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International Agreement Report

Validation of RELAP5/MOD3.3 Friction Loss and Heat Transfer Model for Narrow Rectangular Channels

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ABSTRACT

The friction loss and the heat transfer models in RELAP5/MOD3.3 were assessed using CNNC experiments and KAERI OFEL tests, which are experiments for narrow rectangular channels. The test sections of the experiments were modeled with PIPE, TMDPVOL and TMDPJUN, considering the geometry and boundary conditions. Since the friction loss and heat correlations of RELAP5/MOD3.3 are supplied with a form of “geometry set”, the default set for circular geometry and a narrow rectangular set were compared to find an adequate set which properly simulated the experiments.

The assessments included the friction coefficients of the isothermal and non-isothermal channels, and the heat transfer coefficients of forced convection in the channel. The friction and pressure drop in the isothermal channel were well reproduced by RELAP5/MOD3.3 over the whole flow range in the experiments, but a proper shape factor in the laminar flow region was necessary. Also, the non-isothermal friction coefficients matched the experimental results well with the proper viscosity ratio exponent. The heat transfer coefficients in the turbulent flow region matched well with the 101 set, whereas the 102 set tended to overpredict the heat transfer coefficient in the high Re region. The heat transfer coefficients in the low Re region were overpredicted by RELAP5/MOD3.3 due to its internal logic, which simply selects the highest heat transfer coefficient among those of laminar, turbulent, and natural convection. After modifying that logic, the RELAP5/MOD3.3 showed good agreement with the experimental data.

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EXECUTIVE SUMMARY

Research reactors with plate type fuel have narrow rectangular cooling channels, and many of them are operated in low pressure and low temperature conditions. RELAP5/MOD3.3 has been validated extensively for circular channels or rod bundles with high pressure and temperature conditions, however, validation for narrow rectangular channels with low pressure and temperature conditions is quite limited. Since friction and heat transfer with single phase water is critical for research reactors, the models in RELAP5/MOD3.3 were reviewed and the calculation results were compared with experiments for narrow rectangular channels.

A CNNC experiment for narrow rectangular channels was conducted to simulate a research reactor fuel channel. The channel aspect ratio was 20, and the experimental condition covered laminar to turbulent, Re~1000 to 13000. The experiments were performed with heated and unheated conditions with a heat flux from 14~214 kW/m2. The KAERI OFEL experiment was performed to measure the friction in a narrow rectangular channel, and the Re was up to 35000, which is higher than the conditions in the CNNC experiment. The test section of the CNNC experiment and KAERI OFEL experiment were modeled with PIPE, TMDPVOL and TMDPJUN considering the geometry and the boundary conditions of the experiments.

The friction coefficient of RELAP5/MOD3.3 matched the experimental results well when the proper shape factor was selected for laminar flow, and the viscosity ratio exponent was selected for heated channel flow. The shape factor of the laminar flow is determined by the aspect ratio of the rectangular channel shape, and the viscosity ratio exponent was selected to be 0.25, which is the recommended value from RELAP5/MOD3.3 for the liquid turbulent condition.

The heat transfer coefficient in RELAP5/MOD3.3 varies depending on the selection of the geometry set, which are provided by the code. The 102 set was prepared for the ORNL ANS reactor, however, it does not provide a good prediction of the heat transfer coefficient, compared with the CNNC experimental results. Instead, the default 101 set ,which was originally for circular channels, showed better agreement with the experiment, however, it still overestimated heat transfer in the laminar and transition regions. The overestimation originates with the internal logic used for selecting the laminar, transition and turbulent heat transfer coefficient, which simply selects the maximum value among them. The modified code selected the Nu of natural or laminar forced convection for Re<2500, selected the turbulent Nu for Re$\geq$4000, and interpolated between them.

The effect of this code modification was then examined for a typical 5 MW pool type research reactor. The modification affected the fuel temperature during the accident, when the flow condition was in the laminar and transition regions. Therefore, it is recommended that the RELAP5/MOD3.3 be modified to properly select the laminar and transition heat transfer coefficients.

ABBREVIATIONS

RELAP	Reactor Excursion and Leak Analysis Program
CNNC	China National Nuclear Cooperation
KAERI	Korea Atomic Energy Research Institute
OFEL	Omni Flow Experimental Loop

1 INTRODUCTION

A research reactor with plate type fuel has cooling channels with a narrow rectangular shape, and the thermal-hydraulic behavior is different from that in circular channels. In addition, most research reactors are operated at low pressure and a highly-subcooled region, which also deviates from the conventional power reactor. In this low-pressure and low-temperature condition, the heat transfer from the fuel to coolant mostly occurs by single-phase forced convection and natural convection. Determining the adequacy of hydraulic resistance and heat transfer models for narrow rectangular channels under these conditions is important for analyzing their thermal-hydraulic behavior, especially for safety analysis. Because of these characteristics, a series of experiments were performed to validate a hydraulic and thermal model in narrow rectangular channels.

RELAP5/MOD3.3 incorporates the heat transfer correlation set developed by Argonne National Laboratory (ANL) using the code for the Advanced Neutron Source (ANS) research reactor. The Petukhov correlation included in the ANL correlation set is used for simulating the heat transfer in the narrow rectangular channel of ANS, however, it was developed for the high flow rate region, which does not cover the conditions of research reactors operating with low flow rates. Therefore, the correlation set needs to be validated with various experimental data covering the low flow rate region.

In this study, a proper correlation set in RELAP5/MOD3.3 was selected to correctly simulate the friction loss and the heat transfer in narrow rectangular channels, by validating the results of CNNC and KAERI OFEL experiments with the code. Also, the variables affecting the results were determined by comparing the calculations and the experiments. In addition, the code’s over-estimation of the heat transfer coefficients in the laminar and transition regions were fixed and the effects evaluated.

2 FRICTION AND HEAT TRANSFER MODEL IN RELAP5/MOD3.3

2.1 Friction Coefficients

The friction coefficient in the channel is a nondimensional number which correlates the flow and the pressure drop through the channel. The friction coefficient, f, is defined such that

$$\Delta p = f \frac{L}{D} \frac{\rho V^2}{2},$$

where Δp is the pressure drop through the channel, L and D are the length and the diameter of the channel, respectively. The friction coefficient varies with respect to the channel shape and the flow regime, and usually is a function of channel shape, hydraulic diameter, and Re.

2.1.1 Friction Coefficient of Laminar Flow

The friction factor of a laminar flow can be calculated analytically for various channel geometries. The friction coefficient of laminar flow in RELAP5/MOD3.3 is

$$f = \frac{64}{\mathrm{Re}_{D_h} \Phi_S}$$

where D_h is the hydraulic diameter and Φ_s is the shape factor. Φ_s is 1 for circular channel, and 2/3 for infinite parallel plates. For narrow rectangular channel, Φ_s can be approximated with respect to the aspect ratio of the channel, as

$$\Phi_S = \left[0.88919 + 87.656 \left\{ \frac{1+\alpha(\sqrt{2}-1)}{4(1+\alpha)} - \frac{\sqrt{2}}{8} \right\}^{1.90} \right]^{-1}.$$

Here, α is the aspect ratio of the channel, which is the ratio of the channel gap to width. The approximation has a maximum error of 1.7 % versus the exact solution.

2.1.2 Friction Coefficient of Turbulent Flow

RELAP5/MOD3.3 uses an explicit approximation of the implicit correlation by Coolbrook-White as (Ref. 1)

$$f = \left[-2\log\left(\frac{\varepsilon}{3.7} + \frac{2.51}{\mathrm{Re}} \left(1.14 - 2\log\left(\varepsilon + \frac{21.25}{\mathrm{Re}^{0.9}} \right) \right) \right) \right]^{-2},$$

where ε is the relative roughness of the channel.

The friction coefficient of the transition flow region is interpolated linearly between those of laminar and turbulent flow. The flow region with $\mathrm{Re} \leq 2200$ is considered laminar and that with

Re>3000 as turbulent, and the friction coefficient of the transition region is calculated by the linear interpolation between those at Re=2200 and Re=3000.

2.1.3 Friction in Heated Channel

The friction coefficient in the heated channel is different from that in the isothermal channel, because the fluid temperature near the wall is different from that at the fluid core, and the temperature also varies along the channel. The temperature difference between wall and fluid core predominates as the friction coefficient decreases, therefore a property ratio method is used to compensate the difference as

$$\frac{f}{f_{\mathrm{iso}}}=\left(\frac{\mu_{\mathrm{wall}}}{\mu_{\mathrm{bulk}}}\right)^{D} .$$

RELAP5/MOD 3.3 uses the equation by using a heated perimeter (P_H) and wetted perimeter (P_W) as

$$\frac{f}{f_{\mathrm{iso}}}=1+\frac{P_H}{P_W}\left[\left(\frac{\mu_{\mathrm{wall}}}{\mu_{\mathrm{bulk}}}\right)^{D}-1\right] ,$$

where D is the viscosity ratio exponent, which is recommended to be 0.50~0.58 for a laminar flow of liquid, -0.012~0.25 for a turbulent flow of liquid, 0.8~1.35 for a laminar flow of gas, and -0.1 for a turbulent flow of gas.

2.2 Single Phase Heat Transfer Coefficient

Many research reactors are operated at low pressure-low temperature conditions, and therefore the coolant is in single liquid phase. Therefore, the most important heat transfer correlation is the single-phase forced convection correlation, and a single-phase natural convection correlation is also required. RELAP5/MOD3.3 uses various correlations by selecting the “geometry set”.

The default geometry set is 101 set, which contains the following correlations.

Natural convection : Churchill-Chu (for vertical flat plate)
Laminar forced convection : 4.36 (analytic value for circular channel)
Turbulent forced convection : Dittus-Boelter

In contrast, the 102 set can be selected for a narrow rectangular channel, which contains the following correlations. The set was developed for the rectangular channel of the ANS (Advanced Neutron Source) reactor in ORNL.

Natural convection : Elenbass (for vertical rectangular channel)
Laminar forced convection : 7.63 (analytic value for α=0.0147)
Turbulent forced convection : Petukhov

In addition, RELAP5/MOD3.3 selects the maximum value among natural, laminar forced, and turbulent forced convection coefficient by internal logic as

$$Nu_{D_h} = \max(Nu_{\text{natural}}, Nu_{\text{laminar}}, Nu_{\text{turbulent}}) \,.$$

2.2.1 Natural Convection

The Churchill-Chu correlation is used in RELAP5/MOD3.3 for natural convection on a vertical wall. The correlation is

$$Nu_L = \left[0.825 + \frac{0.387 Ra_L^{1/6}}{\left[1 + \left(0.492 / \mathrm{Pr} \right)^{9/16} \right]^{8/27}} \right]^2 ,$$

$$Ra_L = \mathrm{Pr} \cdot Gr_L = \frac{\mu C_p}{k} \cdot \frac{\rho^2 g \beta \left(T_w - T_b \right) L^3}{\mu^2} ,$$

where β is the heat expansion coefficient, μ is the fluid viscosity, k is the thermal conductivity of the fluid, T_w and T_b are the temperatures of the bulk and wall, and L is the length for natural convection. The length of natural convection is the height of a single vertical plate.

The Elenbass correlation is for the natural convection in a vertical narrow rectangular channel, which is

$$Nu_b = \frac{1}{24}\frac{b}{L} Ra_b \left[1 - \exp\left(-\frac{35}{Ra_b}\frac{L}{b} \right) \right]^{3/4},$$

where *b* is the channel gap. *L* is the natural convection height, which is the height of the channel.

2.2.2 Laminar Forced Convection

The heat transfer coefficient for laminar forced convection is derived analytically. For constant heat flux from the wall, the Nu_D=4.36 in a circular pipe, and Nu_D=4.36 in parallel plates. The solution for a rectangular channel with constant heat flux can be approximated as

$$Nu_{D_h} = 8.235(1 - 2.0421\alpha + 3.0853\alpha^2 - 2.4765\alpha^3 + 1.0578\alpha^4 - 0.1861\alpha^5),$$

where α is the aspect ratio of the channel. The 102 geometry set of RELAP5/MOD3.3 uses Nu_D=7.63, which is calculated for the narrow rectangular channel of the ANS reactor. The model research reactor in this report has Nu_D=7.67.

2.2.3 Turbulent Forced Convection

With the default geometry set, 101, the Dittus Boelter heat transfer correlation is used for turbulent forced convection, which is

$$Nu_{D_h} = 0.023\,\mathrm{Re}_{D_h}^{0.8}\,\mathrm{Pr}^{0.4} \qquad \mathrm{Re} = 10^4 \sim 1.2\times10^5,\ \mathrm{Pr} = 0.7 \sim 120,\ L/D_h \geq 60.$$

The Petukhov correlation is used for turbulent forced convection with the 102 geometry set of RELAP5/MOD3.3. The Petukhov correlation is

$$Nu_{D_h} = \frac{\frac{f}{8}\mathrm{Re}_{D_h}\,\mathrm{Pr}\left(\frac{\mu_b}{\mu_{ws}}\right)^{0.11}}{(1+3.4f) + \left(11.7 + \frac{1.8}{\mathrm{Pr}^{1/3}}\right)\left(\frac{f}{8}\right)^{0.5}(\mathrm{Pr}^{2/3}-1)} \qquad \mathrm{Re} = 9000 \sim 35000$$

where *f* is the friction coefficient of the channel as

$$f = \frac{1.0875 - 0.1125\alpha}{(1.82\log\mathrm{Re}_{D_h} - 1.64)^2}.$$

This friction coefficient is the result of combining the Filonenko's friction coefficient for a smooth circular channel with Kakaç's equation for rectangular channel compensation (Ref.2, Ref.3).

3 EXPERIMENTS FOR VALIDATION

3.1 CNNC Experiment for Narrow Rectangular Channel

A CNNC test loop was constructed to simulate the pressure drop and heat transfer of single phase flow in a narrow rectangular channel (Ref. 4). Table 1 shows the parameters of the experimental setup. Figure 1 shows the schematic of the experimental setup, which is composed of a supply tank, pumps, a pressurizer, a filter, a preheater, a flowmeter, a heat exchanger, valves and a test section. Figure 2 shows the test section. The test section is installed upright in the test loop, and consists of three layers of components. The core layer is composed of heating plates with the grooves that make up the narrow rectangular channel. The middle layer is mica blocks which serve as a thermal insulator. The outer layer is the clamps that keep the layers together. Both the heating plates and the clamps are made of stainless steel (0Cr18Ni10Ti). Smooth inlet and outlet transition sections (each 110 mm long) are provided at both ends of the test section.

The temperature at the inlet and outlet of the test channel is measured using sheathed thermocouples (N-type, 1 mm). The two temperature measurement locations are 150 mm before the inlet and after the outlet of the test channel. A total of 14 sheathed thermocouples (N-type, 1 mm) are divided into two groups and symmetrically placed on the outer sides of the two heating plates to measure the outer-wall temperatures. The thermocouples are at axial distances of 160.0, 360.0, 560.0, 790.0, 860, 930 and 1000 mm from the inlet. The local pressures are measured at the five vessels with a diameter of 4 mm on the outer side of one heating plate. The pressure vessels are at axial distances of 170.0, 370.0, 570.0, 870, and 1070 mm from the inlet.

Figure 3 shows the channel cross section. The channel is 2mm (e) deep and 40mm (b) wide, therefore the aspect ratio (e/b) is 0.05. The hydraulic diameter ($D_h = 4A_c/P$, where A_c and P are the cross-sectional area and the wet perimeter of the fluid channel, respectively) is about 3.64 mm. The total length to diameter ratio (L/D_h) is 300, and the effective heated (L_h/D_h) ratio is 285. The mean wall relative roughness in the test channel (ε/D_h, where ε is the mean wall absolute roughness) is $8.5\text{x}10^{-4}$.

The heating plates are energized using a DC power supply (20 kW total power). The accuracy of the temperatures and pressure differences are ±0.3 °C and ±30 Pa, respectively. The uncertainty in the measured mass flow rate is ±2%, and that in the measured operational pressure is ±1 kPa.

The CNNC experiments includes Isothermal and non-isothermal friction coefficient measurements, and measurements of the heat transfer coefficients by forced convection. The forced convection experiment covers the laminar, transition and turbulent flow regions.

Table 1 Design Parameters of the CNNC Experimental Apparatus

Parameters	Data	Remarks
Flow direction	Upward	Vertical channel
Channel gap (e, mm)	2	
Channel span (b, mm)	40	
Heater block thickness (δ, mm)	3	
Hydraulic diameter (D_h , mm)	3.64	
Roughness (ε, mm)	3.09×10^{-3}	$\varepsilon/D_h = 8.5 \times 10^{-4}$
Channel length (L, m)	1092	$L/D_h = 300$
Heated channel length (L_h, m)	1037.4	$L_h/D_h = 285$
Inlet temperature measurement	150mm before the inlet.	
Outlet temperature measurement	150mm after the outlet	
Thermocouple position (mm)	160.0, 360.0, 560.0, 790.0,860, 930 and 1000	From the inlet
Pressure vessel position (mm)	170.0, 370.0, 570.0, 870, and 1070	From the inlet
Parameters	Data	Remarks
Isothermal experiments		
- Inlet temperature ($T_{f,in}$, °C)	24 ~ 37.5	Adjusted by preheater
- Mass flux (G, kg/(m^{2}s))	285 ~ 2000	Re = 1090~10200
- Prandtl number (Pr)	4.6 ~ 6.2	
Non-isothermal experiments		
- Inlet temperature ($T_{f,in}$, °C)	27.8 ~ 30	Adjusted by preheater
- Mass flux (G, kg/(m^{2}s))	306 ~ 2320	Re = 1460~13000
- Heat flux (q, kW/m^2)	14 ~ 214	Q = 1.22 ~ 18.6 kW
- Prndtl number (Pr)	3.9 ~ 5.7	

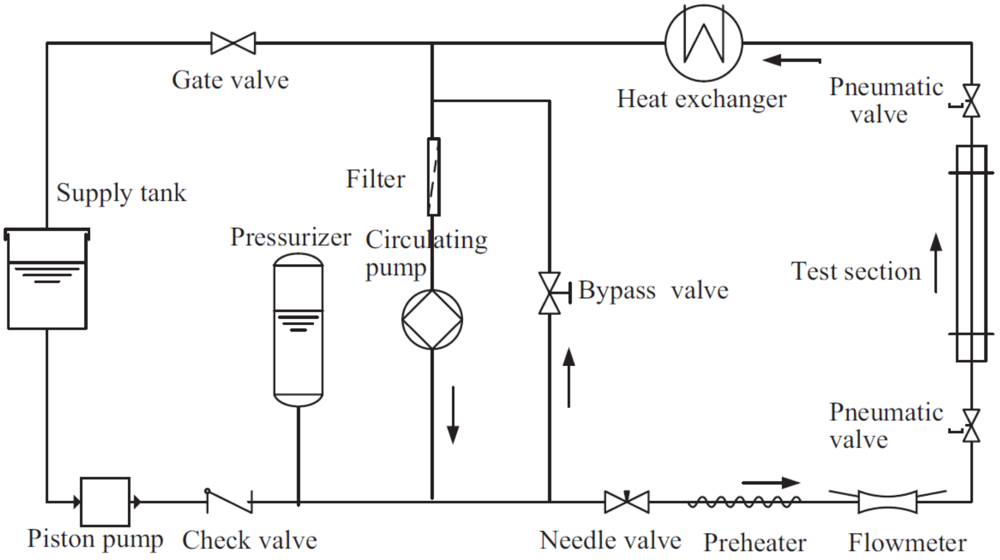


Figure 1 Schematic Diagram of the CNNC Test Loop

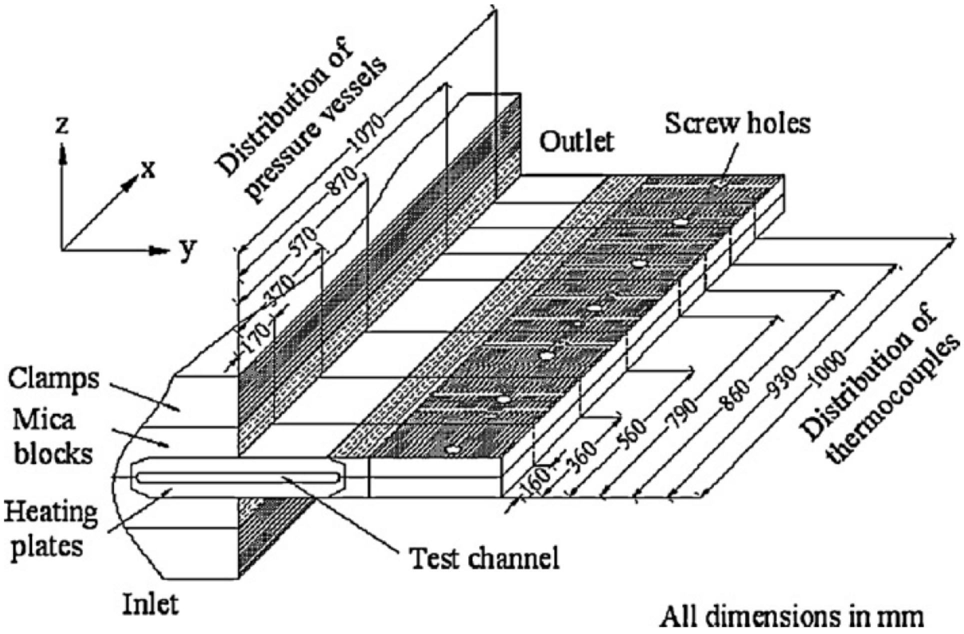


Figure 2 Schematic of the Test Channel

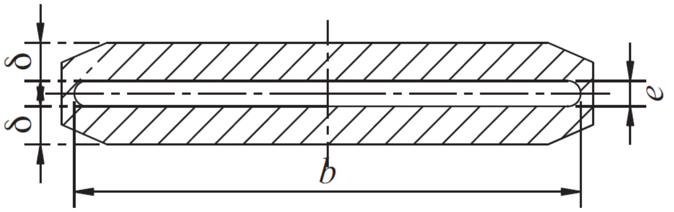


Figure 3 Schematic Diagram of the Channel Cross-section

3.2 KAERI OFEL Experiment

KAERI (Korea Atomic Energy Research Institute) performed the OFEL (Omni Flow Experimental Loop) experiment to measure the pressure drop across the narrow rectangular channel [5]. The experiment measures the isothermal friction coefficient in the narrow rectangular channel with higher flow rates than those of the CNNC experiment. Table 2 shows the major variables of the KAERI OFEL experiment.

Table 2 Major Variables for KAERI OFEL Experiment

Parameters	Data	Remarks
Flow direction	Downward	Vertical channel
Channel gap (e, mm)	2.35	
Channel span (b, mm)	66.6	
Hydraulic diameter (D_h , mm)	4.53	
Channel length (L, mm)	680	
Re_D (isothermal)	5544-34890	For D_h

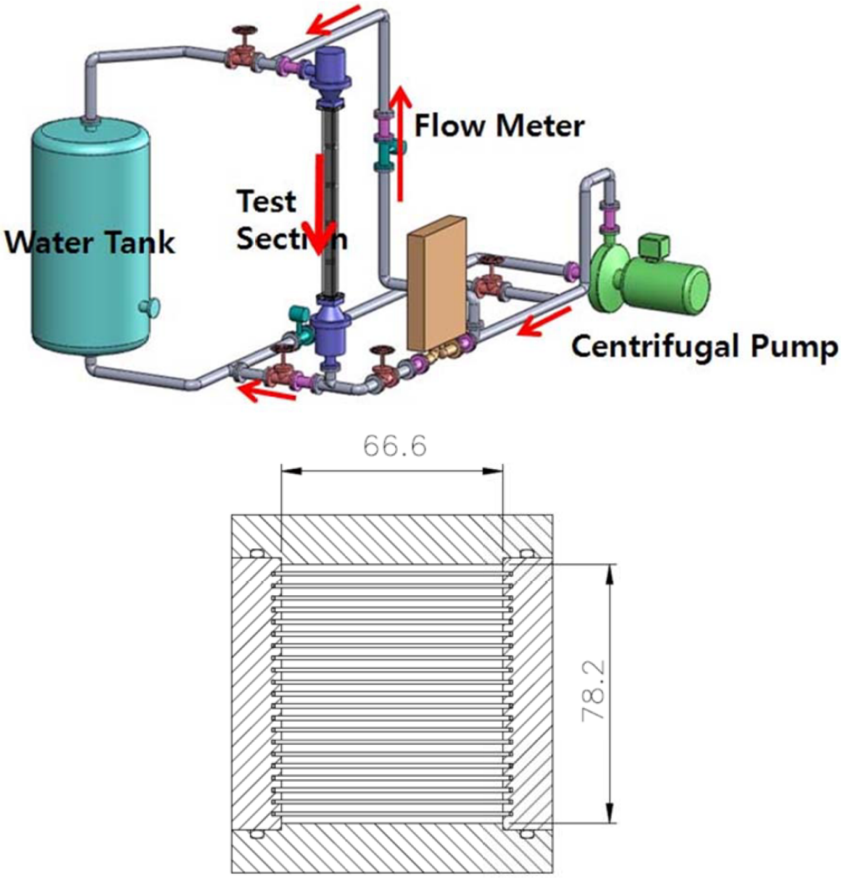


Figure 4 Experimental Setup and Channel of KAERI OFEL

4 COMPARISON OF RELAP5/MOD3.3 AND EXPERIMENTS

4.1 RELAP5/MOD3.3 Model

Figure 5 shows the node diagram of RELAP5/MOD3.3 for modelling the CNNC isothermal flow and non-isothermal convective heat transfer experiments. The test section was modelled as a heated pipe (150) and the remaining parts were simplified as a single junction, time dependent junction and time dependent volumes. Time dependent volumes of 140 and 160 were set for the system pressure and temperature, and the time dependent junction 155 controls the mass flow rate through the channel. The pipe component has 22 subvolumes for estimating the precise temperature and pressure changes along the channel axial direction. Table 4 shows the summary of the nodes and junctions used in the model. Since the pipe material is stainless-steel, the thermal properties of the s-steel table in RELAP5/MOD3.3 are used for the calculation.

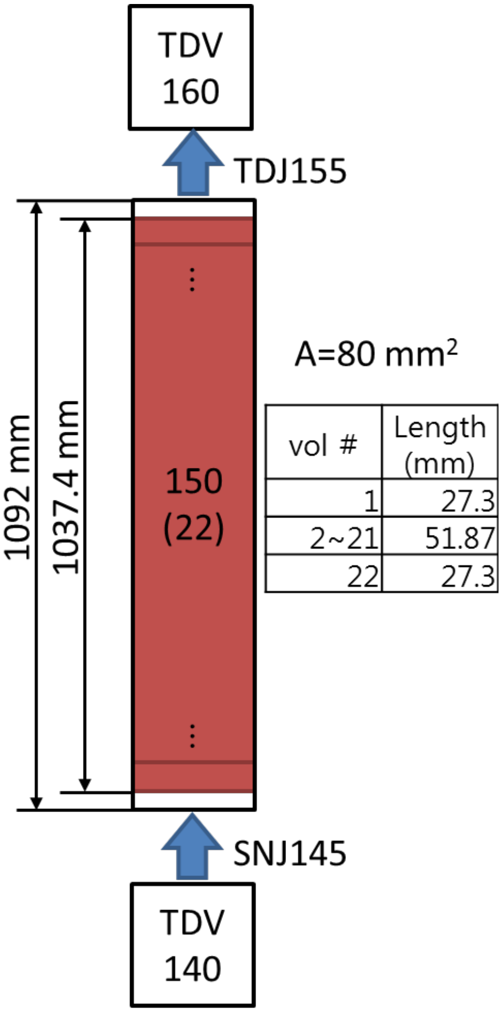
The RELAP5/MOD3.3 model used for the KAERI OFEL experiments is similar to that used for the CNNC experiment, but the channel dimension and the flow direction were modified to simulate the KAERI OFEL channel.

In both models, the isothermal experiment was modelled by setting the heating power to be zero, thus the fluid temperature is constant throughout the channel. The mass flow rate at time dependent junction 15 was set to be the same as in the experiments.

The non-isothermal experiment was modelled by varying the mass flow rate and heating power according to the experimental condition. The local Nusselt numbers (Nu_x) at each subvolumes of the pipe component were calculated using the equations in Ch.2.2.3, and then averaged to get the mean Nusselt number (Nu_m) for comparison with the experimental results.

Table 3 Description of the Nodes and Junctions

Node/Junc. No.	Model types	Description
140	Time dependent volume	Inlet boundary of the channel
145	Single junction	Connection between 140 and 150
150	Pipe with 22 subvolumes	Test section
155	Time dependent junction	Connection between 150 and 160 Controls the channel mass flow rate
160	Time dependent volume	Outlet boundary of the channel
150	Heat structure	Stainless steel. 20 axial node, 10 interval .



vol #	Length (mm)
1	27.3
2~21	51.87
22	27.3

Figure 5 Node Diagram of RELAP5/MOD3.3 Model

4.2 Friction Coefficient

4.2.1 CNNC Rectangular Channel Experiment

Figure 6 shows the comparison between the isothermal friction coefficients measured in the CNNC experiment and those obtained with te RELAP5/MOD3.3 calculation. The shape factor of the RELAP5/MOD3.3 calculation is $\Phi_s = 0.71$, which is the value for the aspect ratio of the CNNC experimental channel, 0.05. The RELAP5/MOD3.3 calculation results match well with the experimental results in the laminar and turbulent regions. The calculation overestimates the friction coefficient in the transition region.

Figure 7 shows the friction coefficient in the heated channel measured by the CNNC experiments. The RELAP5/MOD3.3 calculation is compared with three different viscosity ration exponents, *D*=0, 0.25 and 0.58. The 0.25 is recommended for the liquid turbulent region and 0.58 is for the liquid laminar region following the RELAP5/MOD3.3 manual. As recommended, the results show better coincidence with *D*=0.25 as the flow rate increases.

4.2.2 KAERI OFEL Experiment

Figure 9 shows the isothermal friction coefficients from the KAERI OFEL experiment and the RELAP5/MOD3.3 calculation. The results of the experiment and the calculation match well over a wide range of Re.

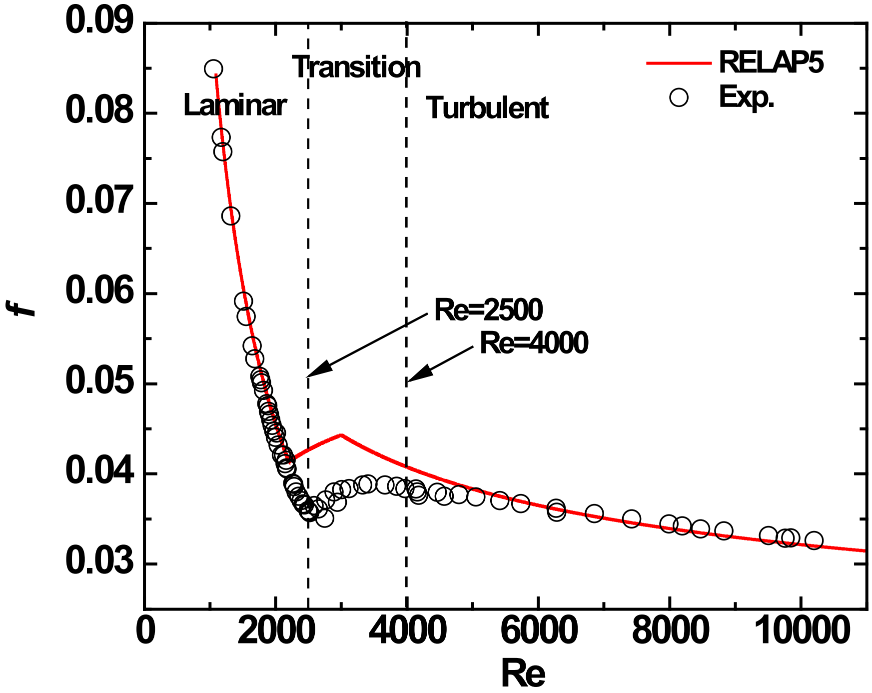


Figure 6 Isothermal Friction Factor from the CNNC Experiments and RELAP/MOD3.3 Calculation

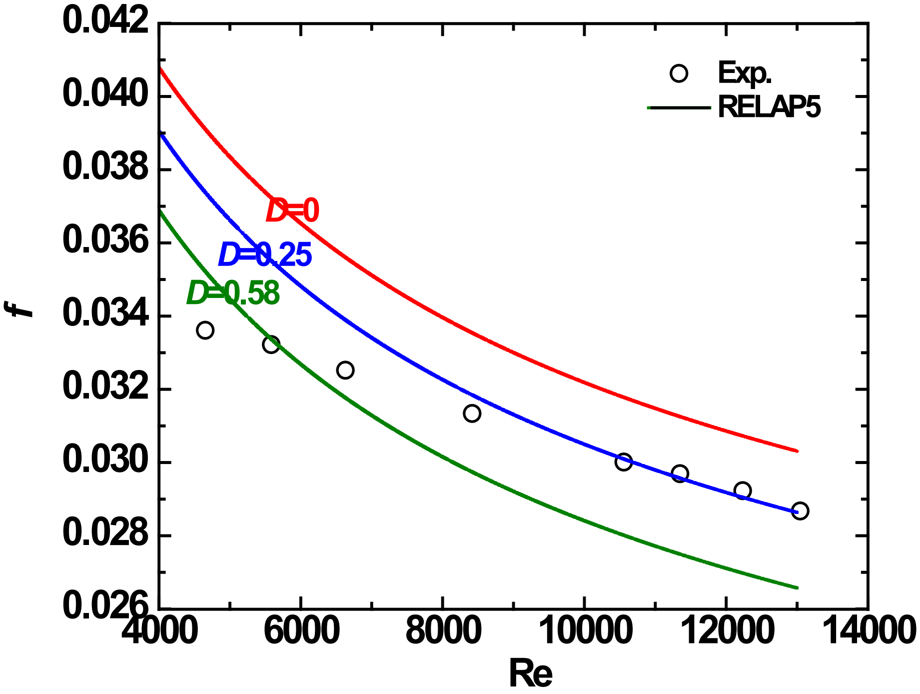


Figure 7 Friction Factor for the Heated CNNC Channel and RELAP5/MOD3.3 Calculation

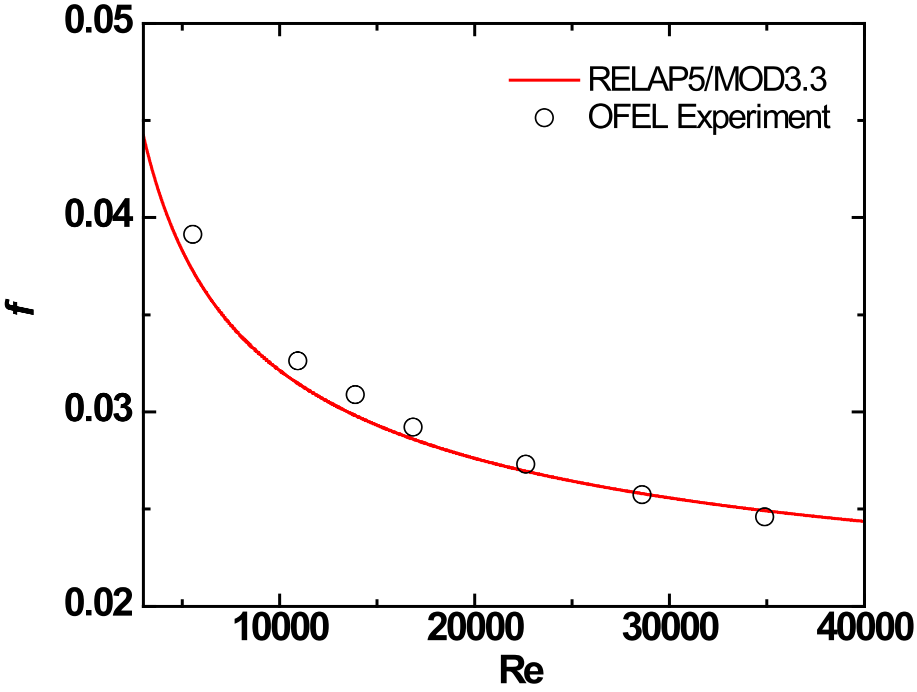


Figure 8 Friction Factor from the KAERI OFEL Experiment and RELAP5/MOD3.3 Calculation

4.3 Heat Transfer Coefficient

4.3.1 CNNC Rectangular Channel Experiment

Figure 9 shows the comparison between the heat transfer from the CNNC experiments and that calculated by RELAP5/MOD3.3 with different geometry sets, 101 and 102. Also, the Nu numbers for the laminar forced convection for the circular and the rectangular channels are shown for reference. The aspect ratio of the rectangular channel is that of the CNNC channel.

The 102 geometry set of RELAP5/MOD3.3 calculation tends to overestimate the heat transfer coefficient comparing the CNNC experimental results over the whole experimental range. The Petukhov correlation seems to overpredict the heat transfer in this Re range. On the other hand, the 101 set estimates the turbulent heat transfer properly in relation to the experiment, but the set still overestimates the heat transfer in the laminar and transition regions. Specifically, the calculation greatly overpredicts the heat transfer in the laminar region.

RELAP5/MOD3.3 overpredicts the laminar heat transfer because of the internal logic by which the code selects the heat transfer coefficient for natural, laminar and turbulent convection. The RELAP5/MOD3.3 has an internal logic which selects the maximum value among natural, laminar and turbulent Nu. Since the laminar Nu is much smaller than the turbulent Nu in most of the laminar region, the code selects the turbulent Nu even though the flow is, in fact, laminar. Furthermore, the 102 set uses the Nu at Re=2200 where Re<2200, causing a further discrepancy.

4.3.2 Modification of RELAP5/MOD3.3 and Result

The internal logic of RELAP5/MOD3.3 which selects the laminar, transition and turbulent Nu was modified such that the code selects Nu with respect to the Re. The modified code selects the Nu of natural or laminar forced convection for Re<2500, and selects turbulent Nu for Re≥4000, and interpolates between them.

Figure 10 shows the calculation results for the original and the modified RELAP5/MOD3.3. The modified code still overpredicts the Nu a little at low Re, but the difference between the calculation and the measurement is now dramatically low. The Nu of the laminar and transition regions especially follow the experimental data quite well.

The effect of the modified Nu selection logic in RELAP5/MOD3.3 was then examined for an actual scenario of reactor transition. For a typical 5 MW pool type research reactor with downward flow, the loss of flow accident by an all pump failure scenario was selected as the sample problem. Table 5 shows the major variables of the reactor.

When all of the primary cooling pumps fail, the pumps start to coastdown and the flow decreases. The reactor is tripped by the primary coolant flow low or the low core differential pressure signal of the reactor protection system. When the flow coastdown finishes, the core flow reverses from downward to upward due to natural convection. Once the core flow reverses, the core is cooled by natural convection via the flap valves which are passively opened as the core flow decreases. Since the core flow reverses in this accident, the core flow rate experiences a turbulent-transition-laminar region, which is affected by the code modification.

Figure 11 shows the maximum fuel temperature calculated using the original and the modified code, which represents a more significant difference. Since the fuel temperature is directly determined by the heat transfer coefficient at the fuel surface, the fuel temperature obtained with the modified code shows higher values at the laminar and transition regions, 20 s after the accident initiation.

The fuel temperature is affected by modifying the RELAP5/MOD3.3. Although the difference does not affect the maximum fuel temperature of the accident, proper modification is recommended for the laminar and transition heat transfer coefficient calculation.

Table 4 Major Variable of Model Reactor

Parameters		Value	Remarks
Power (MW)		5.0	
Pressure (MPa)		0.18	Core inlet
Temperature (^{0}C)		35.0	Core inlet
Flow direction		Downward	Vertical channel
Re (for D_h) at normal operation		17400	
Average heat flux (MW/m^2)		0.166	

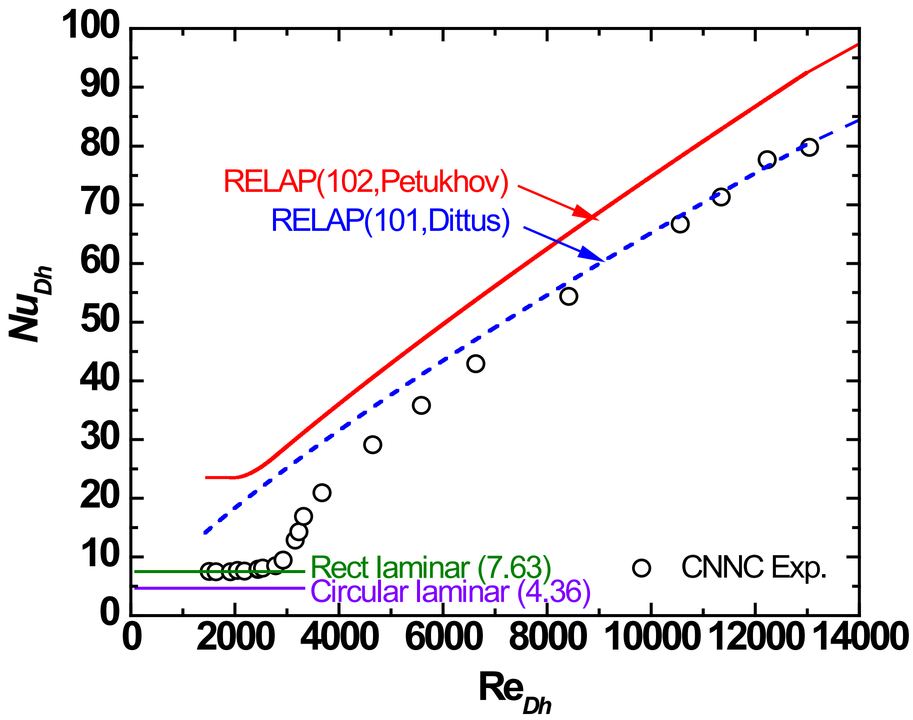


Figure 9 Heat Transfer from the CNNC Experiment and RELAP5/MOD3.3 Calculation

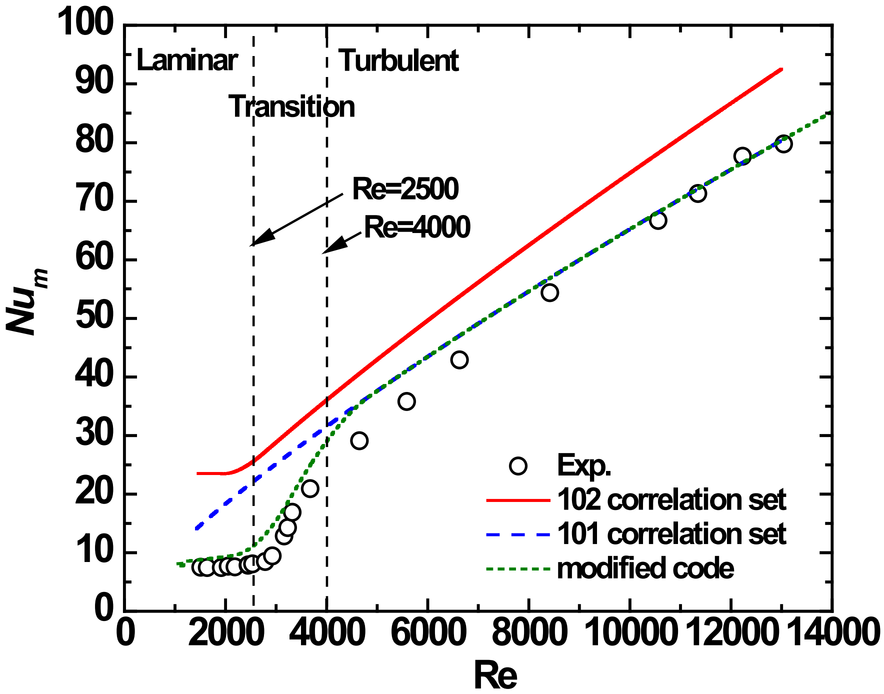


Figure 10 **Heat Transfer Calculation using the Original and Modified RELA5/MOD3.3**

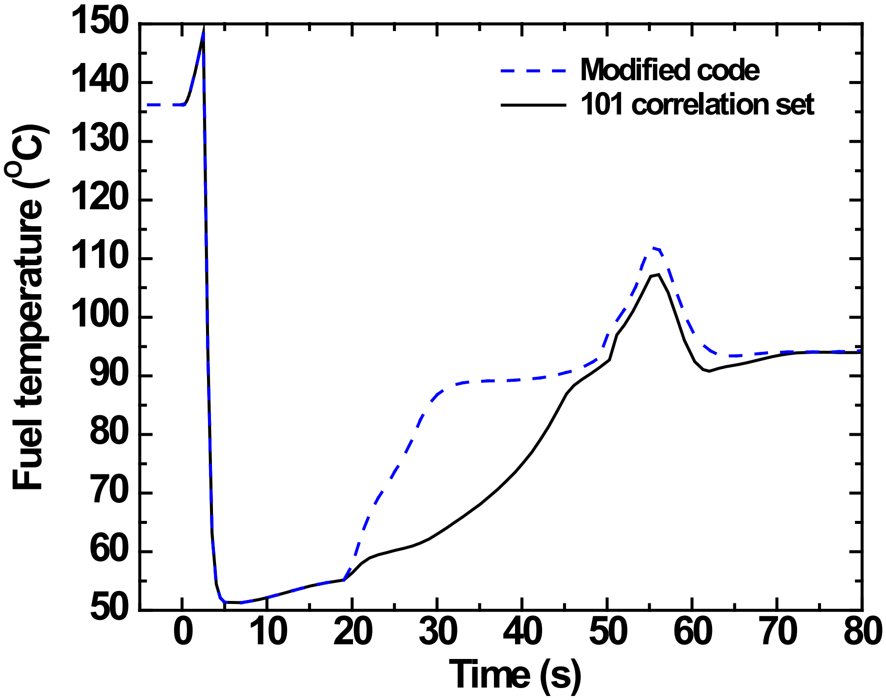


Figure 11 **Maximum Fuel Temperature during an All Pump Failure Accident**

5 CONCLUSIONS

The friction loss and the heat transfer models in RELAP5/MOD3.3 were assessed using CNNC experiments and KAERI OFEL tests, which are experiments for narrow rectangular channels. The friction coefficient of RELAP5/MOD3.3 matched the experimental results well when the proper shape factor was selected for the laminar flow, and the proper viscosity ratio exponent was selected for the heated channel flow. The shape factor for laminar flow was determined using the aspect ratio of the rectangular channel shape, and the viscosity ratio exponent was selected using the recommended value from RELAP5/MOD3.3

The heat transfer coefficient of RELAP5/MOD3.3 varies depending on the selection of the geometry set, which are provided by the code. The 102 set was prepared for the ORNL ANS reactor, however, it does not provide a good prediction for heat transfer coefficient compared with the CNNC experimental results. Instead, the default 101 set for circular channels showed better agreement with the experiment, however, it still overestimated heat transfer in the laminar and transition regions. The overestimation originates with the internal logic used for selecting the laminar, transition and turbulent heat transfer coefficient, which simply selects the maximum value among them. The RELAP5/MOD3.3 internal logic for selecting heat transfer coefficient was modified so that the code selected the proper heat transfer coefficient with Re. After the modification, the modified code provided better predictions of heat transfer coefficients in the laminar and transition regions.

The effect of code modification was examined for a typical 5 MW pool type research reactor. The modification affected the fuel temperature during the accident, where the flow condition is in the laminar and transition regions. Although the difference did not influence the accident conclusion, or the fuel integrity, it is recommended that RELAP5/MOD3.3 be modified to properly select the laminar and transition heat transfer coefficients.

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11. ABSTRACT (200 words or less)

The friction loss and the heat transfer models in RELAP5/MOD3.3 were assessed using CNNC experiments and KAERI OFEL tests, which are experiments for narrow rectangular channels. The test sections of the experiments were modeled with PIPE, TMDPVOL and TMDPJUN, considering the geometry and boundary conditions. Since the friction loss and heat correlations of RELAP5/MOD3.3 are supplied with a form of “geometry set”, the default set for circular geometry and a narrow rectangular set were compared to find an adequate set which properly simulated the experiments.

The assessments included the friction coefficients of the isothermal and non-isothermal channels, and the heat transfer coefficients of forced convection in the channel. The friction and pressure drop in the isothermal channel were well reproduced by RELAP5/MOD3.3 over the whole flow range in the experiments, but a proper shape factor in the laminar flow region was necessary. Also, the non-isothermal friction coefficients matched the experimental results well with the proper viscosity ratio exponent. The heat transfer coefficients in the turbulent flow region matched well with the 101 set, whereas the 102 set tended to overpredict the heat transfer coefficient in the high Re region. The heat transfer coefficients in the low Re region were overpredicted by RELAP5/MOD3.3 due to its internal logic, which simply selects the highest heat transfer coefficient among those of laminar, turbulent, and natural convection. After modifying that logic, the RELAP5/MOD3.3 showed good agreement with the experimental data

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