Modification of SPACE Code for Safety Analysis of Research Reactors with Plate-Type Fuel

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1. Introduction

Most of the existing system codes, such as RELAP5, RETRAN, CATHARE and CATHENA, have been developed for the safety analysis of nuclear power plants. A number of verification and validation calculations ensure the accurate performance and reliability of the system codes. These codes have been widely used after numerous validation calculations to determine whether safety analysis capabilities are appropriate for research reactors. KAERI also performed an applicability assessment of the RELAP5 code for the safety analysis of Jordan Research and Training Reactor (JRTR) [1].

SPACE code, licensed in Korea, is developed for nuclear power plants which is operating under high temperature and pressure conditions. The thermal-hydraulic models used in the SPACE code were mainly validated for the operating conditions of nuclear power plants. In order to apply the SPACE code to research reactors, additional validations are required, and thermal-hydraulic models need to be added if necessary. Unlike power plants, many research reactors use plate-type fuels to obtain high neutron flux. Hence, thermal-hydraulic models should be selected to adequately simulate the flow phenomena in the narrow rectangular channels.

In this study, single-phase thermal-hydraulic correlations, such as friction factor and heat transfer, for the narrow rectangular channels were implemented on the code as a starting point to improving the SPACE code for research reactors with plate-type fuel. Validation analysis was performed to evaluate whether the single-phase thermal-hydraulic correlations were correctly implemented in the code.

2. Correlations for narrow rectangular channels

The single-phase thermal-hydraulic correlations used in SPACE 3.0 and RELAP5/MOD3.3 are summarized in Table 1. In the friction factor correlations, RELAP5 is applied to the shape factor, Φ_S, considering the shape of the flow path in the laminar flow region. The Churchill correlation used in the SPACE has no such factor that takes into account shape effects. In the case of a narrow rectangular channel, the shape factor is less than one and the friction coefficient is largely predicted, which may be conservative in the safety analysis. Therefore, in this study, the correlations of the RELAP5 were selected as appropriate correlations for the research reactors with plate-type fuels.

The heat transfer correlations for the forced convection region were identical in both codes. In the natural convection region, the two codes use different heat transfer correlations. The trend of Nusselt number of two correlations are compared in Fig. 1. The Churchill-Chu correlation predicts heat transfer coefficients higher than the Spore correlation. The acceptance criteria for the prevention of fuel failure in the safety analyses are the maximum fuel temperature (MFT) and the minimum critical heat flux ratio (MCHFR). In the natural convection region, the margin of MCHFR is relatively smaller than that of MFT.

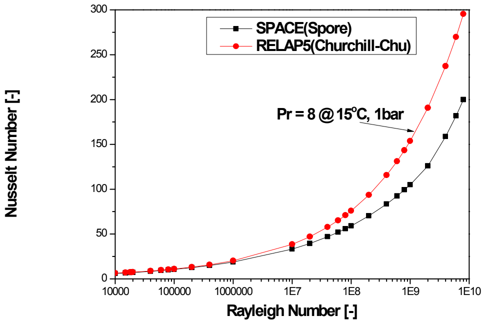

Fig. 1. Heat transfer coefficient in natural convection

Table 1. Single-Phase thermal-hydraulic correlations used in SPACE3.0 and RELAP5/MOD3.3

Flow regime	**RELAP5/MOD3.3**	**SPACE3.0**
	Friction factor correlations	
Laminar (Re ≤ 2200)	$f_{lam} = \frac{64}{Re\Phi_s}$	Churchill $f' = 2\left[\left(\frac{8}{Re}\right)^{12} + \frac{1}{(a+b)^{3/2}}\right]^{1/12}$ $a = \left[2.475\ln\left(\frac{1}{c}\right)\right]^{16}$ $b = \left(\frac{37530}{Re}\right)^{16}$ $c = \left(\frac{7}{Re}\right)^{0.9} + 0.27\min\left(0.02, \max\left(10^{-9}, \frac{\varepsilon}{D_h}\right)\right)$
Transition (2200<Re ≤3000)	$f_{tran} = \left(3.75 - \frac{8250}{Re}\right)(f_{tur,Re=3000} - f_{lam,Re=2200}) + f_{lam,Re=2200}$	
Turbulent (Re>3000)	$f_{tur} = \left[-2\log_{10}\left(\frac{\varepsilon}{3.7D} + \frac{2.51}{Re}\left(1.14 - 2\log_{10}\left(\frac{\varepsilon}{D} + \frac{21.25}{Re^{0.9}}\right)\right)\right)\right]^{-2}$	
	Heat transfer correlations	
Natural convection	Churchill-Chu $Nu = \left[0.825 + \frac{0.387 Ra_f^{1/6}}{[1 + (0.492/Pr)^{9/16}]^{8/27}}\right]^2$	Spore $Nu = 0.59(Ra_f)^{1/4}$ $(10^4 \le Ra_f \le 10^9)$ $Nu = 0.10(Ra_f)^{1/3}$ $(10^9 \le Ra_f \le 8 \times 10^9)$
Laminar forced convection	Sellars et al. **Nu=4.36**	
Turbulent forced convection	Dittus-Boelter $Nu = 0.023 Re^{0.8} Pr^{0.4}$	

It is more conservative to predict higher heat transfer coefficients because the MCHFR decreases as the heat transferred to the coolant increases. Therefore, the Churchill-Chu correlation was chosen in this study.

3. Implementation

The thermal-hydraulic correlations selected for the safety analysis of the plate-type research reactors were implemented as an additional user option not to affect the existing thermal-hydraulic models of the SPACE code.

4. Code Assessment

In China national nuclear corporation (CNNC), experiments were carried out to research the pressure drop and the single-phase heat transfer phenomena in a narrow rectangular channel [2]. CNNC pressure drop tests are classified into isothermal test and non-isothermal test. The isothermal experiment is a test in which the pressure drop is measured by changing only the inlet flow rate without heating. The non-isothermal experiment is a test in which the pressure drop is measured by changing the heat flux and inlet flow rate. Table 2 summarizes the experimental parameters ranges of the isothermal and non-isothermal tests.

The nodalization for the SPACE calculation is shown in Fig. 2. A narrow rectangular channel was modeled using a pipe component (Pipe #150). The heating plate of the test section was modeled using a heat structure (HS #150). The experimental conditions were specified with boundary conditions at the inlet and outlet of the test section. The temperature and flow rate were specified at the inlet TFBC #145, and the pressure was fixed at the outlet TFBC #155.

Table 2. Experimental parameters of isothermal and non-isothermal tests

Parameters	**Data**	**Remarks**
Isothermal experiments		
Inlet temp., °C	24 ~ 37.5	Adjusted by preheater
Mass flux, kg/(m^{2}s)	285 ~ 2000	Re = 1090~10200
Prandtl number	4.6 ~ 6.2	
Non-isothermal experiments		
Inlet temp., °C	27.8 ~ 30	Adjusted by preheater
Mass flux, kg/(m^{2}s)	306 ~ 2320	Re = 1460~13000
Heat flux, kW/m^2	14 ~ 214	Q = 1.22 ~ 18.6 kW
Prandtl number	3.9 ~ 5.7	

4.1 Single-phase Friction Factor

Figure 3 shows SPACE 3.0 and modified SPACE calculations versus Reynolds number for the friction factor by isothermal experiments. The friction factor decreases fast in laminar region, and flips up at the transition region, then slowly decreases again in turbulent region as the Reynolds number increases. The laminar-turbulent transition occurs at Reynolds number between 2500~4000 in the experiment, whereas the modified SPACE has transition region at 2200~3000. The friction factor by the modified SPACE calculation agrees well with the experiment except for the transition region. The modified SPACE calculation predicts the higher friction factor than the SPACE 3.0.

Figure 4 compares SPACE 3.0 and modified SPACE calculations with the friction factor by non-isothermal experiments. In the turbulent region, both SPACE calculations show the same results and good prediction performance than the experiment. Although the modified SPACE calculation shows a difference from the experiments in the laminar and transition region, it is conservative in safety analyses aspect because it predicts higher than the SPACE 3.0 calculation.

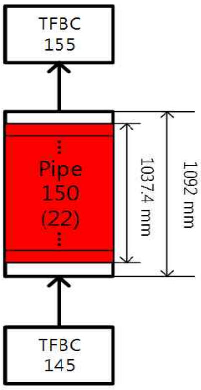

Fig. 2. SPACE nodalization for CNNC experiments

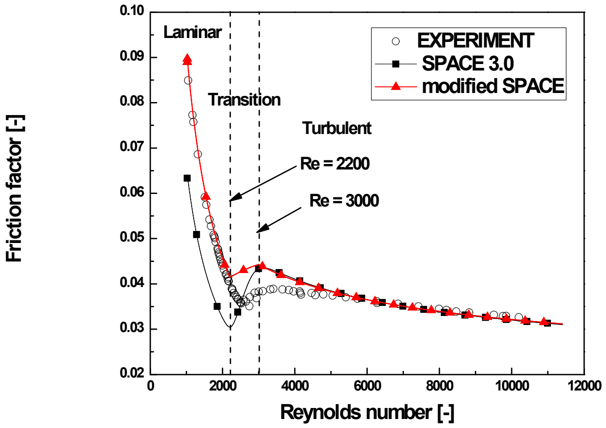

Fig. 3. Friction factors of isothermal experiment and SPACE simulations

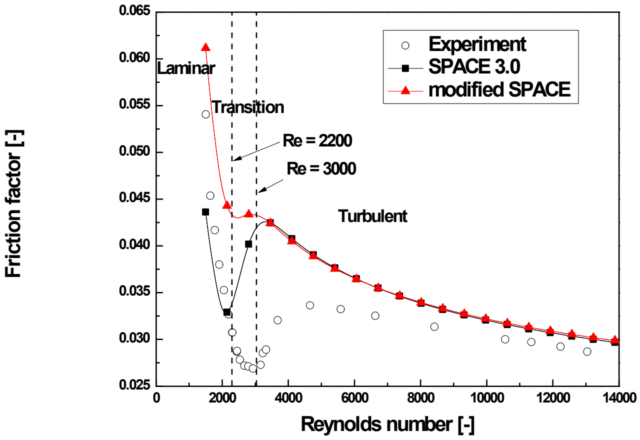

Fig. 4. Friction factors of non-isothermal experiment and SPACE simulations

4.2 Single-phase Heat Transfer

Figure 5 compares SPACE 3.0 and modified SPACE calculations with the Nusselt numbers of the non-isothermal experiments as a function of Reynolds number. Overall Nusselt numbers of both SPACE calculations show higher value than that of the experiment except at higher Reynolds number region. Since the experiments were performed only in forced convection region, the natural convection correlation doesn't affect the results. Therefore, the calculations by both SPACE codes are identical. Further validation of natural convection correlation needs to be performed.

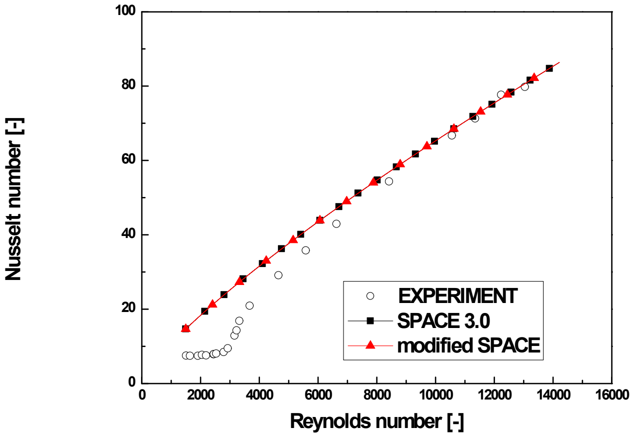

Fig. 5. Nusselt numbers of non-isothermal experiment and SPACE simulations

5. Conclusions

The modifications and assessments of the SPACE code were carried out to extend predictive capability for thermal-hydraulic phenomena in a narrow rectangular channel. The friction factor and Nusselt number for CNNC experiments have been calculated by the modified SPACE code, and compared with the experimental results. For the isothermal case, the modified SPACE predicts the friction factor very well at laminar and turbulent flow region. For the non-isothermal case, the modified SPACE predicts the friction factor and Nusselt number higher than those of experiment results.

For further study, various validation calculations in the natural convection region should be performed, and the friction factor correlations in laminar and transition flow region should be improved.

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