Heat Transfer Performance Test for a Sodium-to-Air Heat Exchanger with Inclined Finned-Tube Banks

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Abstract. A sodium thermal-hydraulic test facility that is called SELFA (Sodium thermal-hydraulic Experiment Loop for Finned-tube sodium-to-Air heat exchanger) has been constructed. SELFA is a kind of separate effect test facilities being progressed with STELLA (Sodium Test Loop for Safety Simulation and Assessment) program, which is indispensable for the support of PGSFR (Prototype Gen IV Sodium-cooled Fast Reactor) development. The model heat exchanger (M-FHX) of SELFA was designed for performance demonstration of FHX (Forced-draft sodium-to-air heat exchanger) in PGSFR, which has three-row inclined finned-tube banks with staggered arrangement. By using this dedicated sodium heat exchanger test facility, the first step of heat transfer performance test has been conducted for validation of computational codes such as the heat exchanger thermal-sizing code (FHXSA) and the safety analysis code (MARS-LMR). In this study, we report the heat exchanger performance test results for the M-FHX at the specific point (i.e., thermal duty of ~270 kWt). The test database obtained from this work has been used for its heat transfer performance evaluation through comparisons with the analyses results obtained from the dedicated CFD analysis.

Key Words: finned-tube bank, staggered tube arrangement, cross flow, computational code V&V.

1. Introduction

The generation IV (Gen IV) nuclear power plants have been being developed for a minimal waste and effective utilization of uranium resources. A sodium-cooled fast reactor (SFR) is one of the most promising options to pursue these purposes, and the Korea Atomic Energy Research Institute (KAERI) is currently developing Prototype Gen IV Sodium-cooled Fast Reactor (PGSFR) [1,2]. For a more reliable design of the safety-grade decay heat removal system (DHRS) in a PGSFR, two kinds of sodium-to-air heat exchangers have been employed in the system as an ultimate heat sink [1,2]. One is a natural-draft sodium-to-air heat exchanger (AHX) with helically-coiled sodium tubes in a passive decay heat removal system (PDHRS), and the other is a forced-draft sodium-to-air heat exchanger (FHX) with an inclined finned-tube banks in an active decay heat removal system (ADHRS). Among them, FHX is normally operated in active mode with forced air draft conditions, its predictable performance should be verified for any anticipated operating conditions [3].

To confirm the heat transfer performance of FHX, we designed a separate effect test facility called SELFA (Sodium thermal-hydraulic Experiment Loop for Finned-tube sodium-to-Air heat exchanger) including a model heat exchanger (M-FHX), and its construction was also completed [4-7]. In this paper, we introduce the first heat transfer performance test result of the M-FHX in SELFA, and we also report the comparison results between the computational analyses and experiments using liquid sodium in SELFA.

2. Experimental Setup

2.1.The SELFA Facility

The piping and instruments diagram of SELFA is illustrated in FIG. 1. It consists of the main test loop, sodium purification system, gas supply system, and related auxiliary systems. The main components for liquid sodium are M-FHX, an electromagnetic pump (EMP), an electric loop heater, flowmeters, sodium valves, an expansion tank, and a sodium storage tank. Sodium storage tank contains about 1.4 tons of sodium, and it is used ~700 kg of sodium during operation. A loop heater and an electromagnetic pump let the temperature and flowrate of liquid sodium be controlled. Also, one blower and two dampers are equipped for controlling air flowrate in air side. FIG. 2 represents constructed images of SELFA and its equipment.

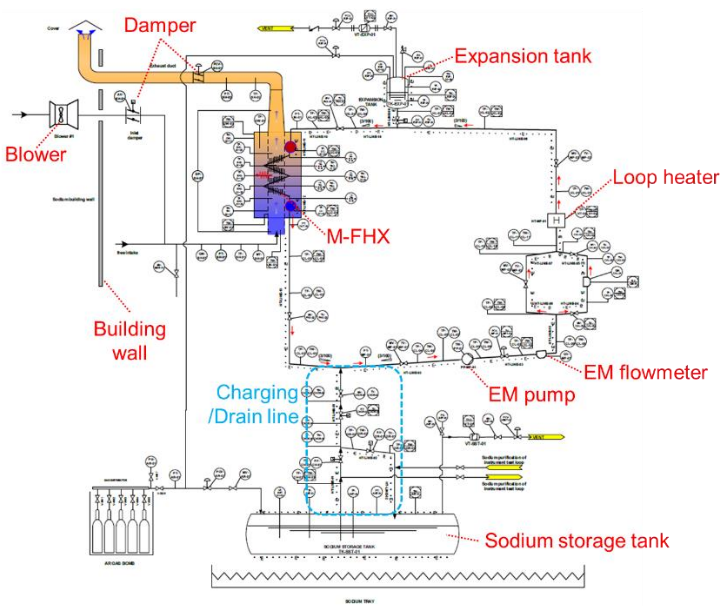

FIG. 1. Constitution of the SELFA facility.

FIG. 2. Installation status of SELFA.

2.2.Model Heat Exchanger (M-FHX)

The SELFA facility has a finned-tube type sodium-to-air heat exchanger which is consistently designed with the reference FHX in PGSFR. The reference FHX was designed to have a four-pass serpentine shape (M-shape) with inclined finned tube banks in a staggered arrangement to enhance its heat transfer efficiency. Helical-fins with a narrow pitch on tubes extend the effective heat transfer surface area in contact with the shell-side cold air. FIG. 3 shows the schematic drawing and fabricated finned tubes of M-FHX, and Table I describes key design parameters of both the reference FHX in PGSFR and M-FHX in SELFA. The overall length scale of M-FHX has been preserved to minimize any distortions coming from the power scale reduction. For this, the number of tube columns was reduced in accordance with a power scale of 1/8. Geometrical features of the finned-tube such as tube pitches, tube diameters, tube inclined angle, fin height, fin thickness, fin spacing, total fin surface area in each tube were also preserved with the reference. Small discrepancy of fin spacing came from the fabrication process to allow thermal expansion.

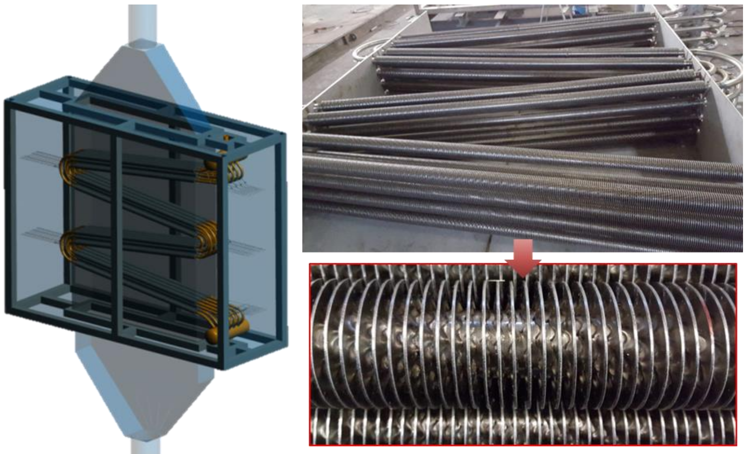

FIG. 3. Schematic of M-FHX and its fabricated finned tube geometry.

TABLE I: COMPARISON OF KEY DESIGN PARAMETERS BETWEEN FHX AND M-FHX.

Design parameters	**FHX (PGSFR)**	**M-FHX (SELFA)**	**Ratio**
Thermal duty (MWt) at a design condition	2.5	0.3125	1/8
No. of tube columns	32	4	1/8
No. of tubes	96	12	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

2.3.Test Condition

Table II represents the experimental conditions of two fluids (i.e., liquid sodium and air) being described in this paper. The measured values was average values in steady state condition for 10 min. Sodium flowrate was obtained by the electromagnetic flowmeter through additional calibration process using a Coriolis flowmeter as a reference.

TABLE II: EXPERIMENTAL CONDITIONS OF FLUIDS.

	Sodium (inlet)		**Air (inlet)**	
	Target	Measured	Target	Measured
Temperature	370.0 ℃	370.1 ℃	Outside Temperature	10.21 ℃
Mass flowrate	1.10 kg/s	1.14 kg/s	1.250 kg/s	1.247 kg/s

3. Results and Discussions

3.1.Experimental Results

The steady-state values were obtained for 10 min as shown in FIG. 4. In this period all measured values maintained without any continuous increase or decrease as time passes. Table III contains overall heat transfer performance test result, and it has excellent consistency between tube-side and shell-side in the calculated heat transfer rate.

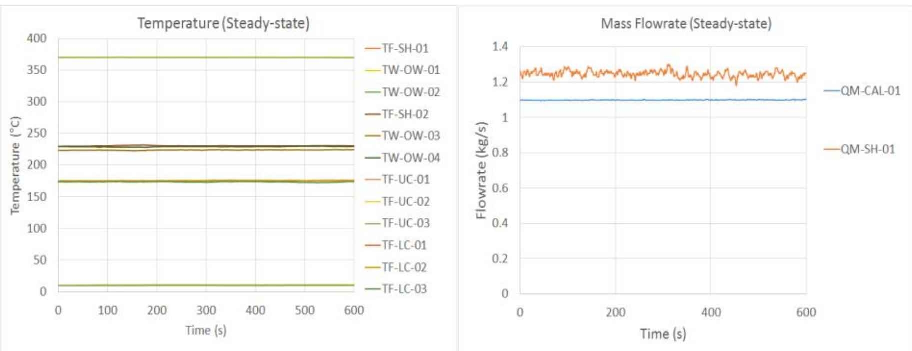

FIG. 4. Temperature and mass flowrate results for 10 min.

TABLE III: OVERALL EXPERIMENTAL RESULTS.

Exp. Results	**Tube-side (sodium)**		**Shell-side (Air)**	
	Inlet	**Outlet**	**Inlet**	**Outlet**
Temperature (℃)	370.1	174.7	10.21	227.7
Mass flowrate (kg/s)	1.142		1.247	
Heat Transfer rate (kWt)	273.86		276.86	

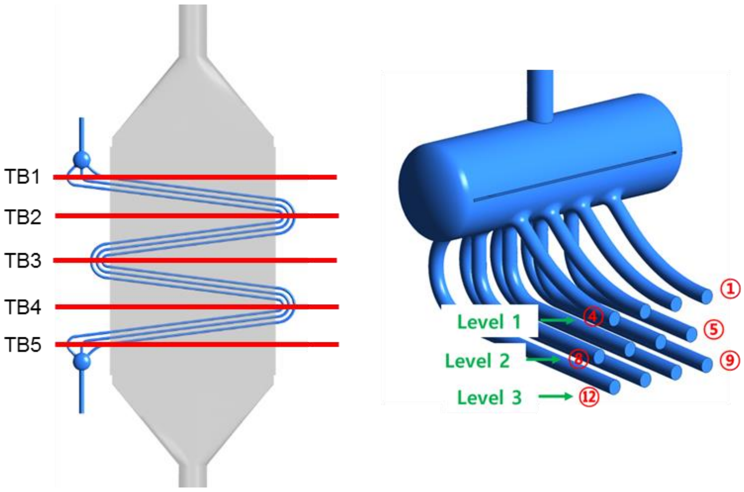

FIG. 5. Sodium tube and location numbering instruction.

TABLE IV: SODIUM TEMPERATURES IN EACH TUBES AT EACH BENDING PARTS.

Tube No.	**Temperature at TB1 (℃)**	**Temperature at TB2 (℃)**	**Temperature at TB3 (℃)**	**Temperature at TB4 (℃)**	**Temperature at TB5 (℃)**
1	370.1	320.5	270.1	223.1	172.7
2	369.5	319.6	270.7	231.8	176.0
3	368.9	319.3	270.9	226.5	178.0
4	365.1	314.2	266.2	222.5	178.8
5	369.4	314.6	273.0	226.6	173.1
6	369.4	318.3	273.4	225.3	173.4
7	368.7	316.9	271.9	223.2	171.9
8	367.9	305.5	257.4	210.3	164.9
9	368.5	310.4	269.1	223.5	176.8
10	368.9	317.2	276.8	224.4	177.2
11	368.1	319.4	273.4	224.4	176.7
12	367.7	312.9	266.0	218.3	174.4
Average	368.5	315.7	269.9	223.3	174.5

Table IV represents sodium temperatures of each tubes between the upper chamber and the lower chamber at every bending location (see FIG. 5). Sodium of no. 8 tube has larger cooling rate than those of others. This tube locates near wall alone, and it means that the air flow around this tube is easier to pass than those around the other tubes (i.e., because of less flow resistance of air). So the tube is available to face much amount of cold air directly and it makes the sodium of this tube show the best cooling performance.

At the case of shell-side air temperature, relatively stagnant air in near wall region show quite big discrepancy with others at the same horizontal plane (see FIG. 6 and Table V). Thermal radiation from hot sodium tubes to the flow guide walls makes the wall heat up. The heated walls make the adjacent air warm up, even though the total amount of heat transfer is very small.

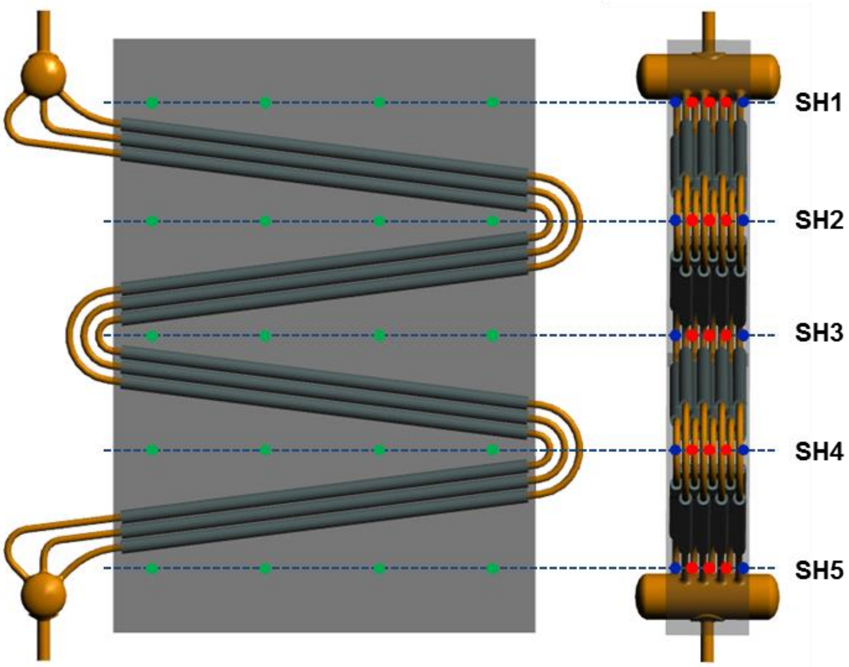

FIG. 6. Measuring points of air (blue: near wall region, red: central region).

TABLE V: LOCAL AIR TEMPERATURES IN EACH PLANES.

Plane No.	**Air. Temp. [°C]**	
	Central Region	**Near Wall Region**
Inlet	10.21	
SH5	11.95	24.51
SH4	76.67	57.57
SH3	139.28	98.98
SH2	190.97	141.97
SH1	239.91	198.66
Outlet	227.74	

3.2. Comparison with Computational Analysis

3.2.1. CFD Analysis

The CFD analysis was previously performed using the commercial code of ANSYS CFX V16.2. A total of 95,896,560 hybrid meshes (hexa + tetra/prism) were generated as shown in FIG. 7. The SST k-w turbulence model and a conjugate heat transfer model were used, and a mass flow rate of 1.10 kg/s at 370 °C in the sodium-side and 1.25 kg/s at 20 °C in the air-side were applied (slightly different with the experiment). FIG. 8 shows the flow velocity and temperature contours from the CFD analysis.

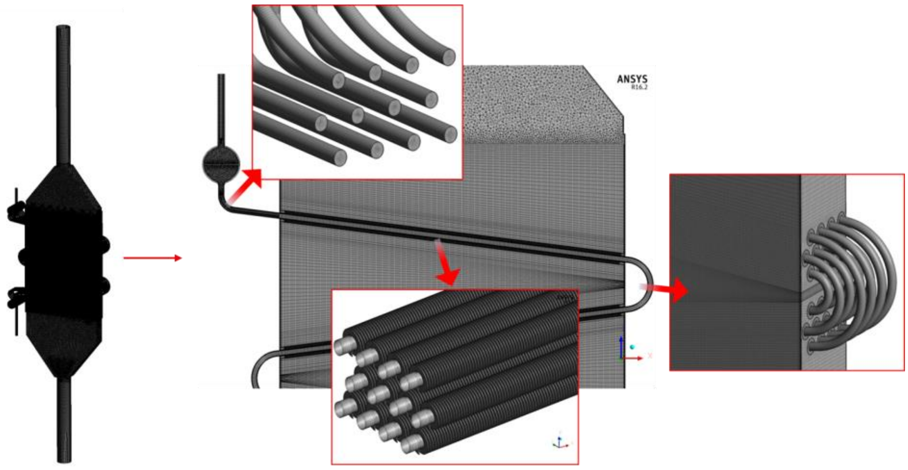

FIG. 7. Mesh generation for the CFD analysis.

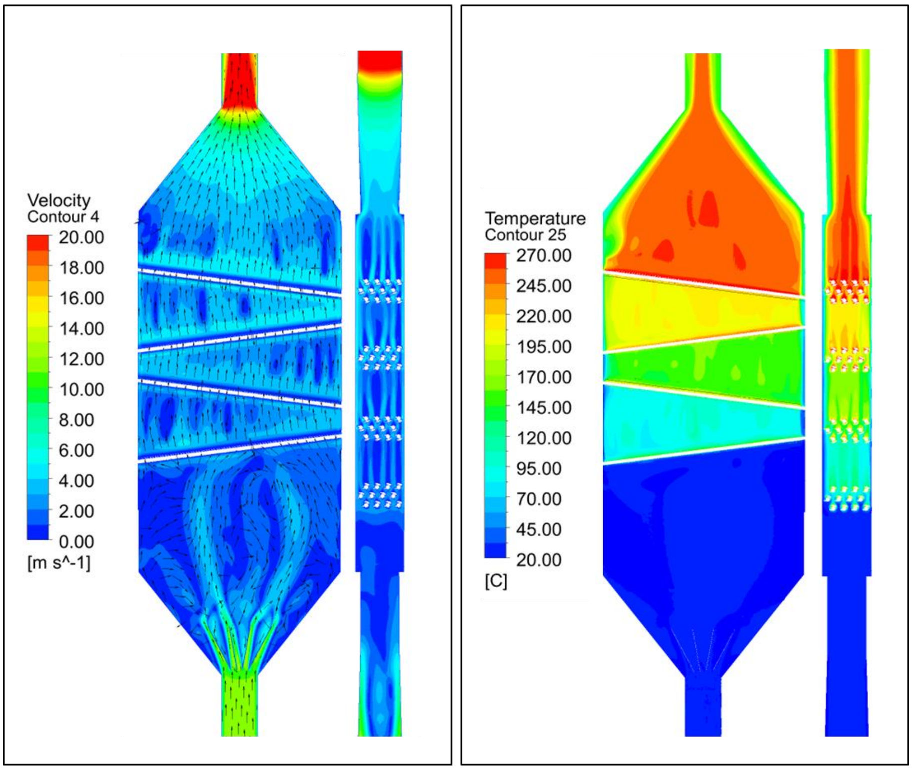

FIG. 8. Flow velocity and temperature contours from the CFD analysis.

3.2.2. Comparison with experimental results

Overall heat transfer rate in CFD analysis shows 252.8 kWt in tube-side and 252.9 kWt in the shell-side. Because intake air temperatures were different as 20 °C in CFD and 10.21 °C in experiment, the case of experiment has larger heat transfer rate than those of the CFD case with a reasonable agreement. FIG. 9 represents sodium temperatures obtained from both the experiment and the CFD analysis. In both cases, sodium temperature tendency of each tubes is similar, but the variation is much smaller in the CFD case. Also, sodium of no. 8 tube has also larger cooling rate in both cases as discussed previously. FIG. 10 shows air temperature increase through the horizontal planes. The comparison results show good agreement each other.

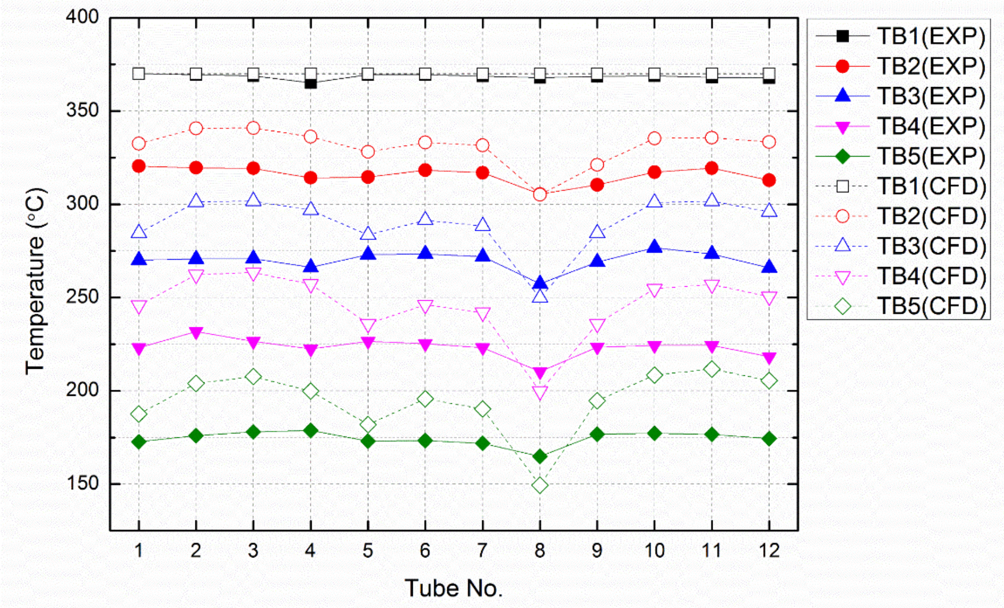

FIG. 9. Sodium temperatures in experiment and CFD.

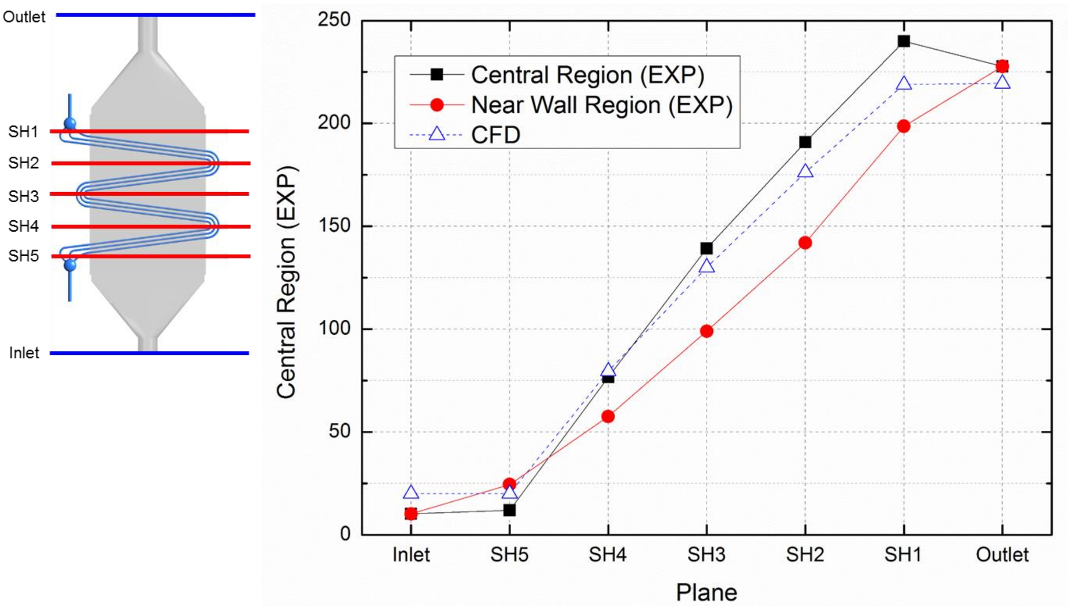

FIG. 10. Air temperatures in experiment and CFD.

4. Conclusion

For a verification of computational codes for a thermal-sizing of the FHX unit and a safety analysis code, a kind of separate effect test facility called SELFA was constructed in 2016. By using this facility, heat transfer performance tests have been in progress to construct experimental database for performance demonstration and design codes V&V for FHX. Here, we reported the first heat transfer performance test including comparison with a CFD analysis. The local temperature distributions of the both-side fluids (i.e., liquid sodium and air) has been reported in this work as well as overall heat transfer rates showed good agreement with representative analytical results. The further analyses and experiments in different conditions are currently in progress.

5. Acknowledgment

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6. References

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