A preliminary study on steam generator sizing for the sodium-cooled fast reactor KALIMER-600

Jin Su Kwon[a], Jeong Ik Lee[a,*], Sang Ji Kim[b]
[a]*Department of Nuclear and Quantum Engineering, Korea Advanced Institute of Science and Technology, 373-1 Guseong-dong Yuseong-gu,Daejeon 305-701, Republic of Korea*

[b]*Korea Atomic Energy Research Institute*
150 Dukjin-dong, Yuseong-gu, Daejon 305-353, Republic of Korea

[*]*Corresponding author: jeongiklee@kaist.ac.kr*

1. Introduction

As a part of the development of the generation IV nuclear power plant, the sodium-cooled fast reactor (SFR) is being considered as one of the most promising future reactor concepts due to high system efficiency, a low proliferation risk, and reusing the stored spent fuels from conventional water-cooled thermal reactors [1]. With the abovementioned purposes, Korea Atomic Energy Research Institute (KAERI) started to develop SFR technologies and conducted a conceptual design of the mid-sized SFR KALIMER-600. It is a fast neutron spectrum reactor designed for 600MWe electricity generation capacity. KALIMER-600 is a pool-type reactor and uses liquid sodium as a coolant in the primary and intermediate side [2].

On the other hand, sodium can readily react with various substances due to its high chemical activity, which may cause difficulty in safety and economic improvement. One of the components that is likely to experience a sodium-water reaction accident is the steam generator. Hence, selecting an appropriate heat exchanger type for the steam generator is important to maintain the reactor system integrity. Steam generators have been developed in many forms, such as U-shaped, J-shaped, straight tube, and helical tube, but the basic consideration is thermal expansion of the material. The U type steam generator has been widely used in light-water reactors; however, the flow path of sodium in the shell is complicated and this type is rarely used. The straight type steam generator, which is shown in Figure 1, is simple to manufacture and small in size. However, there is a problem that the thermal expansion difference between the bundle of tubes and the shell must be absorbed. To overcome these problems, the helical type steam generator was adopted as the steam generator of KALIMER-600. Even helical type steam generator can solve the thermal expansion differences, the difficulty in manufacturing still remains since it requires 65 ~ 100 m length of the tube [3].

Recently, a Printed Circuit Steam Generator (PCSG), which is a Printed Circuit Heat Exchanger (PCHE) type steam generator, has been studied to improve the safety and economics of the advanced nuclear system. The inherent structural rigidity of PCHE, which is shown in Figure 2 [4], is originated from the nature of manufacturing. PCHE is assembled by stacking the multiple chemical-etched plates and diffusion bonded together under high temperature and pressure. It is significantly compact and has a large heat transfer area due to the micro-sized semi-circular channel.

Although it is not easy to make precise comparisons due to the limited information for PCSG, the studies for understanding the characteristics of each heat exchanger are required through a rough comparison. Therefore, the objective of this study is designing the PCSG and straight tube type steam generator for application on KALIMER-600 and comparing with the existing designed helical type steam generator.

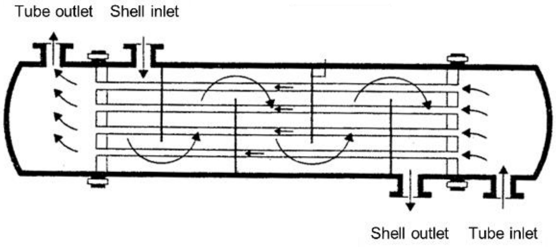

Figure 1. Schematic diagram of a straight type heat exchanger

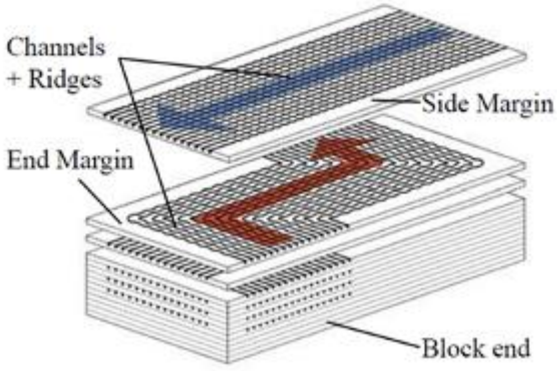

Figure 2. Schematic diagram of PCHE plates [4]

2. Methods and Results

2.1 Heat exchanger design scheme

The conventional heat exchanger analysis methods including log mean temperature difference method

(LMTD) and ε-NTU method may produce errors for steam generator performance evaluation due to a substantial change of heat transfer coefficient in the 2-phase regime. It leads to developing the PCSG analysis tool that solves energy and momentum governing equations by considering the variable properties. The calculation proceeds on the unit channel, which represents the whole heat exchanger. The heat transfer rate can be obtained by the thermal resistance analysis considering convective and conduction resistance. By using the above method, the amount of heat transfer in one control volume can be calculated and given by the following equation.

$$Q = UA\Delta T = \frac{1}{\frac{1}{h_{hot}A} + \frac{t}{h_{conduction}A} + \frac{1}{h_{cold}A}}\Delta T \qquad (1)$$

The friction factor in the control volume can be obtained from the correlation and the pressure drop is calculated. The frictional pressure drop is expressed by the below equation.

$$\Delta P = f\frac{L}{D_e}\frac{\rho v^2}{2} \qquad (2)$$

Accordingly, the temperature of the fluid in the second control volume is obtained by considering the enthalpy change in the first control volume, and the pressure is obtained from the pressure drop of the first control volume. The above calculation continues from the cold side inlet to the cold side outlet. The heat exchanger is usually designed as counter-current type, the hot side outlet should be assumed first to calculate the first control volume corresponding to the cold side inlet. If the calculated hot side inlet results do not match the predetermined temperature and pressure boundary conditions at the hot side inlet, the iterative process proceeds until the updated value is the same as the previous value. The flow diagram of the heat exchanger design method is shown in Figure 3. This scheme is well validated with the results of the KAIST experimental facility [5]. Therefore, the results of this scheme with 100 control volumes are used as the reference data.

2.2 Implemented correlations

For the sodium side, a simple heat transfer coefficient correlation was developed based on empirical data studied in the fully developed turbulent regime. This correlation is well suited in the turbulent region [6]. When it comes to the frictional factor correlation, the Colebrook-White equation was used since this correlation matches the experimental data the best and it is also applicable to liquid-metal fluid [7].

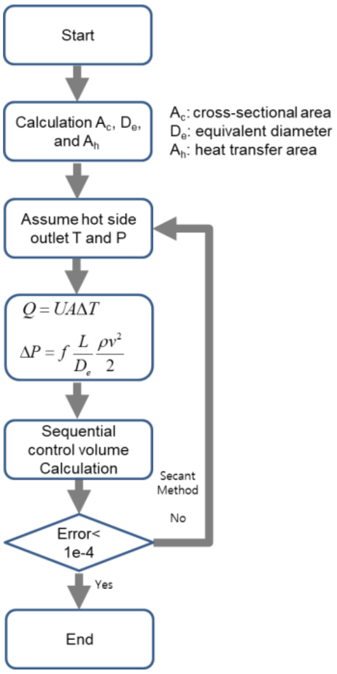

Figure 3. Flow chart of heat exchanger design scheme

For the water-steam side, the steam generator for KALIMER-600 experiences boiling regimes including nucleate boiling, dryout, post-dryout boiling since it is designed to produce superheated steam. It means adequate two-phase correlations should be implemented at each boiling regimes. Most of the correlations come from the latest nuclear system analysis code TRACE developed by U.S.NRC. TRACE provides theory manual as an open access, and manual contains various correlations and the rationale. More detailed information is provided in TRACE theory manual [8]. It is noted that correlations from TRACE are developed under the macro-sized circular tube so that it may not be suitable for the micro-sized semi-circular channel that typically PCSG has. However, many of these correlations were applied to the PCSG design scheme since the purpose of this study is to understand the characteristics of each heat exchanger roughly. The summarized correlations, which are applied to the steam generator design scheme, are suggested in Table I.

2.3 Design condition of the steam generator

Design conditions of KALIMER-600 steam generator, which are shown in Table II, were obtained from KAERI report. The inlet temperature, pressure, and mass flow rate are boundary conditions for the study. In order to compare the size of the heat exchanger, the same heat duty and similar pressure drop constraints are given. However, since the pressure drop on the water side is significant in the helical type steam generator, the pressure drop of 100 kPa was given in cases of PCSG and straight type steam generator.

When designing the PCSG, sodium side channel diameter is fixed at 5 mm to relieve the fouling effect and smoothly drain the sodium in the event of an accident. The optimized heat exchanger can be obtained by adjusting the geometry parameters such as water side channel diameter, channel length, and the number of channels to match the target heat duty and pressure drop. It is noted that PCSG uses the straight flow path with the semi-circular cross-sectional area.

In the case of straight type shell and tube heat exchanger, liquid sodium and water are allocated to shell and tube respectively. The tubes in a heat exchanger are arranged in hexagonal array to make it more compact. Similar to designing the PCSG, the optimized heat exchanger can be obtained by parametric study with water side channel diameter, channel length, the number of channels, and the pitch between channels.

2.4 Steam generator design results

The parametric study results of PCSG presented in Figure 4 show that the volume of the steam generator is minimized when the channel diameter is 1.75 mm under the same heat duty and pressure drop condition. It indicates that the optimum volume exists, and smaller diameter channel does not guarantee compact heat exchanger. Comparing with the existing helical type steam generator, the PCSG volume is almost one-fortieth of that. PCSG is attractive in the view of compactness. As shown in Figure 4, the volume of PCSG does not monotonically increase with channel diameters when comparing with the straight type steam generator case. It can be inferred that the relative increase in the channel diameter is different between them.

For the straight type steam generator, the optimum volume does not exist for channel diameter as shown in Figure 5. The volume of steam generator decreases when channel diameter decreases. It means the volume of straight type steam generator can be reduced until there is a manufacturing problem. However, the biggest problem that can be caused by decreasing the diameter of the heat exchanger is economics. As shown in Figure 5, the number of channels increases sharply as the diameter of the channel decreases. In a shell and tube heat exchanger, the tubesheet and tube are to be welded at each end of the heat exchanger. In this case, when the number of channels is large, the amount of welding is increased and it leads to the cost increase. Consequently, the optimized straight steam generator volume was chosen to be at a position right before the number of channels increased sharply, which is the value at the channel diameter is 8 mm. The volume of straight channel steam generator is 21.5 m^3 and it is one-tenth of helical type steam generator.

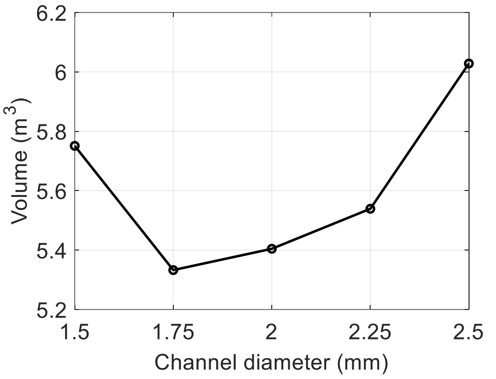

Figure 4. PCSG volume versus channel diameter

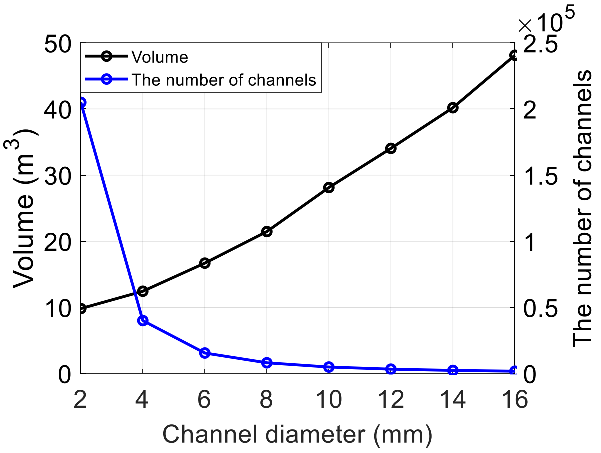

Figure 5. Straight type steam generator volume and the number of channels versus channel diameter

Table II: Comparison of designed steam generators

	PCSG (without header)	Straight (without header)	Helical (with header)
Heat duty [MW$_t$]	764.45		
Number	2		
Primary Side			
Mass flow rate [kg/sec]	2900.3		
Inlet temperature [°C]	526		
Outlet temperature [°C]	319.9	319.9	320
Inlet Pressure [MPa]	2.5		
Pressure drop [kPa]	38.5	41.9	40.6
Secondary Side			
Mass flow rate [kg/sec]	331.6		
Inlet temperature [°C]	230		
Outlet temperature [°C]	507.6	507.5	503.1
Inlet Pressure [MPa]	17.62		
Pressure drop [kPa]	100	99	1120
Geometry			
Volume [m^3]	5.3	21.5	232.4
Height [m]	1.4	16.6	17.6
Channel diameter [mm]	1.75	8	16

3. Summary and conclusions

The preliminary evaluation of steam generator size in the sodium-cooled fast reactor was conducted. The results show that PCHE type steam generator is the most compact steam generator compared to the straight channel steam generator and helical type steam generator. It can be further studied by considering the appropriate heat transfer and frictional correlations on PCSG two-phase regimes.

ACKNOWLEDGEMENTS

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean Government (MIST). (No. 2018M2A8A4081307)

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Table I: Summarized correlations for the steam generator design scheme

Single phase	Sodium		Lubarsky's correlation $Nu = 0.625Pe^{0.4}$ Colebrook-White $\frac{1}{\sqrt{f_d}} = -2\log\left(\frac{\varepsilon}{3.7D_h} + \frac{2.51}{\mathrm{Re}\sqrt{f_d}}\right)$
	Water, steam	PCSG	Baik's correlation $Nu = 0.2829\,\mathrm{Re}^{0.6686} \quad f_f = 6.9982\,\mathrm{Re}^{-0.766}$
		Straight	Gnielinski $Nu = \frac{\left(\frac{f}{8}\right)(\mathrm{Re}-1000)\mathrm{Pr}}{1+12.7\left(\frac{f}{8}\right)^{0.5}(\mathrm{Pr}^{\frac{2}{3}}-1)} \quad f = \left(0.79\ln(\mathrm{Re})-1.64\right)^{-2}$ Colebrook-White
Two-phase	ONB		MARS-KS $T_{ONB} = T_{sat} - 0.001$
	Nucleate boiling		TRACE
	CHF		CHF lookup table 2006
	Inverted annular film boiling		TRACE
	Inverted slug film boiling		TRACE
	Dispersed flow film boiling		TRACE
	Void fraction		Lockhart-Martinelli $X^2 = \left(\frac{\mu_f}{\mu_g}\right)^{0.2}\left(\frac{x_f}{x_g}\right)^{1.8}\left(\frac{\rho_g}{\rho_f}\right) \quad \alpha = 1 - \frac{X}{\left(1+20X+X^2\right)^{0.5}}$