Modification of Laminar and Transition Single Phase Heat Transfer Model in SPACE code for Research Reactor Application

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1. Introduction

As the SPACE code is developed for the safety analyses of nuclear power plants, suitability should be checked for the application to the research reactor thermal-hydraulic conditions. One part is heat transfer calculation for the fuel flow channels of research reactors in the laminar flow and transition regions where the flow speed is low. However, there are considerable errors between the analysis and the experimental result, since the SPACE code treats that region as the maximum value among the laminar and turbulent heat transfer coefficients. In addition, the different shape of the nuclear fuel of the research reactor from that of the power plant should be considered in the calculation model.

In this research, in order to apply the SPACE code to the safety analysis of research reactors with plate type fuels, appropriate heat transfer models for laminar and transition regions have been selected and applied to the code. In addition, in order to validate the selected models, validation calculation was performed for heat transfer experimental data of a plate-type fuel.

2. Laminar and Transition Heat transfer Correlations

2.1 Correlations in SPACE 3.0

Eq. 1 and 2 are the laminar and turbulent heat transfer correlations currently built in the SPACE 3.0 code, respectively. The laminar flow correlation is Sellars [1] correlation, the turbulent flow correlation is Dittus-Boelter [2] correlation, and both models were developed from experimental data for heat transfer in pipes. However, since the SPACE code uses the method of Eq.3 to determine the heat transfer coefficient, the Dittus-Boelter correlation is used for the transition and some part of laminar flow regions.

$$Nu = 4.36 \tag{1}$$
$$Nu = 0.023\, Re^{0.8} Pr^{0.4} \tag{2}$$
$$Nu = max(Nu_{lam}, Nu_{tur}, Nu_{nc}) \tag{3}$$

2.2 Modification of Laminar and Transition Correlations

Sellars correlation has been used for heat transfer analysis of laminar flow region in many of safety analysis codes. However, this equation is not appropriate for the rectangular channels in typical plate type fuel of research reactors. Therefore, Hartnett-Kostic[3] correlation of Eq.4 was adapted for heat transfer analysis in laminar flow in a rectangular channel. In this equation, the term of (t/w) is the ratio between channel height and width.

$$Nu = 8.235\left(1 - 2.0421\left(\frac{t}{w}\right) + 3.0853\left(\frac{t}{w}\right)^2 - 2.4765\left(\frac{t}{w}\right)^3 + 1.0578\left(\frac{t}{w}\right)^4 - 0.1861\left(\frac{t}{w}\right)^5\right) \tag{4}$$

In the transition flow region, an interpolation method is adapted as described in Eq.5 to correct the excessive prediction of the heat transfer coefficient in the previous model. The terms of Nu_{lam} and Nu_{turb} in Eq.5 are calculated by using the Hartnett-Kostic and Dittus-Boelter models, respectively.

$$Nu = Nu_{lam} + \left(\frac{Nu_{turb} - Nu_{lam}}{Re_{turb} - Re_{lam}}\right)(Re - Re_{lam}) \tag{5}$$

3. Description of the Validation Experiment and Modeling

The experiment used in the validation calculation with SPACE code is a single-phase heat transfer experiment in a plate-type fuel conducted by China National Nuclear Corporation (CNNC) [4]. This experiment is suitable as a validation data because the shape of cooling channel is similar to that of the research reactor, and the experiment was conducted in a wide range from laminar to turbulent flow in research reactor operating conditions.

3.1 Description of the CNNC experiment

The design parameters of test section of the CNNC experiment are shown in table 1.

In CNNC experiment, isothermal and non-isothermal experiments were carried out with various mass flow rate and heating power. In the isothermal experiment, flow rate was controlled without heat into the test section. In the non-isothermal experiment, the heater in the test section was turned on and controlled on the corresponding flow rate. Total 24 sets of experiments were performed for varying with inlet temperature, heat flux and flow rate. The experimental parameters of isothermal and non-isothermal tests are listed in table 2.

Table 1. Design parameter of the CNNC experiment apparatus

Parameter	Data
Flow direction	Upward
Channel gap	2 mm
Channel span	40 mm
Heater block thickness	3 mm
Hydraulic diameter	3.64 mm
Channel length	1092 mm

Table 2. Experimental parameter of CNNC tests

Parameters	Data
Isothermal case	
Inlet Temp.	24 ~ 37.5 ℃
Mass Flux	285 ~ 2000 kg/(m^{2}s)
Prandtl Number	4.6 ~ 6.2
Non-Isothermal case	
Inlet Temp.	24 ~ 37.5 ℃
Mass Flux	285 ~ 2000 kg/(m^{2}s)
Heat Flux	14 ~ 214 kW/m^2
Prandtl Number	4.6 ~ 6.2

3.2 Modeling of the CNNC experiment

Fig. 1 shows the node diagram for simulating the CNNC experiments by the SPACE 3.0. The test section is modeled as a pipe (150) which has the 22 sub-volumes, and inlet and outlet are treated as temporal face boundary conditions. The heat structure simulating the heater in narrow channel is attached to the side of the pipe component.

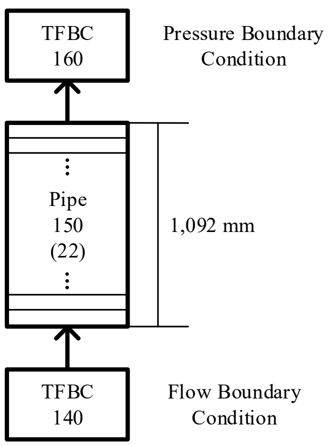

Fig. 1 Node diagram of SPACE 3.0 modeling

4. Result and Discussion

Fig. 2 shows the analysis results using SPACE 3.0 with the existing built-in model. In high Reynolds number, Re>10000, the simulation results well predict the experiment results. Therefore, the Dittus-Boelter correlation is appropriate for turbulent heat transfer of plate type fuel in research reactors. On the other hand, in the laminar flow and transition regions with relatively low flow speed, a large error is shown between the experimental results and the analysis results. In particular, looking at the results in the laminar flow region, in the case of the experiment, the Nusselt number is constant regardless of the change the Reynolds number. However, in the analysis, Nusselt number increases as the Reynolds number increases, indicating that the turbulence correlation is applied in the corresponding region. Therefore, it can be seen that the correlations applied in the laminar flow and transition regions have to be modified for accurate analysis.

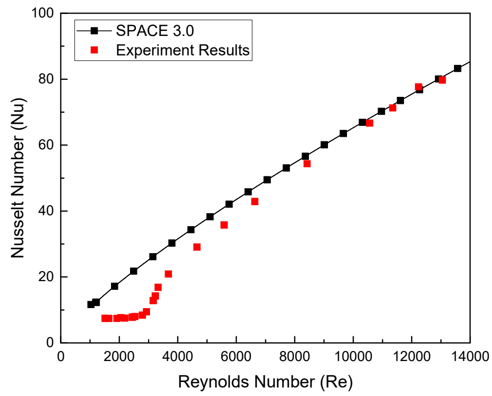

Fig. 2 Validation Calculation results (SPACE 3.0)

Fig. 3 shows the results of the analysis using the modified model of Eq. 5. In the laminar flow region, the experimental results and the analysis results are matched well, and the accuracy is improved in the transition region. Therefore, it was confirmed that the modified model is suitable for heat transfer analysis of plate-type fuel using in the research reactor.

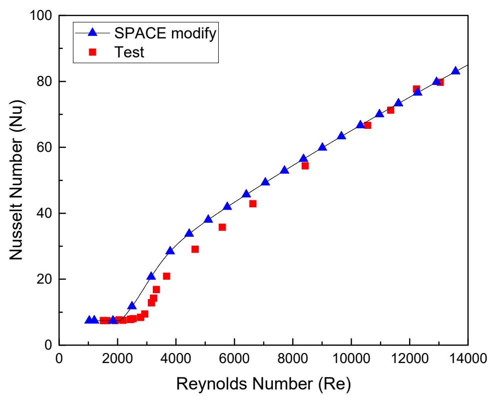

Fig. 3 Validation Calculation Results (Improved Model)

4. Conclusions

In order to apply the SPACE code to the safety analysis of the research reactor, a study on the improvement of the heat transfer model for laminar and transition regions has been performed. As a result of validation calculation using the modified model, it is confirmed that the heat transfer predictions in the laminar and transition regions is improved.

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REFERENCES

[1] J. R. Sellars, M. Tribus, and J. S. Kelin, "Heat Transfer to Laminar Flows in a Round Tube of Flat Conduit: The Graetz Problem Extended," International Journal of Heat and Mass Transfer, Vol. 31, pp. 13-25, 1956.
[2] F.W. Dittus, and L. M. K. Boelter, "Heat Transfer in Automobile Radiators of the Tubular Type," Publication in Engineering, 2, University of California, Berkeley, pp. 443-461, 1930.
[3] J. P. Hartnett, and M. Kostic, "Heat Transfer to Newtonian and Non-Newtonian Fluids in Rectangular Ducts," Advances in Heat Transfer, Vol. 19, pp.247-356, 1989.
[4] J. Ma, L. Li, Y. Huang, and X. Liu, "Experiment studies on single-phase flow and heat transfer in a narrow rectangular channel", Nuclear Engineering and Design, Vol. 244, pp. 2865-2873, 2011.