Proposal of a New Convective Heat Transfer Correlation for Sodium-to-Sodium Heat Exchanger

Jonggan Hong*, Jewhan Lee, Jaehyuk Eoh
Korea Atomic Energy Research Institute, 111, Daedeok-daero 989beon-gil, Yuseong-gu, Daejeon, 34057
**Corresponding author: hong@kaeri.re.kr*

1. Introduction

A shell-and-tube type with straight-tube arrangement has been widely adopted for the sodium-to-sodium heat exchanger of a sodium-cooled fast reactor. Thus, the liquid metal heat transfer characteristics inside the tube and around the straight-tube bundle have to be fully understood to design a sodium-to-sodium heat exchanger and evaluate its thermal performance accurately. Numerous studies were conducted on the convective heat transfer of various kinds of liquid metals to present the Nusselt number (Nu) correlations with respect to the Péclet number (Pe). However, those correlations still deviated from each other considerably. Accordingly, it is difficult for a design code developer to choose a proper heat transfer coefficient correlation for the sodium-to-sodium heat exchanger [1,2].

Recently, heat transfer performance tests of sodium-to-sodium heat exchangers for PGSFR were successfully accomplished at the STELLA-1 facility in the Korea Atomic Energy Research Institute (KAERI) [3]. Two consecutive tests with a model DHX were conducted at the Korean indigenous large-scale sodium experimental facility. In the first test, steady-state tests were performed under low Pe range conditions that accommodate the operating range of the DHX in the PGSFR [4]. In the second test, experimental results under high Pe range conditions for the IHX in the PGSFR were obtained by revamping the electro-magnetic pumps to increase the pump capacity [5].

In this work, a new combination of convective heat transfer correlations is proposed for the tube- and shell-sides of the sodium-to-sodium heat exchanger, based on the experimental results of STELLA-1. The newly proposed correlation is implemented on the SHXSA design code developed by KAERI for designing a sodium-to-sodium heat exchanger. The adequacy of the suggested correlations is assessed by comparing the calculated results of the SHXSA code with the test results of STELLA-1.

2. STELLA-1 Experiment

Table I shows the design specifications of the model DHX installed at the STELLA-1 facility. The model DHX is a shell-and-tube type counter-flow sodium-to-sodium heat exchanger with a straight-tube arrangement (Fig. 1). Test conditions for the model DHX experiments were chosen based on the anticipated operating conditions of the DHX and IHX of the PGSFR [4,5]. Sixteen conditions were composed as combinations of the mass flow rates and inlet temperatures of the shell- and tube-sides of the model DHX, considering the design condition, normal operating condition, and refueling mode condition of the PGSFR (Table II). The steady-state test results of the model DHX were obtained repeatedly around the test conditions with marginal deviations. The average Reynolds number (Re) and Pe of the shell- and tube-sides were calculated with sodium properties at the average temperature of the inlet and outlet. Re in the shell- and tube-sides ranged from 6,122 to 91,900 and from 7,116 to 72,165, respectively, which indicates that all test cases were under the turbulent flow condition. Pe in the shell- and tube-sides varied from 45.4 to 524.4 and from 50.3 to 437.1, respectively.

Table I: Design specification of model DHX in STELLA-1

Parameters	Design value
Heat exchanger type	Shell-and-tube, straight-tube
Tube arrangement	Triangular lattice
No. of tubes	42
Tube outer diameter (mm)	21.7
Tube thickness (mm)	1.65
Tube pitch (mm)	32.6
Effective tube length (m)	1.73
Material	Mod.9Cr-1Mo

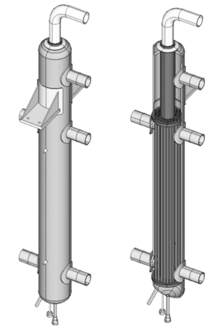

Fig. 1. Model DHX of STELLA-1.

3. Proposal of a New Convective Heat Transfer Coefficient for Liquid Sodium

For the sodium-to-sodium tubular heat exchangers, the fouling effect inside and outside the tubes can be neglected, and the overall heat transfer coefficient can be derived as in Eq. (1).

$$U = \left[\frac{D}{d}\frac{1}{h_t} + \frac{D}{2k}\ln\left(\frac{D}{d}\right) + \frac{1}{h_s}\right]^{-1} \quad (1)$$

Table II: Test conditions of model DHX

Case	Shell-side		Tube-side	
	Inlet temp. (°C)	Flowrate (kg/s)	Inlet temp. (°C)	Flowrate (kg/s)
1	215.1	2.00	179.8	1.99
2	390.0	2.83	294.9	2.85
3	475.1	4.51	290.0	8.01
4	390.1	6.22	194.9	4.38
5	473.5	4.01	189.2	2.78
6	418.0	4.03	165.1	2.63
7	337.1	4.02	133.7	2.33
8	403.3	5.89	120.8	1.84
9	319.8	22.30	250.1	15.92
10	330.2	18.59	250.5	13.29
11	369.8	14.00	260.5	8.60
12	356.1	12.40	259.9	7.30
13	355.1	10.70	268.2	5.90
14	245.1	9.00	179.9	5.00
15	264.8	5.40	199.8	2.71
16	215.4	4.80	179.7	2.20

where *D*, *d*, *h*, *k* and *U* denote the outer diameter of the tube, inner diameter of the tube, heat transfer coefficient, thermal conductivity of the tube wall, and overall heat transfer coefficient, respectively. Subscripts *s* and *t* mean the shell-side and tube-side.

Assuming the Lyon-Martinelli, Seban-Shimazaki, or Lubarsky-Kaufman correlation for the heat transfer coefficient of the tube-side, the heat transfer coefficients of the shell-side were obtained from Eq. (1). Consequently, four sets of Nu data with respect to Pe, varying according to four kinds of tube-side assumptions, were acquired from the experimental results of STELLA-1. Those calculated Nu data sets were plotted in Fig. 2 with various Nu correlations of liquid sodium. It is evidently shown that the previous heat transfer correlations do not agree well with each other, and all the Nu data sets obtained from STELLA-1 also deviated from them over a wide range of Pe, which motivated us to propose a new correlation based on the STELLA-1 experimental data.

Thus, a new Nu correlation for the shell-side convective heat transfer in the sodium-to-sodium heat exchanger was derived from the selected shell-side Nu data set (the solid circles in Fig. 2). The Schad equation form was adopted by engineering judgment. It should be noted that the calculated Nu at a low Pe of approximately 45 approached Mochizuki's curve K, which describes Nu at low Pe of less than 30. The low Pe datum point was not taken into account in the regression analysis, and the following equations obtained through curve fitting are proposed based on the data of the Pe ranging from 67.8 to 524.4.

$$Nu = -24.2 + 5.9Pe^{0.3} \quad (2)$$

for $P/D = 1.5$ and $Pe \geq 250$

$$Nu = 6.72 \quad (3)$$

for $70 \leq Pe \leq 250$

The regression curve L plotted in Fig. 2 using Eqs. (2) and (3) indicated that the newly proposed heat transfer equations agree well with the STELLA-1 experimental data.

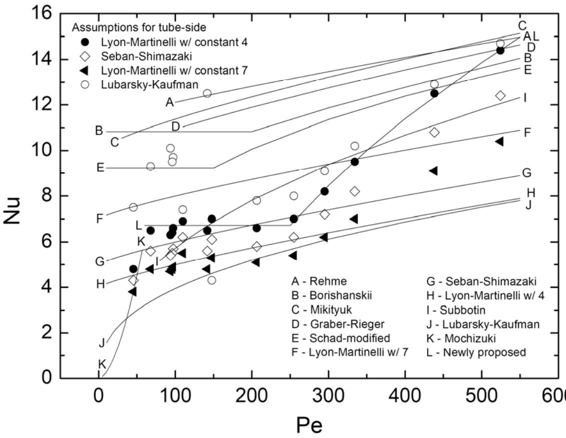

Fig. 2. Shell-side convective heat transfer characteristics in STELLA-1 sodium-to-sodium heat exchanger.

4. Validation of SHXSA computer design code with the New Correlation

The SHXSA code developed by KAERI is a one-dimensional thermal sizing computer code for the shell-and-tube type sodium-to-sodium heat exchanger [1,3]. Both the model DHX of STELLA-1 and the DHX and IHX of PGSFR were designed using the SHXSA. A reasonable prediction capability was shown by the SHXSA in previous works related to the STELLA-1 experiments [4,5]. In this section, the proposed combination of the convective heat transfer correlations was employed in the SHXSA version 1.2, and a validation process using SHXSA was carried out with the experimental results of the sodium-to-sodium heat exchangers of STELLA-1. In the modified SHXSA, the convective heat transfer correlation for the tube-side was unchanged as the Lyon-Martinelli correlation ($\mathrm{Nu} = 4 + 0.025Pe^{0.8}$) , and the Schad and Graber-Rieger correlations were replaced by the proposed Eqs. (2) and (3) for the shell-side.

In the SHXSA validation using the proposed correlation, the measured outlet temperatures of the model DHX shell- and tube-sides were compared with the corresponding calculated results (Fig. 3). The discrepancies in the outlet temperatures did not exceed a deviation band from -1.92% to 0.53%. Figures 4 and 5 shows the change in the deviation before and after refurbishing the shell-side correlation of the SHXSA with sixteen test cases obtained from STELLA-1. In most cases, the deviations of the shell- and tube-sides outlet temperatures were reduced owing to the use of the new correlation. The average absolute deviations of the shell-side outlet temperature and tube-side outlet temperature decreased from 0.70% to 0.51%, and from 0.37% to 0.17%, respectively. Therefore, it was revealed that the SHXSA calculated results using the proposed correlation have a better agreement with the STELLA-1 experimental results.

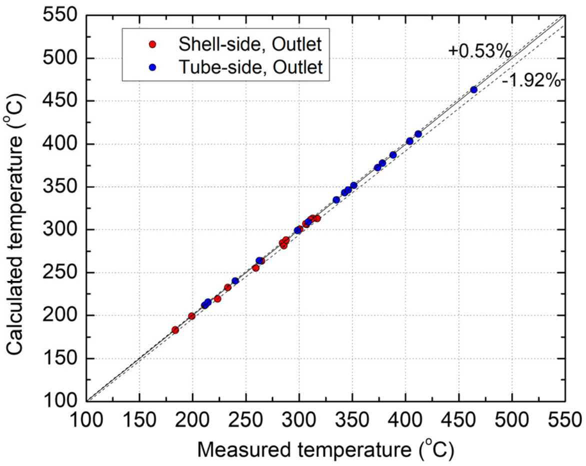

Fig. 3. Comparison of outlet sodium temperatures in STELLA-1 DHX experiment and SHXSA calculation.

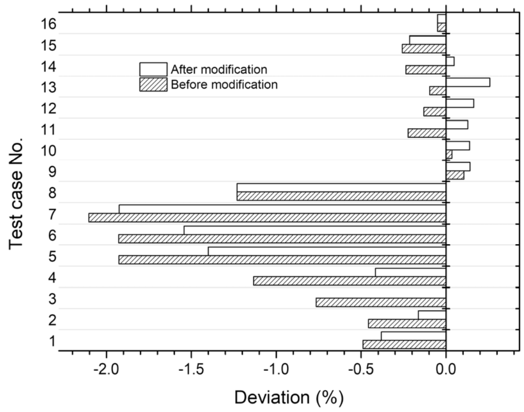

Fig. 4. Change in deviations of shell-side outlet temperature by use of proposed heat transfer correlation.

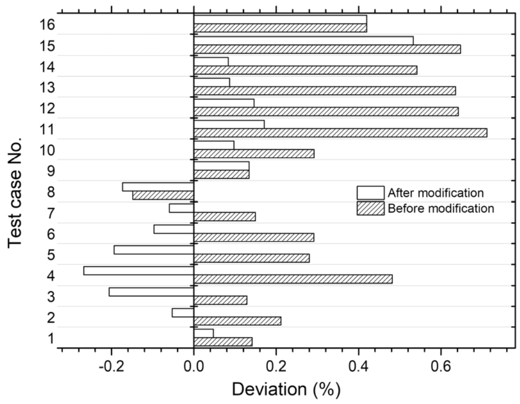

Fig. 5. Change in deviations of tube-side outlet temperature by use of proposed heat transfer correlation.

5. Conclusions

A new convective heat transfer correlation for the sodium-to-sodium heat exchanger was suggested by analyzing the STELLA-1 experimental data. The Lyon-Martinelli and the newly proposed correlations were employed for the tube- and shell-sides of the in-house SHXSA design code, respectively. It was concluded that the deviations between the SHXSA calculated results and the STELLA-1 experimental results were considerably reduced owing to the use of the new correlation. The average absolute deviations of the shell- and tube-sides outlet temperature were 0.51% and 0.17% in the assessment with STELLA-1 data, respectively. The newly proposed correlation is expected to be practically used for the thermal sizing and performance evaluation of the sodium-to-sodium heat exchanger.

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