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Numerical Analysis of Flow Distribution in a Sodium Chamber of a Finned-tube Sodium-to-Air Heat Exchanger

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1. Introduction

The design of 150MWe PGSFR (Prototype Gen-IV Sodium-cooled Fast Reactor) has been progressed by the Korea Atomic Energy Research Institute (KAERI). In order to enhance plant safety, reliable Decay Heat Removal Systems (DHRS) with forced- as well as natural-draft sodium-to-air heat exchangers have been considered as an ultimate heat sink.

Basically DHR systems consist of two diverse heat removal loops such as passive and active DHR systems [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, e.g. M-shape and helical-coil type air-coolers. The former is called as an FHX(Forced-draft sodium-to-air Heat Exchanger) and the latter is simply called as an AHX(natural-draft sodium-to-Air Heat Exchanger)[2,3].

In a general sodium-to-air heat exchanger design, convection resistance in a shell-side air flow path becomes dominant factor affecting the mechanism of conjugate heat transfer from the sodium flow inside the tube to the air path across the sodium tube wall. Hence verification of the flow and heat transfer characteristics is one of the most important tasks to demonstrate decay heat removal performance.

To confirm a kind of ultimate heat sink heat exchanger, a medium-scale Sodium thermal-hydraulic Experiment Loop for Finned-tube sodium-to-Air Heat exchanger (here after called the SELFA) has been designed and is recently being constructed at KAERI site. A model FHX unit with multiple columns of M-shape tubes will be installed at SELFA, which has been reasonably scaled-down from the prototype FHX in PGSFR so that local phenomena of the prototype can be well preserved. Various scaling methodologies to make a suitable simulation of single-phase heat transfer with natural circulation of sodium and air have also been implemented.

This paper deals with how the liquid sodium coolant inside the upper sodium chamber flows into each heat transfer sodium tubes, and provides the CFD analysis results regarding the ways to improve flow distribution to make uniform flowrates at each heat transfer tube. The introduction of the flow baffle inside the upper sodium chamber of the model FHX unit in the SELFA facility is briefly proposed and discussed as well.

2. Methods and Results

2.1 Finned-tube Sodium-to-air heat exchanger (FHX)

The FHX is a counter-current flow shell-and-tube type heat exchanger with M-shape tube arrangement. Atmospheric air enters the air inflow duct at the lower part of the unit and flows upward across the finned-tube located in the shell-side FHX. The air is heated as it passes the shell-side region and the heated air is collected Air exhaust path in 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 shape of the FHX unit is shown in Figure 1.

The key design features of the FHX in PGSFR have been preserved in the scaled-down model FHX unit in SELFA, but number of the heat transfer tubes is reduced to 1/8 in the model FHX unit corresponding to the power scale of 1/8[4].

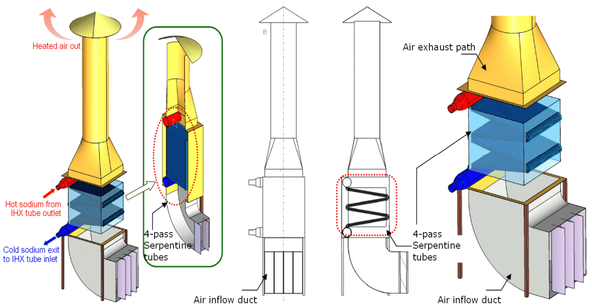


Fig. 1 Typical shape of FHX unit

2.2 Design parameters of the FHX unit in SELFA

The FHX unit in SELFA consists of four-pass serpentine tubes with an inclined angle of 7.2 degree. The tube bank consists of 12 parallel and finned tubes, which are connected to the upper and lower sodium chambers[2]. The tube bundle and each chamber are mounted in a support structure, which allows thermal expansion of each heat transfer tube. Tube-side sodium flows inside the tubes and shell-side air flows across the tube bank. Annular type fins are attached on the outer surface of each bare tube with high-frequency welding method to extend the heat transfer surface area, and the fin effect is well reflected in the thermal sizing code.

A thermal sizing code for designing the FHX was developed by physical models for the tube- and shell-side heat transfer medium, i.e., mass conservations, one-dimensional energy balances, pressure losses, etc. Proper heat transfer correlations for each heat transfer coefficients of sodium-side[5] and air-side[6] have been implemented[2]. The pressure loss terms for each flow medium were obtained for each control volume, which comprises the acceleration, frictional, and gravitational pressure drop elements.

Based on the parameters of the prototype FHX design, the model FHX design in SELFA have been defined as shown in Table I.

Table I: Model FHX design data

Parameter	unit	Nominal value
Number of tubes per FHX	EA	12
Tube arrangement	-	4 passes serpentine tube with [P_L= 2.05] & P_T=2.5]
FHX sodium tube ID	mm	30.7
FHX sodium tube OD	mm	34
FHX sodium tube thickness	mm	1.65
Finned length of each tube	m	2
Fin height	mm	15
Fin thickness	mm	1.5
Inclined tube angle	degree	7.2
Number of Fins per unit length	EA/m	152

2.3 CFD analysis of flow distribution for model FHX

Since the model FHX design is basically performed by using a one-dimensional design approach based on several empirical correlations, the multi-dimensional effect of the heat transfer tube flowrate distribution should be evaluated to confirm the design methodology mentioned previously. To confirm the flow distribution inside the upper sodium chamber in SELFA FHX, CFD analyses for the tube-side sodium flow has been performed by using the commercial code of ANSYS V16.1[7]. The model FHX unit consists of total 12 heat transfer tubes and 2 sodium chambers with connecting heat transfer tube paths. Total 9,000,000 tetra meshes have been implemented as shown in Figure 2. The SST $\kappa-\omega$ equation has been implemented.

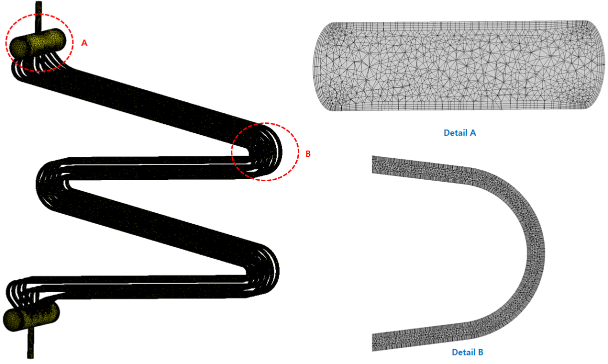


Fig. 2 Mesh planar views at each calculation domain

Two different kinds of inlet boundary conditions have been applied, which are mass flowrates of 0.99 kg/s and 4.38 kg/s with the sodium temperatures of 173°C and 273.7°C, respectively. A typical average static pressure condition has been applied to the outlet of the calculation domain shown in Figure 3. The index of heat transfer tube rows and columns to monitor sodium flowrates are shown in Figure 4.

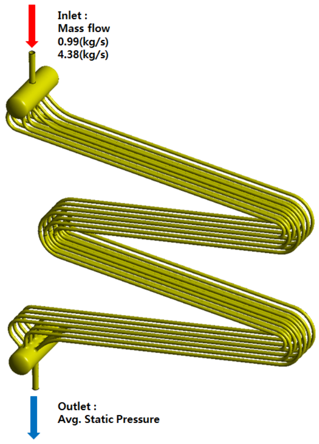


Fig. 3 Applied boundary conditions

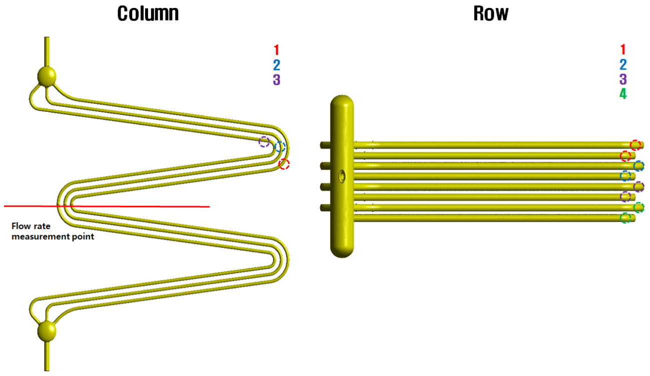


Fig. 4 Index of flowrate monitoring

The CFD analysis to evaluate flowrate distribution for the above two cases have been made. For the results of inlet flow conditions of 0.99kg/s and 4.38kg/s, it was observed that larger sodium flowrates than other heat transfer tubes were obtained at the monitoring point of "column-2/row-2." In both cases, around 34% and 49% higher flowrates than the average values were observed as shown in Table II, and the features are well shown in Figure 5.

Table II. CFD analysis result for flowrate distribution

		Row-1	Row-2	Row-3	Row-4
0.99 kg/s (173°C) w/o baffle	Column-1	0.074 (-10%)	0.082 (-1%)	0.083 (+0%)	0.076 (-7%)
	Column-2	0.091 (+10%)	0.11 (+34%)	0.092 (+12%)	0.076 (-7%)
	Column-3	0.074 (-10%)	0.079 (-5%)	0.080 (-3%)	0.073 (-12%)
4.38kg/s (273.7°c) w/o baffle	Column-1	0.322 (-12%)	0.357 (-2%)	0.359 (-2%)	0.313 (-14%)
	Column-2	0.418 (+15%)	0.545 (+49%)	0.429 (+17%)	0.317 (-13%)
	Column-3	0.306 (-16%)	0.349 (-4%)	0.351 (-4%)	0.314 (-14%)

The result shows that this kind of unequaled sodium flowrate at each heat transfer tube would result in an unexpected heat exchanger performance. Hence, we have introduced a flow baffle inside upper sodium chamber to make uniform flow distribution at each heat transfer tube.

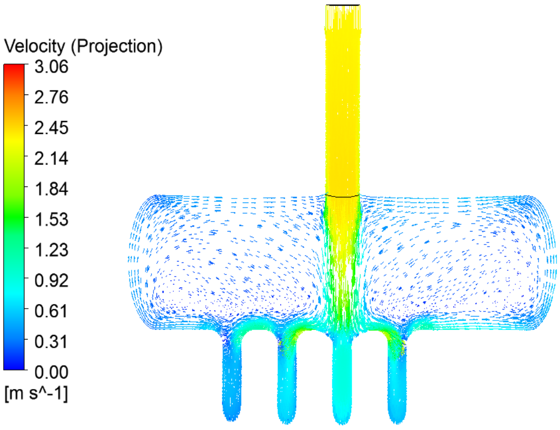


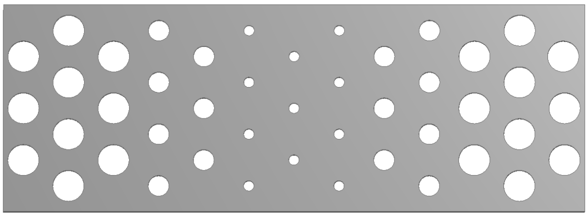
Fig. 5 Vertical velocity contour at Column-2/Row-2 (inlet mass flowrate of 4.38kg/s)

2.4 CFD analysis of flow distribution for model FHX (with a flow baffle)

Perforated flow baffle with a 5mm flat plate has been installed inside the upper sodium chamber of the model FHX unit, which consists of 10 holes with 10ϕ and 14 holes with 20ϕ, and 20 holes with 30ϕ as shown in Figure 6.

Total 9,300,000 tetra meshes including flow baffle strucutr have been implemented as shown in Figure 7. The SST κ–ω equation has been also implemented.

Fig. 6 Geometry of the perforated flow baffle



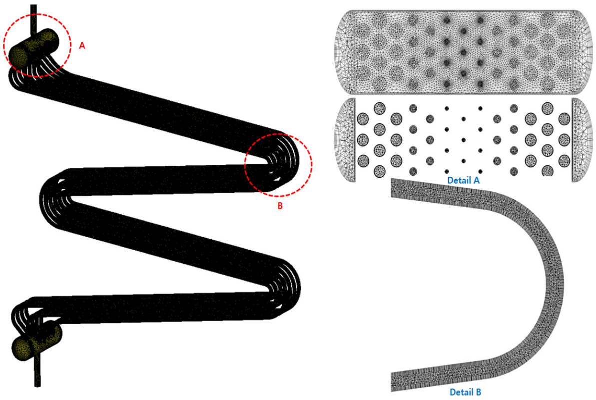


Fig. 7 Mesh planar views at each calculation domain (with a flow baffle)

The CFD analysis to evaluate flowrate distribution for the two cases defined in Section 2.3 have been also made. For the results of inlet flow conditions of 0.99kg/s and 4.38kg/s, it was observed that the discrepancies of sodium flowrates at the identical monitoring point of “column-2/row-2” are drastically decreased at around 1/10 of the cases without a flow baffle. The quantitative values of the discrepancies for both cases were respectively obtained at around 3.9% and 4.9% as shown in Table III. This is mainly because the flow baffle structure installed inside the upper sodium chamber prevents the direct inflow into the closest heat transfer tube facing the inlet sodium pipe connecting to the upper sodium chamber, which results in more equalized flowrates at all heat transfer tubes of the model FHX unit. The features are also shown in Figure 8.

Table III. CFD analysis result for flowrate distribution (with a flow baffle)

		Row-1	Row-2	Row-3	Row-4
0.99 kg/s (173°C) with baffle	Column-1	0.084 (+2%)	0.083 (+1%)	0.083 (+0%)	0.083 (+1%)
	Column-2	0.083 (+0%)	0.083 (+4%)	0.082 (+0%)	0.083 (+1%)
	Column-3	0.081 (-2%)	0.080 (-3%)	0.080 (-3%)	0.081 (-2%)
4.38kg/s (273.7°c) with baffle	Column-1	0.374 (+3%)	0.369 (+1%)	0.365 (+0%)	0.372 (+2%)
	Column-2	0.364 (+0%)	0.383 (+5%)	0.362 (-1%)	0.367 (+1%)
	Column-3	0.362 (-1%)	0.352 (-4%)	0.351 (-4%)	0.359 (-2%)

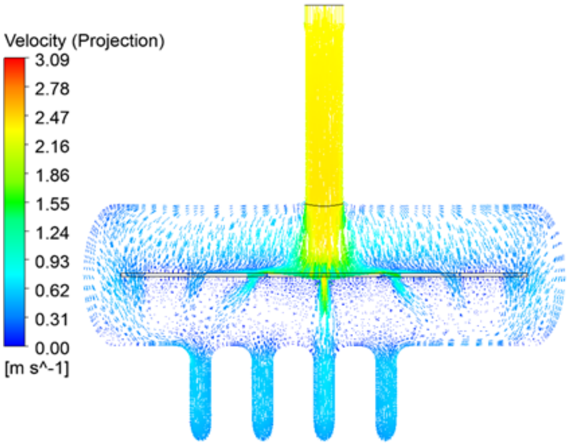


Fig. 8 Vertical velocity contour at Column-2/Row-2 (inlet mass flowrate of 4.38kg/s with a flow baffle)

3. Conclusions

The present study aims at introducing a flow baffle design inside the upper sodium chamber to make more equalized flowrates flowing into each heat transfer tube of the model FHX unit. In the cases without the flow baffle geometry, it was observed lager discrepancies in flowrates at the heat transfer tubes. However it was also found that those kinds of discrepancies could be definitely decreased at around 1/10 by employing a flow baffle. As a result, in order to have more equalized flowrates at all heat transfer tubes, it was recommended to use a flow baffle structure inside the upper sodium chamber of the model FHX unit in SELFA.

ACKNOWLEDGEMENT

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