Performance Evaluation in Sodium-to-Sodium Heat Exchangers in STELLA-2

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1. Introduction

The Korea Atomic Energy Research Institute (KAERI) is carrying out the design of a "Prototype Gen IV Sodium-cooled Fast Reactor (PGSFR) [1]" in cooperation with Argonne National Laboratory (ANL) in the US. In regard to computer code V&V, a large-scale sodium thermal-hydraulic test program, which is called Sodium Test Loop for Safety Simulation and Assessment (STELLA), is currently being progressed in parallel with the PGSFR design. The final objective of this program is to collect a separate and integral effect test database to validate the safety analysis codes and other thermal hydraulic design codes.

The program aiming at an integral effect test is called STELLA-2, which will be used for synthetic review of the key safety issues of PGSFR. The basic and detailed design phases of the STELLA-2 test facility are underway in accordance with the specific design requirements reflecting the whole design features of PGSFR. Based on the STELLA-2 platform, a simulation of the PGSFR transient will be made to evaluate the plant dynamic behaviors and demonstrate the decay heat removal performance. The multi-dimensional effects coming from a large sodium pool system will be identified as well.

Among several components of STELLA-2, there are five different types of model heat exchangers such as IHX, DHX, FHX, AHX, and UHX. Each heat exchanger has different characteristics, and it is very important to verify the heat transfer and pressure drop performance in each heat exchanger.

In this paper, the CFD analyses of the sodium-to-sodium heat exchangers (IHX, DHX) are performed, and these results are compared with the heat exchanger design codes results. Also, the differences of pressure drop according to the hole shape of the baffle plate in each heat exchanger are compared.

2. Methods and Results

2.1 IHX and DHX units

The IHX unit is a shell-and-tube counter-current flow heat exchanger with a straight tube arrangement. Hot sodium from the core enters the shell-side inlet windows at the upper part of the unit and flow downward across the straight-tubes located in the tube-side. Cold sodium from IHTS passes through the lower chamber and tube inside. And the heat transfer takes place between the shell and tube side of IHX. The typical shape of the IHX unit is shown in Figure 1. The IHX unit consists of 156 straight tubes, which are connected to the upper coaxial pipe and lower sodium chamber.

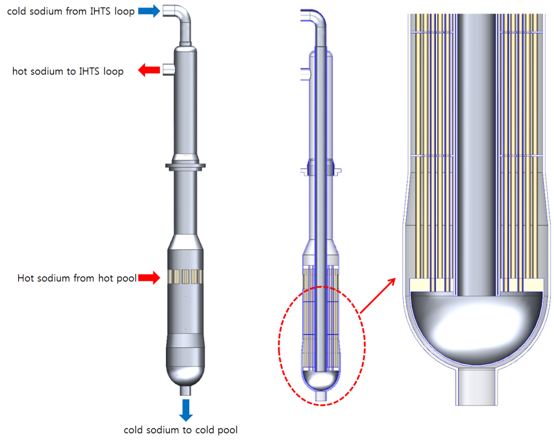

Fig. 1 Typical shape of IHX unit

The DHX unit is a shell-and-tube counter-current flow heat exchanger with a straight tube arrangement. Hot sodium from the cold pool enters the shell-side inlet windows at the upper part of the unit and flow downward across the straight-tubes located in the tube-side. Cold sodium from the DHRS passes through the lower chamber and tube inside. And the heat transfer takes place between the shell and tube side of DHX. The typical shape of the DHX unit is shown in Figure 2. The DHX unit consists of 12 straight tubes, which are connected to the upper coaxial pipe and lower sodium chamber.

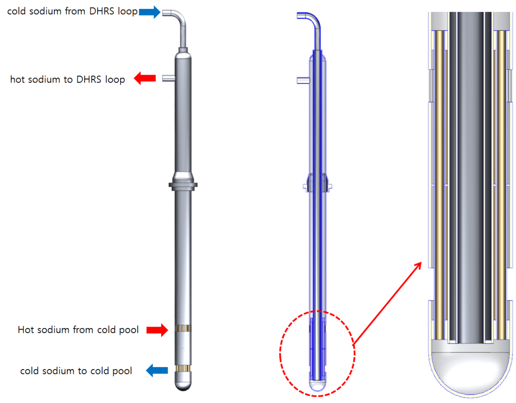

Fig. 2 Typical shape of DHX unit

2.2 CFD analysis for the IHX unit

Since the model IHX design is basically performed by using a one-dimensional design approach based on several empirical correlations, the multi-dimensional effect should be evaluated to confirm the design methodology mentioned previously. In order to evaluate the suitability of the IHX design code, CFD analysis for IHX is performed by using the commercial code of ANSYS V16.1[2]. Total 48,789,108 hybrid meshes (tetra + hexa) are implemented as shown in Figure 3. The SST k-w turbulence model and conjugate heat transfer model are applied.

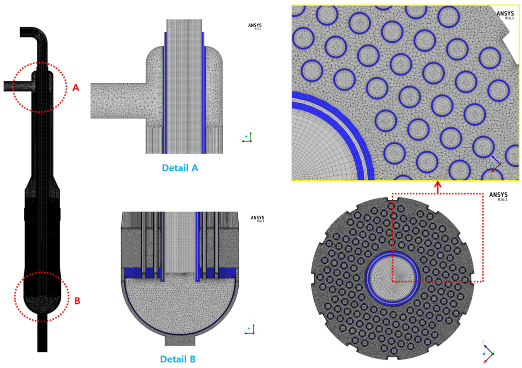

Fig. 3 Mesh planar views at IHX unit

The mass flow rate of 6.7 kg/s with 323.0 ^{o}C at tube-side and 8.91 kg/s with 545.0 ^{o}C at shell-side are applied to the inlet boundary condition. Also a typical relative pressure condition is applied to the outlet boundary condition as shown in Figure 4.

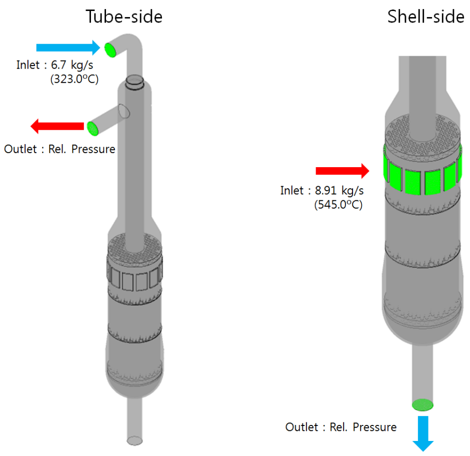

Fig. 4 Applied boundary conditions at IHX unit

The comparison of heat transfer performance between 1-D code and CFD analysis are provided in Table 1[3]. The difference of the heat transfer rate between both cases is about 7.5%. It was also found that unexpected bypass flow in the shell-side IHX unit gave rise to a discrepancy. However, the difference of the pressure drop between both cases is very large. This difference seems to be due to the multi-dimensional effect

Table I: Comparison of Heat transfer performance for IHX

	Exit Temperature (^{o}C)		Pressure Drop (Pa)		Heat Transfer (MW)
	Shell-side	Tube-side	Shell-side	Tube-side	
1-D approach	389.8	527.9	2655	978	1.76
CFD Results	392.9	524.2	9410	1446	1.62
% difference	+0.7%	-0.7%	+254.4%	+47.9%	-7.5%

2.3 CFD analysis for the DHX unit

CFD analysis for DHX is performed by using the commercial code of ANSYS V16.1[2]. Total 4,928,709 hybrid meshes (tetra + hexa) are implemented as shown in Figure 5. The SST k-w turbulence model and conjugate heat transfer model are applied.

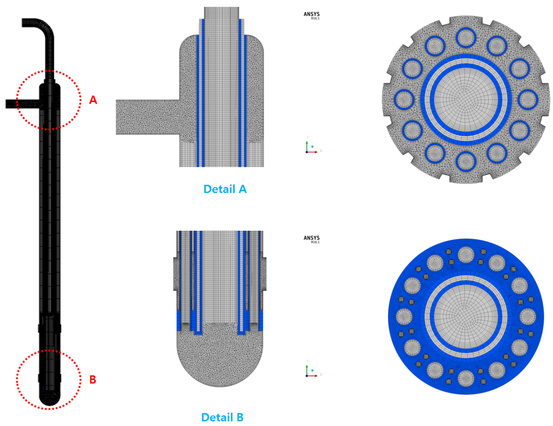

Fig. 5 Mesh planar views at DHX unit

The mass flow rate of 0.314 kg/s with 226.2 ^{o}C at tube-side and 0.228 kg/s with 390.0 ^{o}C at shell-side are applied to the inlet boundary condition. Also, a typical relative pressure condition is applied to the outlet boundary condition as shown in Figure 6.

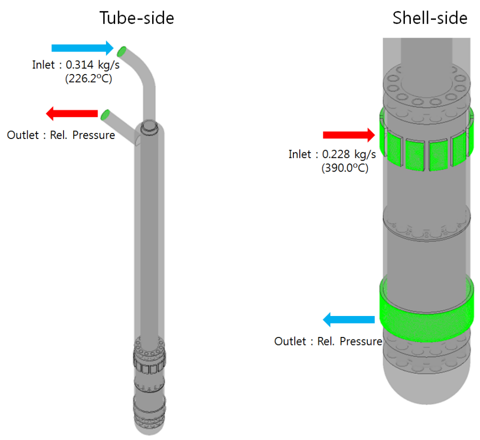

Fig. 6 Applied boundary conditions at DHX unit

The comparison of the heat transfer performance between 1-D code and CFD analysis are provided in

Table 2[4]. The difference of the heat transfer rate between both cases is about 7.3%. Such as IHX, it was also found that unexpected bypass flow in the shell-side DHX unit gave rise to a discrepancy. However, the difference of the pressure drop between both cases is also very large as the case of IHX.

Table II: Comparison of Heat transfer performance for DHX

	Exit Temperature (°C)		Pressure Drop (Pa)		Heat Transfer (kW)
	Shell-side	Tube-side	Shell-side	Tube -side	
1-D approach	239.5	334.7	~100	~100	44.73
CFD Results	245.4	332.7	227.3	70	41.47
% difference	+2.4%	-0.6%	+127.3%	-30%	-7.3%

2.4 CFD analysis of Shell-side Pressure drop for improvement design

As aforementioned, the pressure drop between 1-D and CFD analysis seems to be large difference in IHX and DHX. Most of the pressure drop in the shell side of both heat exchangers is due to the baffle plate for supporting the tube. Thus, it is necessary to evaluate the pressure drop change in accordance with the shape of the baffle plate hole. Since the sharp edge of the baffle plate hole exerts a significant effect on the pressure drop characteristics, the pressure drop according to the change of the edge fillet radius is evaluated. The edge fillet radius is defined by the dimensionless number as shown in Eq. (1).

$$\psi = \frac{r_{edge}}{\phi_{hole}} \qquad (1)$$

The fillet size of the baffle plate holes in DHX and IHX is shown in Table 3.

Table III: Fillet size of baffle plate holes in DHX and IHX

Ψ	Case	Inflow edge size (mm)	Outflow edge size (mm)
0	Sharp-edge	0.0	0.0
0.04	Inlet-face fillet only	0.2	0.0
	Both-face fillet	0.2	0.2
0.08	Inlet-face fillet only	0.4	0.0
	Both-face fillet	0.4	0.4
0.12	Inlet-face fillet only	0.6	0.0
	Both-face fillet	0.6	0.6
0.16	Inlet-face fillet only	0.8	0.0
	Both-face fillet	0.8	0.8
0.20	Inlet-face fillet only	1.0	0.0
	Both-face fillet	1.0	1.0

The geometry of the baffle plate in DHX and IHX is shown in Figure 7, and 8. The sodium passes through the small hole between the heat transfer tubes. The pressure drop of the baffle plate according to the change of ψ is evaluated. The analyses are performed for each case which the single (upper) sharp edge is filleted and the double (upper/lower) sharp edges are filleted as shown in Figure 10.

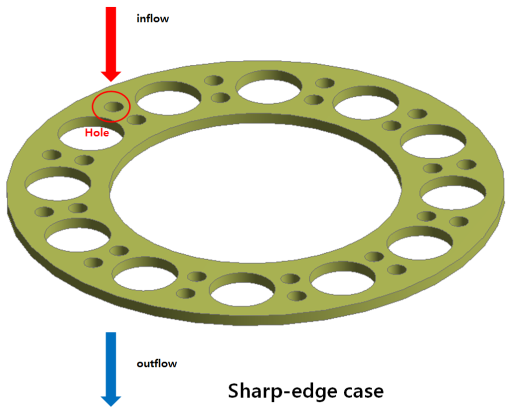

Fig. 7 The shape of baffle at DHX unit

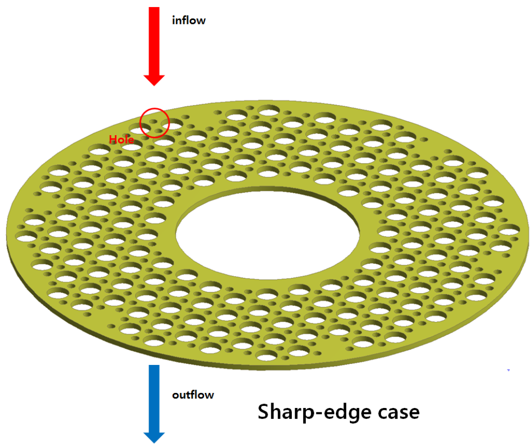

Fig. 8 The shape of baffle at IHX unit

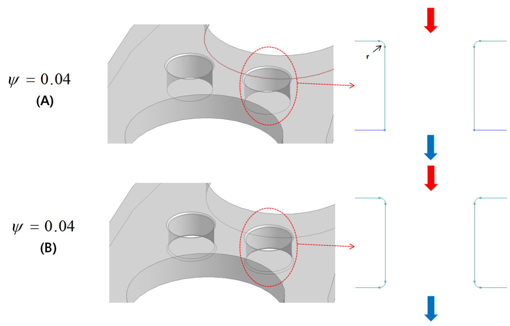

Fig. 9 Two cases of baffle edge fillet shape

(1) DHX

The pressure drop evaluation results in DHX are shown in Figure 10. As ψ is decreased, the pressure drop is decreased. Also, the pressure drop of a case which the double sharp edges are filleted is larger than the single sharp edge. The difference of the maximum/minimum pressure drop in these cases is almost 44%.

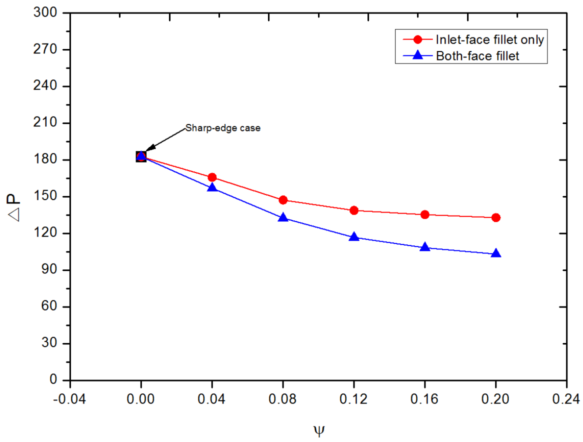

Fig. 10 The Graph of pressure drop with increasing size of fillet with two types at DHX unit

(2) IHX

The pressure drop evaluation results in IHX are shown in Figure 11. Analysis results of IHX seem to be a similar trend with DHX. As ψ is decreased, the pressure drop is decreased. Also, the pressure drop of a case which the double sharp edges are filleted is larger than the single sharp edge. The difference of the maximum/minimum pressure drop in these cases is almost 52%. As a result, the influence of the fillet appears to be larger in IHX.

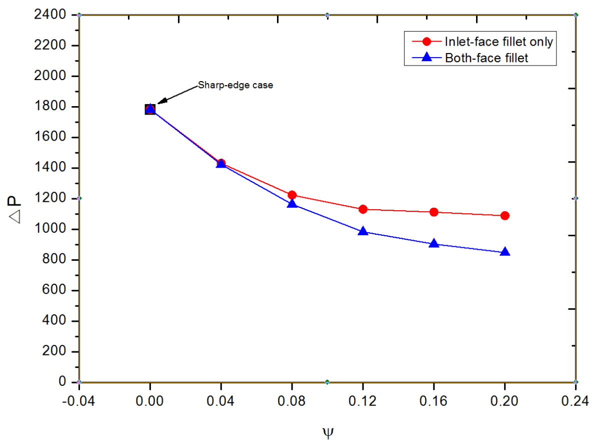

Fig. 11 The Graph of pressure drop with increasing size of fillet with two types at IHX unit

3. Conclusions

The performance evaluation of the sodium-to-sodium heat exchangers (IHX and DHX) in STELLA-2 is performed using CFD. Also, these results are compared with 1-D heat exchanger design code. The shell/tube outlet temperature and heat transfer rate of the heat exchanger obtained by the CFD is not significantly different from the result obtained by the 1-D code. However, the pressure drop is significantly different. Most of the pressure drop in the shell side of both heat exchangers is due to the baffle plate for supporting the tube. Thus, it is performed to evaluate the pressure drop change in accordance with the shape of the baffle plate hole. As a result, the pressure drop due to the sharp edge of the baffle plate hole seems to be very large. Also, it is confirmed that the pressure drop can be reduced by filleting the sharp edge of the baffle plate hole.

ACKNOWLEGEMENT

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