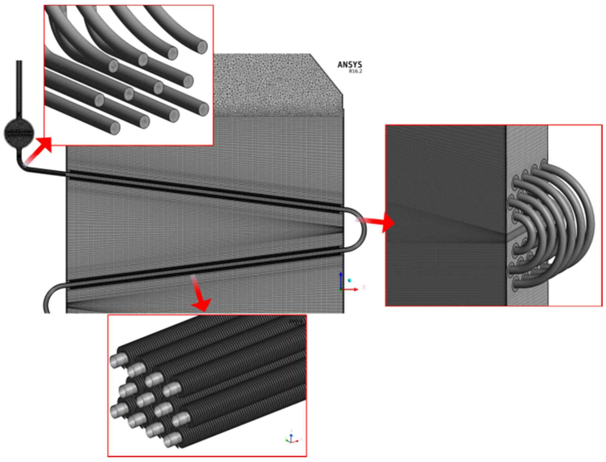

Fig. 8. Mesh generation result of unity scale of M-FHX.

The SST k-w turbulence model and conjugate heat transfer model were used. The mass flow rate of 1.10 kg/s at 370 °C in sodium-side and 1.25 kg/s at 20 °C in air-side were applied. Also, the average y+ value at finned tube area was acceptable. Fig. 9 represents the CFD analysis results in the views of flow velocity and temperature. Further analysis for this model is still in progress.

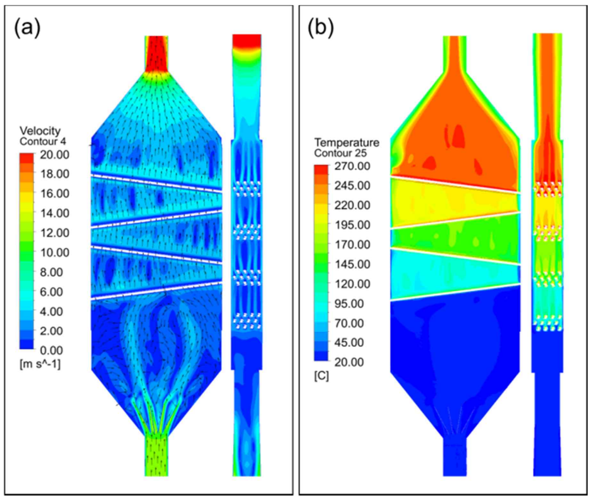

Fig. 9. Flow and temperature distributions for M-FHX: (a) flow velocity and (b) temperature profile.

3. Conclusions

For the verification of the computer code for the thermal design of the FHX unit, a kind of separate effect test facility called SELFA (Sodium thermal-hydraulic Experiment Loop for Finned-tube sodium-to-Air heat exchanger) has been recently constructed. To validate the test section design, evaluations of both thermal-hydraulic and mechanical design have been carried out, and some new concepts or devices were newly employed to replicate the prototypic conditions as closely as possible. Based on the understanding of the design features of the SELFA facility, the main test will be started from FY2016, then the data acquisition, uncertainty analysis, and complimentary experiments will be preceded to construct the extended test database for the design code V&V.

ACKNOWLEDGMENTS

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