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Effect of heat transfer correlations of a channel sodium flow on thermal sizing of sodium-to-sodium heat exchangers

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1. Introduction

A sodium-to-sodium heat exchanger has been widely used in a sodium-cooled fast reactor as an intermediate heat exchanger (IHX) or a decay heat exchanger (DHX). It is basically a shell-and-tube type counter-current flow heat exchanger, and sodium flows along the tube bundles on the shell-side of the heat exchanger. An accurate prediction of a heat transfer performance is very important for the heat exchanger thermal sizing in a sodium-cooled fast reactor (SFR) design application. To this end, a proper heat transfer coefficient for the appropriate design conditions should be provided for a better design of sodium heat exchangers.

However, the experimental correlations for a heat transfer of liquid metal are very rare in the literature and they have large uncertainties since the experiment is very expensive and difficult. The most difficult thing is that the differences among the correlations are so serious that it is difficult to decide which correlation should be used for a particular flow situation. In the present study, we surveyed the conventional heat transfer correlations for single-phase liquid metal flows in a heat exchanger design. The thermal sizing results of sodium heat exchangers with respect to the *Nusselt* (*Nu*) number correlations were quantitatively discussed.

2. Methods and Results

In order to obtain reasonable results of sodium heat exchanger thermal sizing, empirical correlations implemented in the sodium heat exchanger design were surveyed and the effect of the *Nusselt* number correlations were evaluated in the following sections.

2.1 Liquid metal heat transfer correlations

The behavior of *Nusselt* number for liquid metals generally follows the relations:

$$Nu = A + B \cdot (Pe)^C$$

where Pe is the *Peclet* number. The constants (A, B, C) depend on the geometry and the boundary conditions like uniform heat flux or constant wall temperature [1]. The flow paths of shell-and-tube type sodium heat exchangers are generally composed of parallel flow channels with in-line tube bundles, and they are characterized by a pitch-to-tube diameter ratio (P/d). The correlations for a shell-side heat transfer are mainly developed for the design of a fuel assembly and most formulas include the P/d value to represent the heat exchanger geometry effect in regard to the tube bundle arrangement. Various correlations have been proposed in the past, and the *Nusselt* number correlations considered in the present study are as follows;

(1) Westinghouse [2]

$$Nu = 4.0 + 0.33(P/d)^{3.8}(Pe/100)^{0.86} + 0.16(P/d)^{5.0}$$
$$\text{for} \quad 1.1 \le P/d \le 1.4 \quad \text{and} \quad 10 \le Pe \le 5000$$

(2) Schad-Modified [2]

$$Nu = \left[-16.15 + 24.96(P/d) - 8.55(P/d)^{2.0}\right] \cdot Pe^{0.3}$$
$$\text{for} \quad 1.1 \le P/d \le 1.5 \quad \text{and} \quad 150 \le Pe \le 1000$$
$$Nu = 4.496 \cdot \left[-16.15 + 24.96(P/d) - 8.55(P/d)^{2.0}\right]$$
$$\text{for} \quad Pe \le 150$$

(3) Graber and Rieger [3]

$$Nu = 0.25 + 6.2(P/d) + (0.032(P/d) - 0.007) \cdot Pe^{0.8-0.024(P/d)}$$
$$\text{for} \quad 1.25 \le P/d \le 1.95 \quad \text{and} \quad 150 \le Pe \le 3000$$

(4) Borishanskii *et al.* [4]

$$Nu = 24.15 \cdot \log\left[-8.12 + 12.76(P/d) - 3.65(P/d)^2\right] + 0.0174 \cdot \left[1 - \exp(6 - 6(P/d))\right] \cdot \left[Pe - 200\right]^{0.9}$$
$$\text{for} \quad 1.1 \le P/d \le 1.5 \quad \text{and} \quad 200 \le Pe \le 2000$$
$$Nu = 24.15 \cdot \log\left[-8.12 + 12.76(P/d) - 3.65(P/d)^2\right]$$
$$\text{for} \quad 1.1 \le P/d \le 1.5 \quad \text{and} \quad Pe \le 200$$

(5) Hybrid formula with a critical *Peclet* number

$$Nu = 0.25 + 6.2(P/d) + (0.032(P/d) - 0.007) \cdot Pe^{0.8-0.024(P/d)}$$
$$\text{for} \quad P/d \le 1.5 \quad \text{and} \quad Pe_{crit} \le Pe$$
$$Nu = \left[-16.15 + 24.96(P/d) - 8.55(P/d)^{2.0}\right] \cdot Pe^{0.3}$$
$$\text{for} \quad P/d \le 1.5 \quad \text{and} \quad Pe \le Pe_{crit}$$

(6) Rehme [5]

$$Nu = 7.55\left(\frac{P}{d}\right) - 20\left(\frac{P}{d}\right)^{-13} + \frac{3.67}{90(P/d)^2} \cdot Pe^{0.19(P/d)+0.56}$$
$$\text{for} \quad 1.3 \le P/d \quad \text{and} \quad 100 \le Pe \le 4000$$

(7) Lyon-Martinelli [6]

$$Nu = 4.0 + 0.025 \cdot Pe^{0.8}$$

With the above correlations, the heat exchanger thermal sizing works were carried out and the results were discussed.

2.2 Effect of heat transfer correlations on HX design

Among the above correlations, it was reported that the Westinghouse correlation[2] underestimates the heat transfer coefficient when the P/d value is higher than 1.3. Hence, in the present work, it was implemented only with the postulated P/d ratio of 1.5 for the KALIMER(Korea Advanced Liquid Metal Reactor) [7] design and it was used only for comparing with other correlations. For the P/d ratio of 1.5, *Nusselt* numbers in a shell-side sodium channel can be plotted in terms of *Peclet* number as shown in **Figure 1**.

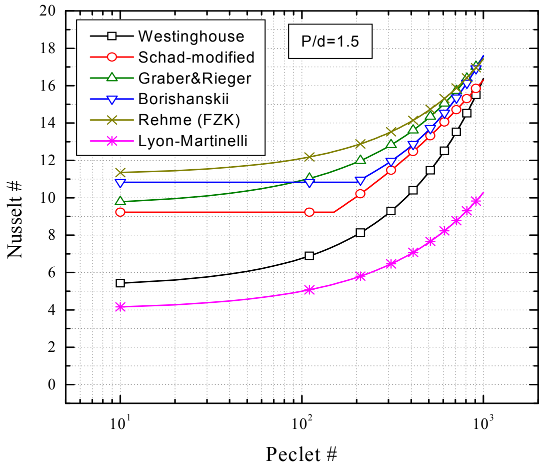

Figure 1. *Nu* # variations in terms of *Peclet* number

As shown in the figure, there are serious differences among the *Nusselt* number correlations with respect to the *Peclet* number variations. Hence, it is difficult to decide which correlation is appropriate to simulate the shell-side sodium channel flow with a tube pitch arrangement. To this end, we need to compare the correlations in order to properly apply them for the heat exchanger design with a particular flow situation.

In regard to the thermal sizing of shell-and-tube type heat exchangers, the overall heat transfer coefficient (*U*) from the hot-side to the cold-side can be obtained from Equation (1), where the subscripts *s*, *t*, and *F* mean the shell-side, tube-side and fouling factor, respectively. The fouling factors can be assumed to be an infinite value to neglect their effect if the heat transfer mediums are sodium.

$$U_{SHX} = \left[\frac{1}{h_s} + \frac{1}{h_{s,F}} + \frac{d_o}{2k}\ln\left(\frac{d_o}{d_i}\right) + \frac{d_o}{d_i}\frac{1}{h_{t,F}} + \frac{d_o}{d_i}\frac{1}{h_t}\right]^{-1} \quad (1)$$

Table 1 shows the results of thermal sizing and major design parameters of the sodium-to-sodium heat exchangers, *e.g.* IHX (Intermediate Heat eXchanger) of KALIMER[7] in terms of various *Nusselt* number correlations. The required heat transfer capacity of the single IHX was 387.5 MWt, and the shell- and tube-side sodium flow rate were 2091.5 kg/s and 1536.5 kg/s, respectively [7]. The reference heat transfer correlation for the shell-side sodium flow was selected to be Graber and Rieger [3], and the *Nusselt* numbers obtained from other correlations were compared to that of the reference case.

Table.1 Results of IHX thermal sizing for KALIMER

Heat transfer correlations	Heat transfer resistance (%)			IHX design (Q_{IHX}=387.5 MW_t)		
	shell-side sodium	Tube wall	tube-side sodium	Heat transfer tube length (m)	Heat transfer surface area (m^2)	% difference
(2)	13.90	51.96	34.14	4.30	1405.72	1.08
(3)	12.98	52.51	34.51	4.25	1390.76	0.00
(4)	13.56	52.16	34.28	4.28	1400.17	0.68
(5)	12.98	52.51	34.51	4.25	1390.76	0.00
(6)	12.62	52.73	34.65	4.23	1385.07	-0.41
(7)	22.04	47.05	30.91	4.75	1552.85	11.65

As shown in the table, most conduction resistances at the tube wall are over 50% of the total heat transfer resistance and are larger than those of sodium convection resistances. In particular, the convection resistances of the shell-side sodium are far less than 15% and are smaller than those of tube-side sodium of about 35%. To this end, the large differences of the *Nusselt* number correlations can be diminished in the overall heat transfer coefficient calculation. As a result, most heat transfer areas obtained from the thermal sizing analysis range within 1% deviations of the reference case using the Graber and Rieger correlation. The maximum deviation was observed when the Lyon-Martinelli correlation was used, but even it was less than 12%.

3. Conclusions

On the basis of the results, the uncertainties coming from the ambiguity of shell-side *Nusselt* number correlations can be overcome with the design margin of about 10% in the sodium-to-sodium heat exchanger design work. This is mainly because the conduction resistance at the tube wall is dominant in the *U* calculation when compared to the sodium convection resistance. The detailed evaluations for the selection of proper *Nusselt* number correlations will be made by using the separate effect test facility completed by the middle of 2011. The low *Peclet* number range will be also investigated with the experimental data to find out the peculiar or appropriate heat transfer correlations of the DHX operation regime.

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