Modeling and Analysis of Finned-tube-type Heat Exchangers Using GAMMA+

Hanna Kim [a], Huije Choo [a], Jiyun Oh[a], Gyeongseo Im[a] Yong-Hoon Shin [b], and Hyungmo Kim [a*]
[a] *School of Mechanical Engineering, Gyeongsang National Univ., 501, Jinju-daero, Jinju*
[b] *Korea Institute of Energy Research, 111, Daedeok-Daero, Yuseong-Gu, Daejeon*
[*] *Corresponding author: hyungmo@gnu.ac.kr*

***Keywords :** sodium heat exchanger, gamma+, heat exchanger performance, STELLA-2

1. Introduction

As climate change intensifies, interest in achieving carbon neutrality has significantly increased, bringing nuclear power generation into the spotlight. Among the innovative Generation IV reactors designed to maximize resource utilization, ensure long-term energy supply stability, reduce nuclear waste, and enable safer operation, the Sodium-cooled Fast Reactor (SFR) stands out for its high efficiency and enhanced safety. Sodium heat exchangers are crucial in these systems, facilitating heat exchange between various reactor subsystems to ensure stable and efficient operation while preventing overheating during emergencies. Evaluating the performance of these heat exchangers is essential for enhancing the safety and reliability of SFRs.

The STELLA-2 system includes five types of simulation heat exchangers, with the Finned-Tube-Type Sodium-to-Air Heat Exchanger (FHX) being a key component in the Decay Heat Removal System (DHRS). This paper aims to evaluate the performance of the FHX within the STELLA-2 system using the GAMMA+ code by comparing experimental results under steady-state conditions. Experimental data and heat exchanger design drawings were provided by Korea Atomic Energy Research Institute (KAERI) to support this evaluation. This analysis will provide fundamental data for verifying the performance of sodium heat exchangers and contribute to optimizing the stability of SFRs.

2. Methods and Results

GAMMA+ is a system transient and safety analysis code developed by KAERI. It has been extensively applied to High-Temperature Gas-cooled Reactors (HTGR) systems [2]. The code has been validated through numerous domestic and international projects, demonstrating its reliability in analyzing complex reactor systems. GAMMA+ has shown excellent performance in analyzing the thermal-hydraulic phenomena of SFRs, making it an indispensable tool for safety assessment and design verification.

2.1 Finned-tube-type Sodium-to-Air Heat Exchanger (Forced-draft Sodium-to-air Heat Exchanger, FHX)

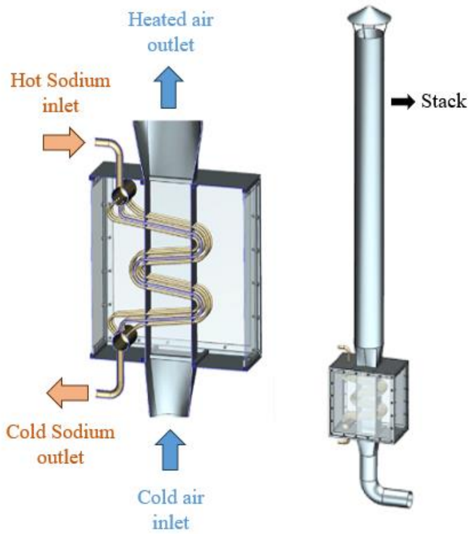

Fig. 1. FHX Configuration and Flow Path

The FHX is a horizontal straight-tube heat exchanger designed to maximize the contact area with air using finned tubes. To accommodate the thermal expansion and contraction caused by high and low temperature sodium coolant during system operation, the tubes include bending sections in the middle. The FHX is a shell-and-tube type heat exchanger, connected to horizontal cylindrical sodium chambers at both the top and bottom, and features a 4-pass serpentine tube layout with three U-bends. Although FHX is an active means of heat removal, it is also designed to have the capability of passive heat transfer by natural circulation. Therefore, the stack (shell-side outlet) is designed to have enough height for natural circulation flow. Heated sodium enters the high-temperature sodium chamber of the FHX through the hot leg of the Active Decay Heat Removal System (ADHRS), is distributed into each sodium tube, and flows downward, being cooled by countercurrent air flow. External air is supplied to the finned tube bundle through air intake ducts at the bottom of the FHX. It then moves upward along the air passages, cooling the finned tube bundle, and the heated air is discharged into the atmosphere through the air outlet ducts. Fig. 1 summarizes the air and sodium heat exchange paths within the FHX [1].

2.2 GAMMA+ 1-D Analysis and Results

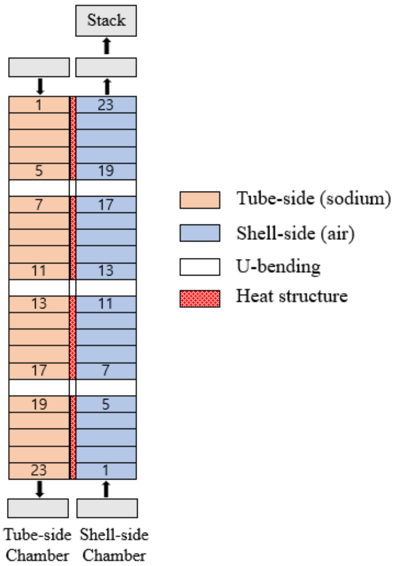

Fig. 2. 1-D Modeling of the FHX

Referring to the actual STELLA-2 design drawings provided by KAERI, we performed 1-D modeling of the FHX, as shown in Figure.2. The 1-D modeling simplifies each component to simulate heat transfer and fluid flow. Figure.2 illustrates the simplification of the complex system into blocks, including finned heat transfer tubes, upper and lower sodium chambers, upper and lower air ducts, and an air stack. This approach allows for accurate prediction of the heat exchanger's performance and analysis of its behavior under various operational conditions [2].

Table I: Experiment and GAMMA+ Input data

	Exp	GAMMA+
Sodium inlet temp[K]	353.680	353.68
Air inlet temp [K]	31.180	31.180
Sodium flow rate [kg/s]	0.165	0.165
Air flow rate [kg/s]	0.281	0.281

The comparison between experimental values from the FHX test in STELLA-2 and GAMMA+ results was conducted under the input data shown in Table 1. In this comparison, the heat transfer area ratio of the finned tube with circular fins was incorporated into the GAMMA+ code, and a fin efficiency of 0.88 was applied to simulate the heat transfer process. This approach was used to minimize the discrepancy between the experimental values and the values derived from the code analysis. The heat transfer area ratio used here is defined as the total heat transfer area of the finned tube divided by the heat transfer area of the tube without fins. Table 2 shows the inlet and outlet temperatures on both the tube and shell sides, as well as the mass flow rates and specific heats of sodium and air, which were used to calculate the heat gained by the air and the heat lost by the sodium in both the experiment and the code. The heat transfer discrepancy between the experiment and GAMMA+ was 0.171% for sodium and 0.915% for air, both within 1%, indicating effective heat exchange within the FHX. This analysis confirms that the GAMMA+ code accurately simulates the heat exchange performance of the actual STELLA-2 system.

TableII: comparison of the GAMMA+ results with experimental value for FHX

Parameter		Exp	GAMMA+
Tube side	**Outlet temperature[K]**	177.250	177.551
	△T [K]	176.430	176.129
	$\dot{m}$ [kg/s]	0.165	0.165
	Q [kW]	38.001	37.936
	Q difference [%]	-	-0.171
Shell side	**Outlet temperature[K]**	164.060	165.276
	△T [K]	132.880	134.096
	$\dot{m}$ [kg/s]	0.281	0.281
	Q [kW]	37.614	37.958
	Q difference [%]	-	0.915

3. Conclusions

This study involved 1-D modeling based on the actual STELLA-2 design drawings provided by KAERI and analyzing the performance of the FHX under steady-state conditions using GAMMA+. The analysis confirmed that GAMMA+ accurately validates the performance of the actual STELLA-2 heat exchanger. Based on these findings, we plan to conduct transient analyses of the FHX under varying conditions. Additionally, a thorough understanding of GAMMA+ will enable us to verify the performance of various operational scenarios and other heat exchangers in future research. Through this study, we aim to obtain characteristic data and conduct safety analyses for sodium heat exchangers under various operational conditions, contributing to the analysis of next-generation nuclear power systems. Furthermore, based on these data, we can propose design alternatives for decay heat removal systems to optimize the safety of SFR systems.

ACKWONLEDGEMENTS

This work was supported by the National Research Foundation of Korea(NRF) funded by the Ministry of Science and ICT(RS-2023-00257279).

REFERENCES

[1] Jewhan Lee, Jaehyuk Eoh, Jung Yoon, Seok-Kwon Son, and Hyungmo Kim, Heat transfer system design of sodium test facility STELLA-2, Annals of Nuclear Energy, Vol.191, 2023

[2] Nam-il Tak, Hong Sik Lim, Jonggan Hong, Jung Yoon, Byung Ha Park, and Jaehyuk Eoh, Improvement of GAMMA+ code for system transient and thermo-fluid safety

analysis of sodium-coolded fast reactors, Nuclear Engineering and Design, Vol.399, 2022
[3] Hyungmo Kim, Jung Yoon, Hyeong-Yeon Lee, Jaehyuck Eoh, Ji-Young Jeong, and Jewhan Lee, Design and thermal-hydraulic evaluation of the finned-tube type sodium-to-air heat exchanger in sodium test facility, Nuclear Engineering and Design, Vol.366, 2020