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연구용 원자로 안전해석 적용을 위한
MARS 코드 검증 계산

Validation Calculations for the Application of of MARS Code to the Safety Analysis of Research Reactors

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제 출 문

한국원자력연구소장 귀하

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주저자 : 박 철

공저자 : 김 헌 일

임 인 철

채 희 택

SUMMARY

Generally speaking, no robust computer codes such as RELAP5, RETRAN, and MARS are available for the analysis of research reactor, and it is highly recommended that computer codes developed for the transient analysis of power reactors should be applied carefully after modifying them appropriately or assessing the applicability for a specific research reactor.

In this work, the following test data were used to investigate the applicability of MARS code to the accident analysis of the HANARO and other RRs.

- ☐ Test data of the HANARO design and operation
- ☐ Test data of flow instability and void fraction from published documents
- ☐ IAEA RR transient data in TECDOC-643
- ☐ Brazilian IEA-R1 experimental data

For the simulation of the HANARO data with finned rod type fuels at low pressure and low temperature conditions, MARS code, developed for the transient analysis of power reactors, was modified. Its prediction capability was assessed against the experimental data of the HANARO. From the assessment results, it can be said that the modified MARS code could be used for analyzing the thermal hydraulic transient of the HANARO.

Some other simulations such as flow instability test and reactor transients were also done for the application of MARS code to RRs with plate type fuel. In the simulation for these cases, no modification was made. The results of simulated cases show that the MARS code can be used to the transient analysis of RRs with careful considerations. In particular, it seems that some improvements on a void model may be necessary for dealing with the phenomena in high void conditions.

TABLE OF CONTENTS

List of Tables

List of Figures

1. INTRODUCTION

A reliable and accurate analysis code is necessary for a safety analysis, because the reactor facility design, for instance the specifications for the containment and safety systems, may depend on the postulated accident analysis. So it is highly recommended that robust computer codes such as RELAP5, RETRAN, and MARS (Multi-dimensional Analysis of Reactor Safety)[1] developed for the transient analysis of power reactors should be applied carefully after modifying them appropriately for a specific research reactor.

However, the applicability of such codes should be confirmed before they are applied to the analysis of a research reactor whose operating conditions are usually much different from those of power plants. This is the case to the assessment of the HANARO (Highly Advanced Neutron Application Reactor) [2] with finned rod type fuels, which is operating under low pressure and low temperature conditions. Thus, the MARS code, which is being developed and verified by KAERI (Korea Atomic Energy Research Institute), was modified to properly simulate the unique HANARO characteristics such as the finned fuel and the plate type heat exchanger.

In research reactors which generally use plate type fuels, the flow instability (or flow excursion) is one condition of important interest in the thermal hydraulic safety analysis of a research reactor with plate type fuel which is operating at low pressure conditions [3,4]. It is because the vapor to liquid volume ratio is so large that the generation of voids in narrow flow channels of research reactors can cause a sudden reduction of the flow rate due to a large pressure drop and can lead to on adverse fuel damage.

So the objective of this work is to develop modified MARS code for the HANARO safety analysis and to perform validation calculations with the experimental data for the HANARO. The MARS code also contains the standard thermal hydraulic correlations, and the applicability of the code to the other research reactor using plate type fuels is also checked through available test data.

To assess the prediction capability of MARS for the HANARO, simulations for single pin heat transfer experiments and plate type heat exchanger performance test were made and compared with experimental results and manufacturer’s data. The natural circulation experiment was also simulated to evaluate the performance of the code. The system behaviors by RELAP5/MOD3 and the modified MARS were compared through the simulations on HANARO transients.

For the validity assessment of MARS code to be applied to the analysis of a research reactor with plate type fuels, some calculations of separate effect tests have been performed. The simulations performed by the MARS code are on the characteristics of the pressure drop along with the flow rate which is related to the T/H condition to induce a flow excursion or flow instability, and on the void distribution in a heated flow channel as well. The simulation results for the selected IAEA benchmark tests and the measurements at the IEA-R1 reactor have been compared with the experimental results.

2. MARS CODE FOR THE ASSESSMENT CALCULATIONS

2.1 Modification of MARS code for the HANARO application

The MARS code, is a realistic system transient analysis code that can be used for the simulation of a wide variety of PWR system transients. This code is a unified version of 1-D reactor system analysis code, RELAP5/MOD3 and 3-D reactor vessel analysis code, COBRA-TF coupled with 3-D reactor kinetics code, MASTER and containment code, CONTEMPT4.

MARS code (Version MARS 2.3) was modified for the application to the analysis of the HANARO. Major modifications were made to the heat transfer correlations since they significantly affect the calculation results. The heat transfer correlations were developed based on the experimental data and the operating conditions of the HANARO fuel or selected carefully among the proper existing correlations, which were implemented into the code. The implemented heat transfer correlations are a single and two phase heat transfer, the onset of nucleate boiling (ONB), the subcooled nucleate boiling heat transfer and critical heat flux (CHF) correlations, which are listed in Table 1 [5]. A separate heat exchanger model was also developed to reproduce the data of the heat transfer and the pressure drop provided by the manufacturer since both the heat transfer and the pressure drop characteristics of the plate type heat exchanger installed in HANARO were quite different from those of the shell and tube type heat exchanger usually used in PWR.

2.2 MARS code for the application to a RR with plate type fuels

For the analysis of a RR with plate type fuels, the standard heat transfer correlations built-in the MARS code were used.

Table 1. Heat transfer correlations for a finned rod fuel implemented in MARS code [5]

Subroutines	Heat Transfer Coefficient & Correlations
DITTUS (Single-Phase)	o Laminar Flow: $h = 3.656\left(\frac{k}{D_e}\right)$ o Turbulent Flow: $h_{sp} = 0.009388\left(\frac{k_f}{D_e}\right)Re_f^{0.9109}\ Pr_f^{0.536}$ o Plate-type Heat Exchanger Model: $h = 0.1302\ \left(\frac{k}{D_e}\right)Re^{0.721}\ Pr^{0.4}, \quad Re \geq 290$ $h = 0.85\ \left(\frac{k}{D_e}\right)Re^{0.39}\ Pr^{0.4}, \quad Re < 290$
	o Chen Correlation:

PREDNB (Two-Phase)	$q'' = h_c(T_w - T_b) + h_{NCB}(T_w - T_{sat})$ o ONB (Onset of Nucleate Boiling) Correlation: $T_{w,ONB} = T_s + \left(\frac{8\sigma_s T_{s,K} v_{fg} h_{sp}}{h_{fg}\, k_s}\right)\left[1.0739\times10^5\, Re_f^{-0.77995}\, Pr_f^{-2.65827}\left(\frac{c_{p,s}\Delta T_{sub}}{h_{fg}}\right)^{0.212271}\right]$ o Subcooled Boiling Model: $h_{sb} = h_{sp}\,(1+\Psi\cdot\Delta T)$ $\Psi = 1.38\times10^5\cdot Bo_m^{0.5}\cdot(1+Re_b)^{-0.877}\cdot Pr_b^{-0.713}\cdot\left(\frac{\rho_f}{\rho_g}\right)^{-0.069}\cdot\left(\frac{D_h}{D_{sh}}\right)^{1.847}$ $\Delta T = \begin{bmatrix} \frac{T_w - T_{w,ONB}}{T_w - T_b}, & T_w \geq T_{W,ONB} \\ 0.0, & T_w \leq T_{w,ONB} \end{bmatrix}$
CHFCAL (Critical Heat Flux)	o High Flow CHF Correlation (HANARO Correlation): $q''_{CHF} = 1.81722\times10^{-2}\, Re^{0.454741}(1-\chi_e)^{7.06122}\left(\frac{\rho_f}{\rho_g}\right)^{-0.0015188}\left(\frac{8}{D_e}\right)^{1/3}\left(\frac{P_{ht}}{P_{ba}}\right)^{0.6}$ o Low Flow CHF Correlation (Modified Zuber Correlation): $q''_{CHF} = 0.1309\; h_{fg}\left(\rho_g\left(\sigma_g\, g\left(\rho_f - \rho_g\right)\right)^{1/2}\right)^{1/2}$

3. VALIDATION CALCULATIONS

Some calculations were carried out using the modified MARS code to verify whether the developed and implemented models such as heat transfer correlations and heat exchanger model are working as intended. The results are described below together with the brief test descriptions.

3.1 Simulation for the HANARO with a finned rod type fuel

3.1.1 Single Pin Experiment

1) Test data and model description

The single pin heat transfer test was performed using the electrically heated fuel element simulator (FES) enclosed in a glass tube as shown in Figure 1, which simulated the hydraulic characteristics of the finned fuel element of HANARO fuel[6, 7]. These fins are to enhance the convective heat transfer to coolant and to reinforce the mechanical strength of the fuel element. To confirm whether the modified code works as intended, a total of 32 data including 8 sets of single-phase, ONB, OSV (Onset of Significant Void), and two-phase data, were chosen from the experimental data [5]. Nodalization of the test section for MARS simulation is depicted in figure 1.

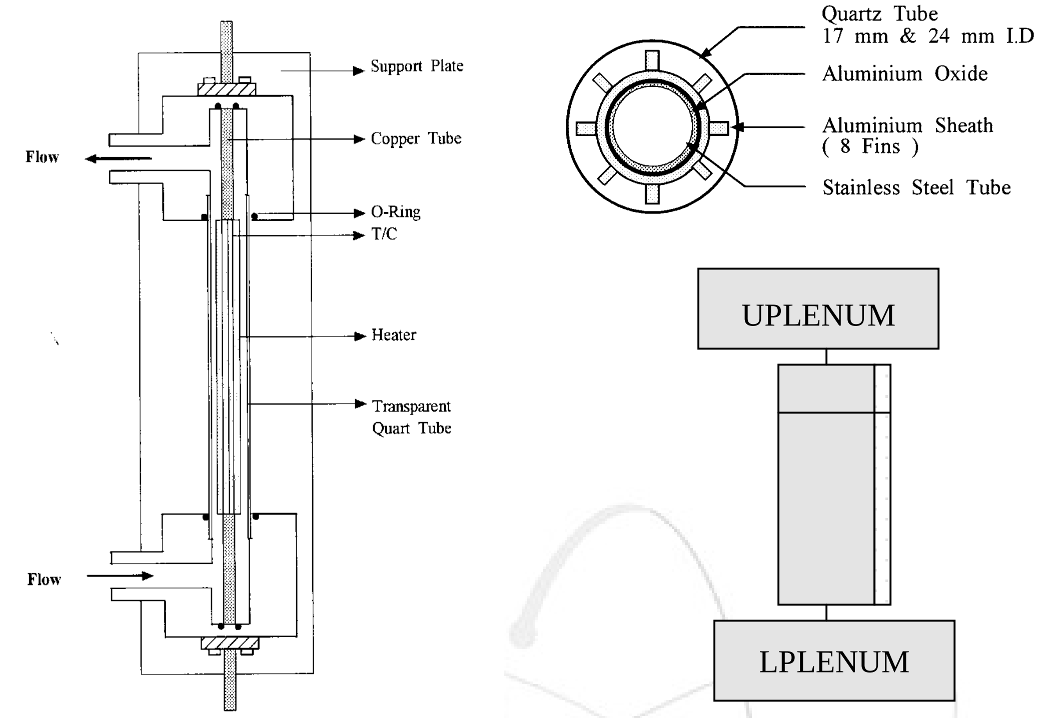


Fig. 1 Test section of single pin heat transfer experiment and nodalization for MARS simulation

2) Results

The comparison of the calculated heater surface temperature with the measured is shown in figure 2. As shown in the figure, the modified MARS shows a good agreement within 10% with the experimental data for the HANARO operating condition.

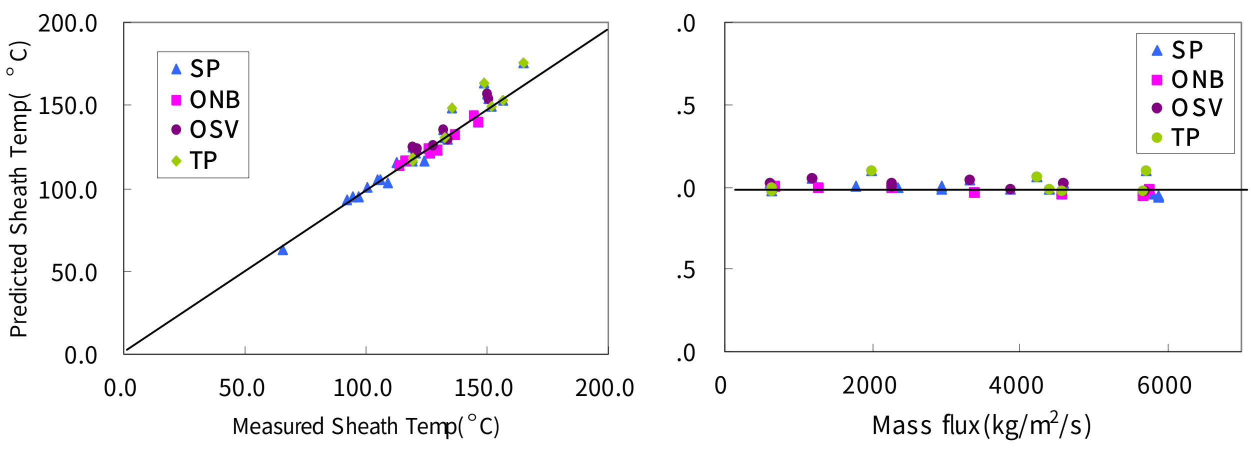


Fig. 2 Comparison of the predicted surface temperature with the measured one

3.1.2 Heat Exchanger Model

1) Test data and model description

As the pressure drops and the heat transfer characteristics as well as the channel geometry are quite different from those of the general shell and tube type heat exchanger, a new model was developed to reproduce the manufacturer's data [5] by implementing a new heat transfer correlation and manipulating code input such as flow area, hydraulic diameter and loss coefficient with a fixed real volume. Figure 3 shows the nodalization of the heat exchanger, which uses 12 volumes (volume number was optimized) and the primary and secondary sides coupled to the heat structures located in-between.

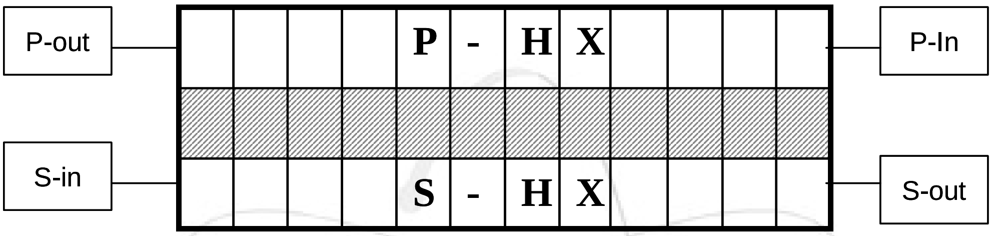


Fig. 3 Nodalization for a plate heat exchanger simulation

2) Results

The predicted heat transfer rate and pressure drop are compared with the manufacturer's data in Figure 4. The calculated results are in good agreement within an average of 2~3% error compared with the test data except in very low flow range. This discrepancy, which occurred in this very low core power range, is judged not to be serious in the simulation of the overall system transient.

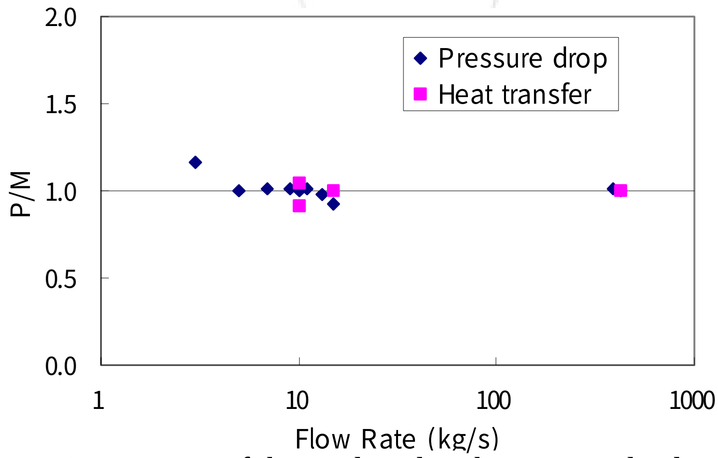


Fig. 4 Comparison of the predicted to the measured values for pressure drop and heat transfer rate

3.1.3 Natural Circulation Test

1) Test data and model description

A natural convection cooling test with a scale-down single heated bundle was performed in a large tank simulating the reactor pool [8] as shown in Figure 5. It was designed to demonstrate the general behavior of the HANARO reactor pool where the decay heat from the core is removed by the pool water re-circulation via flap valves. The bundle used in the test is an 18-element hexagonal array with nominally flat radial and cosine axial heat flux profiles. Coolant temperatures were measured at inlet and outlet of the test section, and then the flow rates were calculated from the relation of temperature and bundle power. The nodalization for MASR simulation is also shown in figure 5 and the atmospheric pressure at the pool surface was used as a boundary condition.

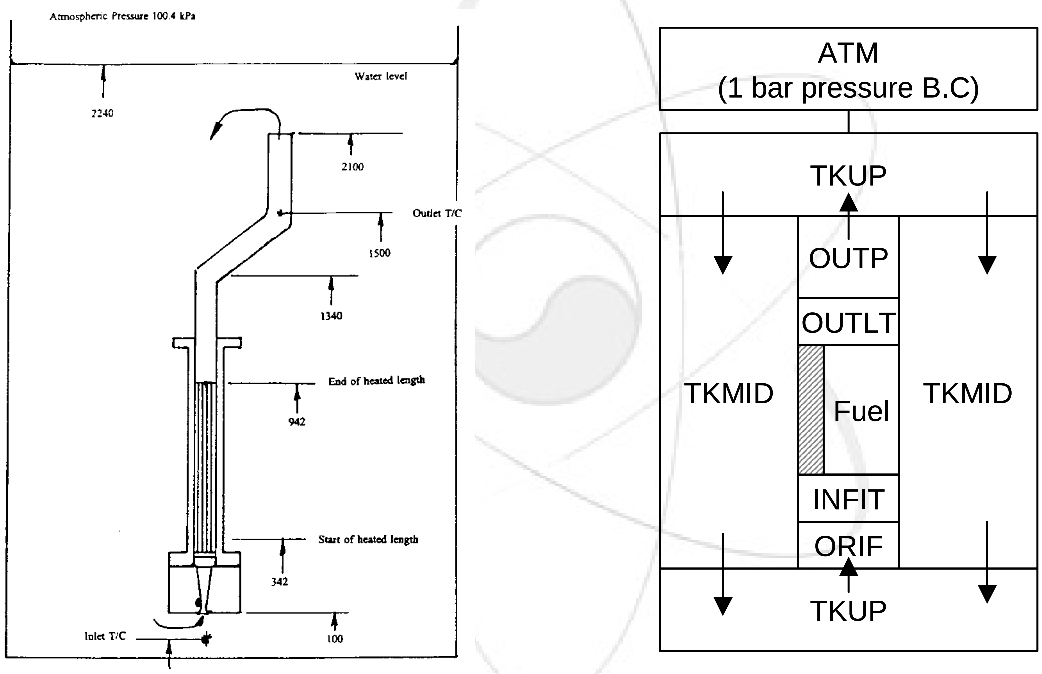


Fig. 5 Schematics of test facility and nodalization for MARS simulation

2) Results

The predicted results of the mass flow rate for each power level are presented in figure 6. The predicted results are similar to the experimental data, even though minor discrepancies of the flow rate are identified. However, these differences, which may be diminished if one use correct input for the frictional pressure loss across fuel bundle, are insignificant and conservatively acceptable in thermal-hydraulic analyses.

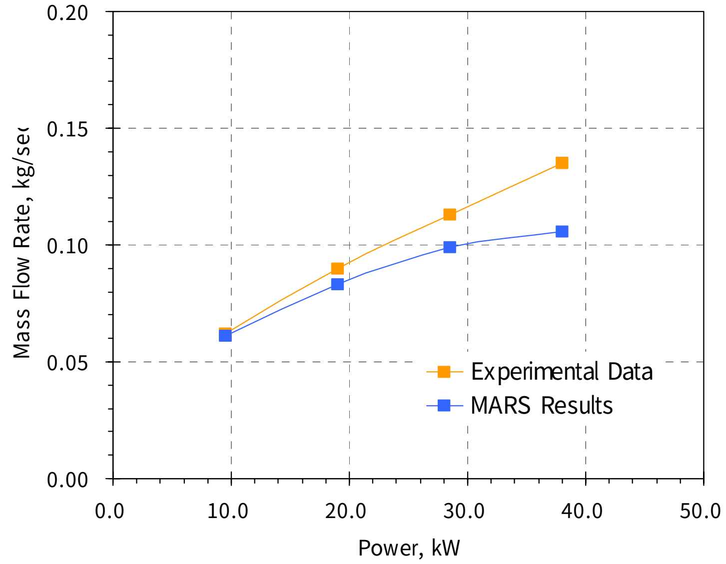


Fig. 6 Comparison of the predicted to the measured flow rate for each power level

3.1.4 HANARO LOEP Transient

HANARO is an upward flowing light water cooled, heavy water moderated open-tank-in-pool type research reactor with 30 MW_{th}[2]. The nodalization of HANARO for MARS simulation is shown in Figure 7. The reactor core is represented by 6 kinds of channels connected in parallel, i.e. a hot channel, an average channel and an unfueled channel for both hexagonal and circular flow channel. The reactor pool surface is connected to a time dependant volume which represents the atmosphere. Other components such as piping and pumps are modeled with proper models of MARS [9].

To compare the modified MARS with RELAP5/MOD3, simulations for HANARO LOEP transient were calculated by both codes.

1) Event and model description

The occurrence of this event results in the simultaneous loss of primary and secondary cooling pumps, cooling tower fans and a reflector pump for core cooling. And CARs(Control Absorber Rod) of which the power is class IV dropped immediately since the electro-magnetic switches were de-energized. Then the insertion of SORs(Shut-off Rod) followed due to the loss of pump supporting them hydraulically. As the uninterruptible power (class II) is connected to RPS, the reactor can be tripped by reactor protective actions if the reactor meets the condition in which RPS should be actuated. After reactor shutdown, firstly the core cooling should be ensured by coastdown flow due to flywheel and later by the natural circulation.

2) Results

Using MARS-h were calculated the thermal-hydraulic parameters such as flow rates and fuel temperatures. Figure 8 shows the comparison of coastdown flow rates at core inlet and fuel temperature during the LOEP transient by both codes. It can be shown that MARS gave reasonable predictions of flow rate and temperatures for the long term LOEP transients in the HANARO.

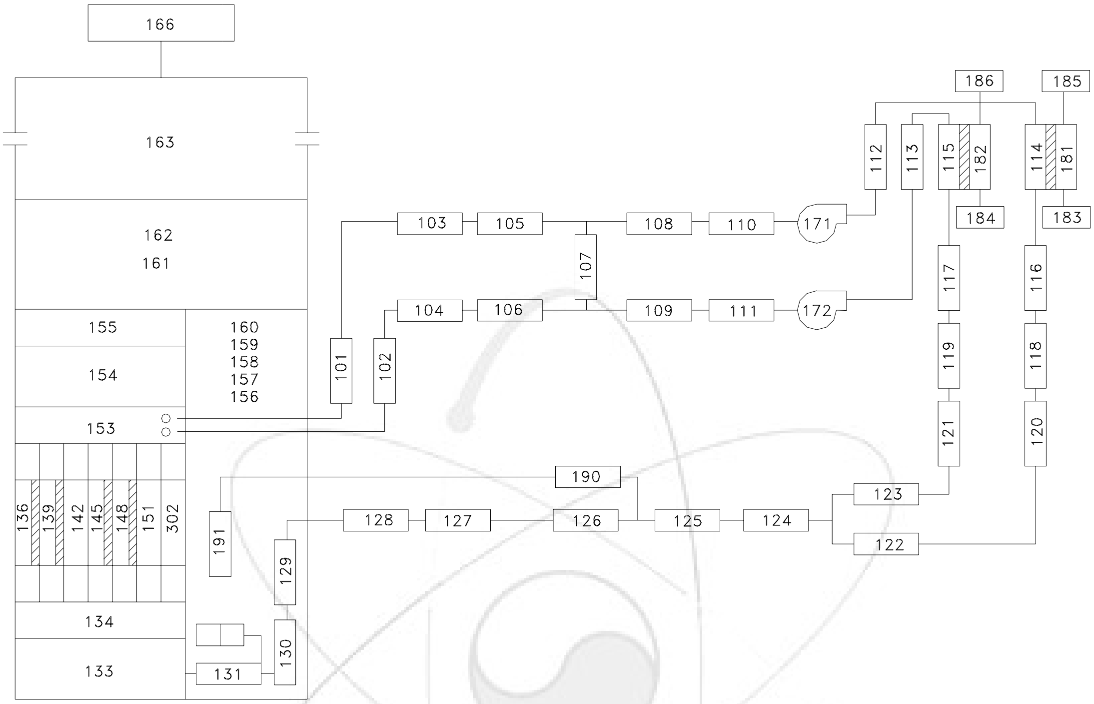


Fig. 7. Nodalization of HANARO for MARS

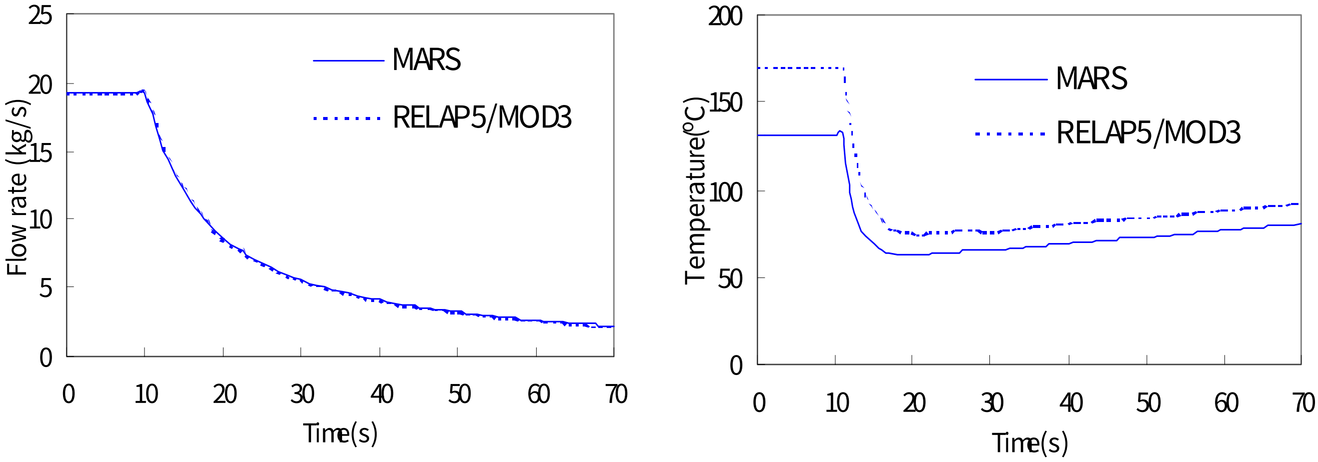


Fig. 8. Comparison of flow rate and fuel temperature for RELAP5 and MARS

3.1.5 Summary

MARS code which is developed for the transient analysis of power reactors was modified for applying to the analysis of the HANARO operating at low pressure and low temperature conditions, and its prediction capability was assessed against the experimental data of the HANARO data. From the assessment results, it can be said that the modified MARS code could be used for analyzing the thermal hydraulic transient of HANARO. However, a further improvement on a void model may be necessary for dealing with the phenomena in high void conditions.

3.2 Simulation for a Research Reactor with plate type fuels

3.2.1 Simulation of a Flow Excursion

The purpose of this task is to simulate the pressure drop characteristics along with the flow rate by the MARS code so that the T/H condition to induce a flow instability or flow excursion, i.e., the Onset of a Flow Instability (OFI) condition is determined. This is done by representing the curve of the pressure drop vs. the mass flux and to identify the minimum flow rate from the curve.

3.2.1.1 Simulation of the Forgan and Whittle Experiment

1) Description of the Experiment [10, 11]

The Forgan & Whittle experiment on the pressure drop characteristics along with the flow rate in a subcooled water has been used for the separate effect assessment of the MARS code in order to confirm the applicability of the code to the T/H analysis for research reactors. The schematics of the test loop and test section are presented in figures 9 and 10, respectively. In the tests, four different rectangular test sections and one round tube test section was used. The detailed dimensions of test sections and parametric ranges of tests are listed in table 2. In this work, experimental data for 3 different geometries of rectangular channels were selected and simulated. It is noted that data for TS No. 1 & 2 are taken directly from a reference [10] while data for TS No. 3 is read from the figure in reference [11].

The coolant in a flow channel is directly heated by on ac current through the walls, and the heat generation is uniform along the sectional length and around the periphery of the channel. Because of a large difference in the electrical resistances of the phosphor-bronze and the nichrome, the power dissipated through nichrome is less than 1% of the total. The pressure drop across the test section was measured by manometers. Detailed descriptions of the test and test procedures can be found in references [10, 11].

Table 2 Details of the Test Sections and Parametric Range of Tests

TS No.	Channel gap (A) (mm)	Channel Width (mm)	Heated Length (mm)	Length btw. Pres Taps(mm)	L_h/D_h
1	3.226	25.4	610	622	94.5
2	2.44	25.4	406	483	83
3	2.032	25.4	406	483	100
4	1.397	25.4	533	546	191
5	Tube Dia.=6.452	25.4	610	622	94.5

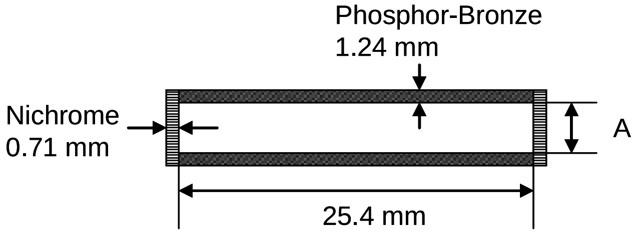


Fig. 9. Cross section of the test section

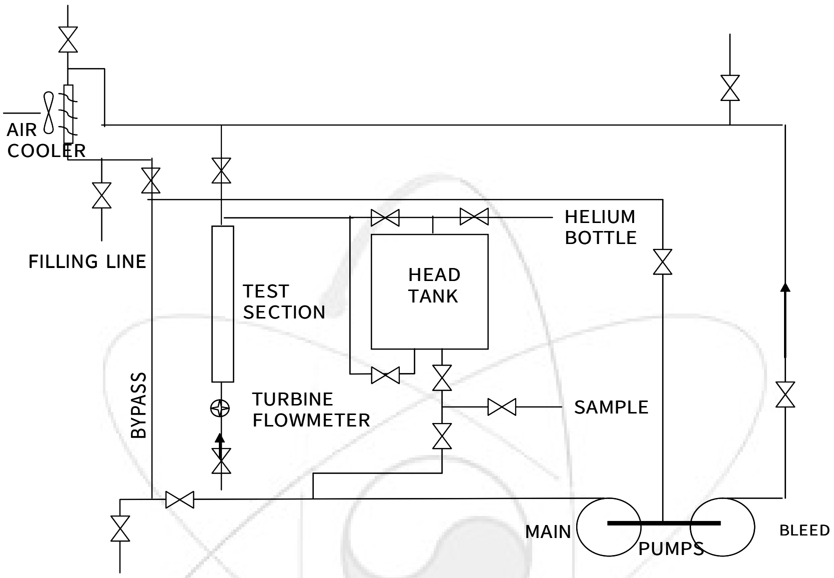


Fig. 10. Flow diagram for the test loop

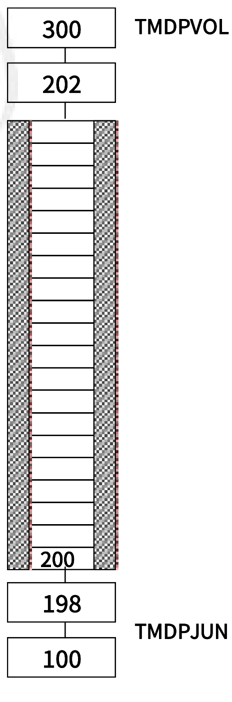


Fig. 11 Nodalization of Test Section

Test procedure is as follows: With no power supplied to the test section, the inlet temperature was fixed and the pressure drop across the channel was measured over a range of flow rates. Then, the flow rate was set to the maximum value required and power was supplied to the test section. And the pressure drop was measured over a range of flow rates. Inlet and outlet temperature were reported at the same time of the pressure drop. This procedure was repeated for different test sections. The exit pressure was maintained at around 0.117~0.14MPa for most of the tests. It is noted that most of the middle scale research reactors are operating at about this pressure.

2) Modeling and Nodalization

Just the test section part was simulated by the MARS code with a specified boundary condition. For the simulation, the test section was modeled with a pipe component of 20 cells and the connected single and time dependent volumes at the top and bottom as shown in figure 11. Experimental conditions are specified with boundary conditions at the inlet and outlet. That is, the inlet fluid conditions of the temperature and mass flux are specified at a time dependant volume (TMDPV 140). The pressure is fixed at on other time dependant volume (TMDPV 300). The flow channel was modeled by using pipe components with 20 cells (PIPE 200). Heating walls of phosphor-bronze and nichrome in figure 9 were modeled with two heat structures, respectively, which are attached to the flow channel of PIPE 200. The typical MARS input for the cold case of test section No. 2 is attached in annex as an example. As the properties of the test section are not sensitive to the results which we are interested in, the generic data was used as in the input of the annex.

The test characteristics for the selected experimental data are given in table 3.

Table 3. Characteristics of the Test Sections

Parameter	TS No.1	TS No.2	TS No.3
Flow Channel Dim. (mm)	3.226 x 25.4 x 610	2.44 x 25.4 x 406	2.032 x 25.4 x 406
Wall thickness (mm) *a	1.24	1.24	1.24
*b	0.71	0.71	0.71
Flow Area (m^2)	8.1940e-5	6.1976e-5	5.16128e-5
Hydraulic Diameter (m)	5.7249e-3	4.452e-3	3.763e-3
Heat transfer area (m^2) *a	0.015494 x 2	0.010323 x 2	0.010323 x 2
(m^2) (total) *b	1.967e-3 x 2	0.992e-3 x 2	0.825e-3 x 2
Heat transfer area (m^2) *a	0.7747e-3 x 2	0.516e-3 x 2	0.516e-3 x 2
(per cell) *b	0.0984e-3 x 2	0.0496e-3 x 2	0.04125e-3 x 2

a. for Bronze
b. for Nichrome

3) Simulation results

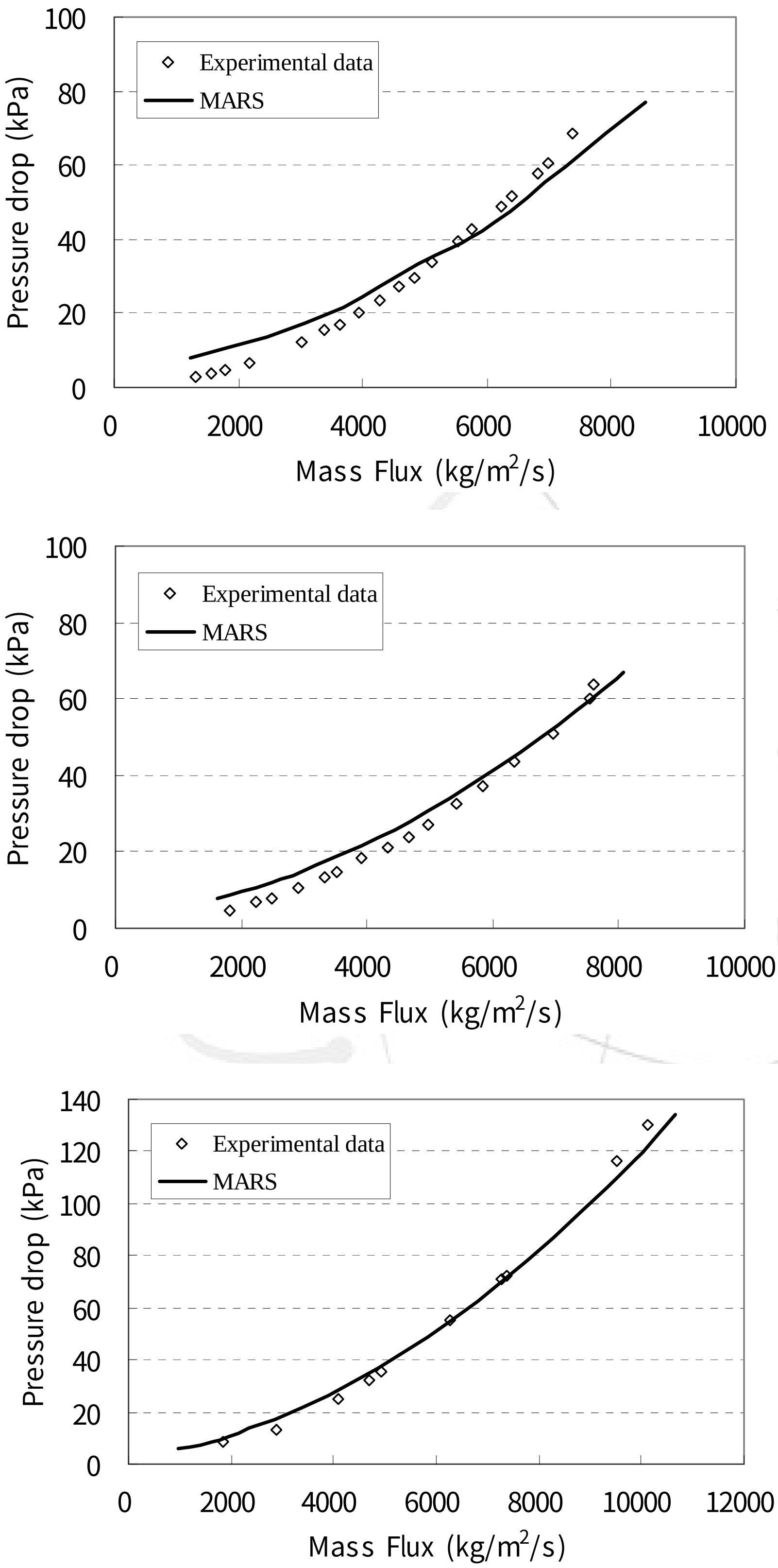
a) Cold case (without power)

For the reference to check the suitability of the nodalization, a cold case with a zero power to the test section was simulated for each type of the test section and the calculated results on the pressure drop versus the mass flux are compared with the experimental data as shown in the figure 12. As seen in the figure, the MARS code shows good predictions and it is more accurate for a narrower channel, but it has a tendency of slightly over-predicting the experimental data as the mass flux decreases. In this task, no tuning was made for the hot case simulations.

b) Hot case (with power)

Several selected experimental conditions for 3 different geometries of the test sections have been simulated by the MARS code with a standard model of the heat transfer, and the comparison of the calculated results with the measured are presented together with a comparison of the conditions at OFI in figure 13 and table 4. The solid symbol and line indicating the predictions are those connecting the predicted results by successive steady state calculations. It is also noted that the predicted void fraction is the value at the end of the test section, i.e., at last cell of PIPE 200 in figure 11.

In the figures, it can be seen that the MARS code gives reasonable predictions and shows the right trends of the OFI conditions, i.e., the OFI point is shifted to a higher mass flux as the surface heat flux increases. The predicted void fractions at the channel exit are around 0.2~0.27 at the OFI points, and it seems to be reasonable when considering the void fraction at the OSV(Onset of Significant Void) points. However, the predicted mass fluxes at an OFI had a different tendency in accordance with the test section geometry. For TS No.1, the calculated OFI points in comparison with the experimental data occur at a higher mass flux. But, the OFI points are predicted to occur earlier than the experimental mass fluxes for TS No. 2 & 3 with a smaller channel gap. Simulations for the other tests described in section 2.1.2, also showed similar results. From the simulation results except for the test section of a 3.226 mm width, it is thought that better results will be given if the initial difference between the predicted to measured one in the cold case is smaller. The void fraction at the channel exit is slightly larger for a higher heat flux, but the difference will be more obvious for much higher heat fluxes. Table 4 shows the calculated that the exit void fraction at the similar are close for different cases. Figure 14 shows the ratio of the predicted to measured mass flux at OFI along with the channel width. A tendency of underprediction is shown for a narrower flow channel while overprediction for a wider flow channel.

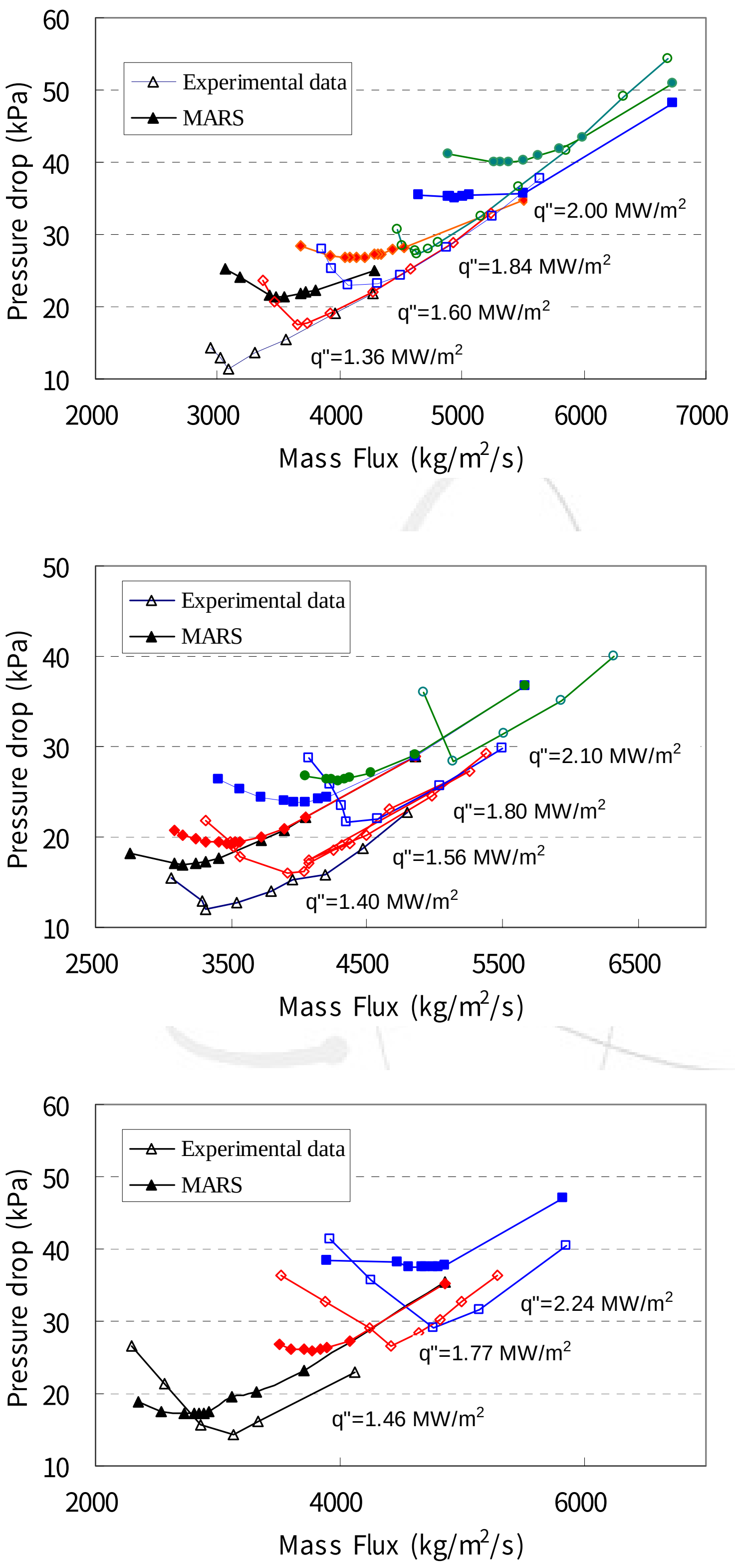


(a) TS No.1

(b) TS No.2

(c) TS No.3

Figure 12 Pressure drop versus the mass flux for the cold cases (q”=0.0 MW/m^2) of TS 1, TS 2 & TS 3



(a) TS No.1

(b) TS No.2

(c) TS No.3

Fig. 13. Pressure drop versus the mass flux for the hot cases of TS 1, TS 2 and TS 3

Table 4. Comparison of Test Data with the Predicted by MARS code

Heat Flux (MW/m^2)	Mass flux at OFI ($kg/m^2/s$)		Tin/Tout (℃)		Void at exit (%)	
	Exp.	MARS	Exp.	MARS	Exp.	MARS
TS No. 1						
1.36	3092	3478	55.5/94	55/94.9	-	21.7
1.60	3648	4137	55/94.2	55/95.2	-	20.5
1.84	4067	4943	55/95	55/93.7	-	23.5
2.0	4632	5382	55/94.2	55/93.6	-	24.1
TS No. 2						
1.40	3312	3146	55/96.5	55/90.6	-	20.6
1.56	3914	3469	55/-	55/90.9	-	20.0
1.80	4356	3969	55.5/97	55/91.2	-	23.3
2.10	5138	4292	55/94.5	55/94.1	-	20.1
TS No. 3						
1.46	3127	2848	45/-	45/94.2	-	26.6
1.77	4416	3778	45/-	45/90	-	23.8
2.24	4763	4805	45/-	45/89.8	-	24.5

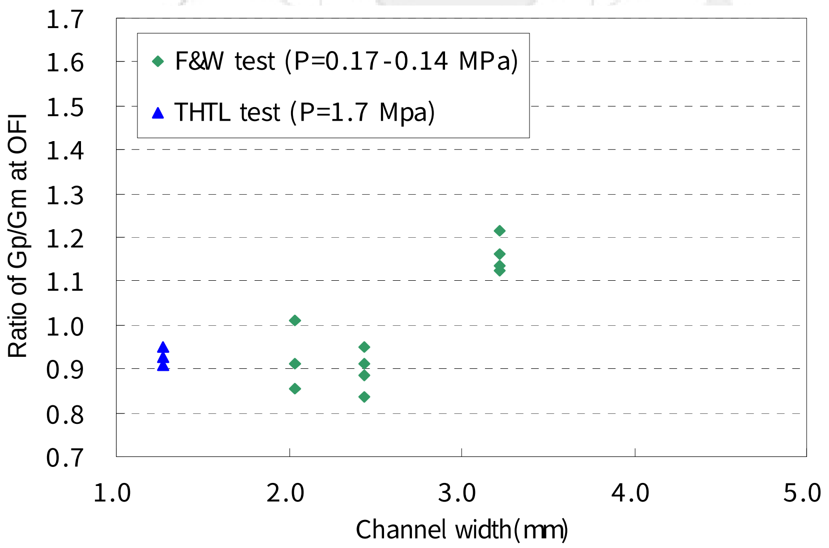


Fig. 14. Ratio of the Predicted to Measured Mass Flux at OFI along with the channel width

3.2.1.2 Simulation of the THTL Test

1) Description of the Experiment [12, 13]

The Thermal Hydraulic Test Loop (THTL) is a facility to support the development of the ANS research reactor with a high power of 200 MW. Flow excursion and CHF tests were carried out in the test loop for the anticipated condition expected in an ANS reactor. The test section used in the experiments is shown in figure 15, which has a heated length of 507 mm, flow channel gap of 1.27 mm, channel width of 12.7 mm, and cladding material of 6061 Al. It is noted that the ratio of the heat flux on the rounded ends to that on the flats is 36% as indicated in figure 15. A detailed description of the test loop and test procedure and summary of the test results as well is found in reference [12~14].

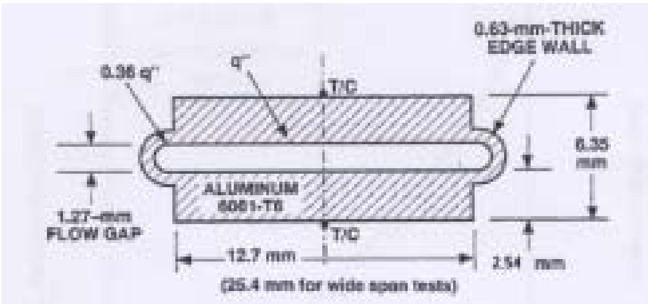


Fig. 15. Cross section of test channel

2) Modeling and Nodalization

As the geometry of the THTL test section is quite similar to that of the W&F test except for the materials used and a small difference in the dimension, the nodalization and modeling is almost the same as that in figure 11 of section 3.2.1. The characteristics of the test section used for the MARS input preparation are given in table 5. Applied axial power distribution of the test section is shown in figure 16. The ratio of the power distribution between the rounded part and the flat part is maintained as described above. Simulation was carried out with a specified boundary condition in the experiment.

Table 5. Characteristics of the Test Section

Parameter	Test Section
Flow Channel Dim. (mm)	1.27 x 12.7 x 507
Wall thickness (mm) *a	2.54
*b	0.63
Flow Area ($m^{2)}$	1.6129e-5
Hydraulic Diameter (m)	2.3091e-3
Heat transfer area (m^2) *a	0.006439 x 2
(m^2) (total) *b	1.0109e-3 x 2
Heat transfer area (m^2) *a	0.32195e-3 x 2
(per cell) *b	0.05055e-3 x 2

a. for Plat side
b. for Rounded side

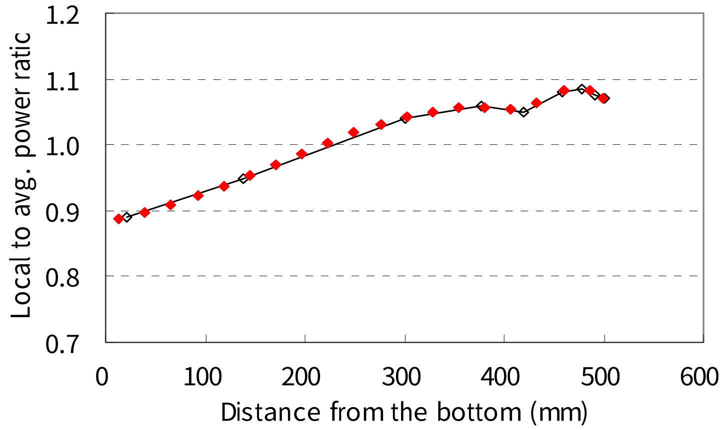


Fig. 16. Axial power distribution of the test section

3) Simulation results

The calculated pressure drops at given flow rates are compared with the measured ones in figure 17. As shown in the figure, the MARS code shows a fairly good agreement with the experimental data, in particular, for the ranges under around 22000 kg/m^2/s of the mass flux where an OFI is expected to occur as shown in figure 18. It indicates that the nodalization for this simulation is proper to simulate the hot cases when a given power is applied to the test section.

As for the hot cases, two selected experimental conditions have been simulated by the MARS code. The calculated results are presented in figure 18 together with a comparison of the conditions at an OFI. The solid line indicating the predictions in the figures are those connecting the predicted points by successive steady state calculations. For the cases where the average heat fluxes are 5.3 MW/m^2/s and 7.4 MW/m^2/s, the predicted mass flux at an OFI is 9% and 5% less than the measured ones, respectively. That is, the MARS code gave under-predictions, but there seems to be a reasonable agreement. The under-prediction trend of the OFI flow rate for a narrower channel is also shown in this test as presented in figure 13. For another case with 9.4 MW/m^2/s of a high heat flux, the code failed to calculate the steady conditions due to it exceeding the CHF, which means there is a necessity to implement a proper CHF correlation for a specific condition.

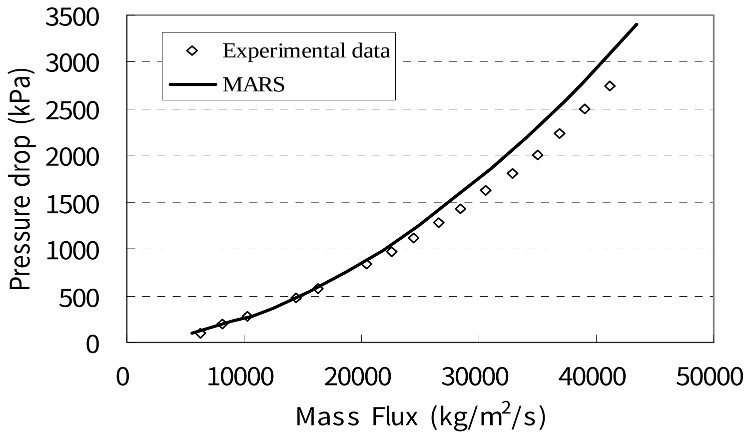


Fig. 17 Pressure drop versus the mass flux for cold case (q”=0.0 MW/m^2)

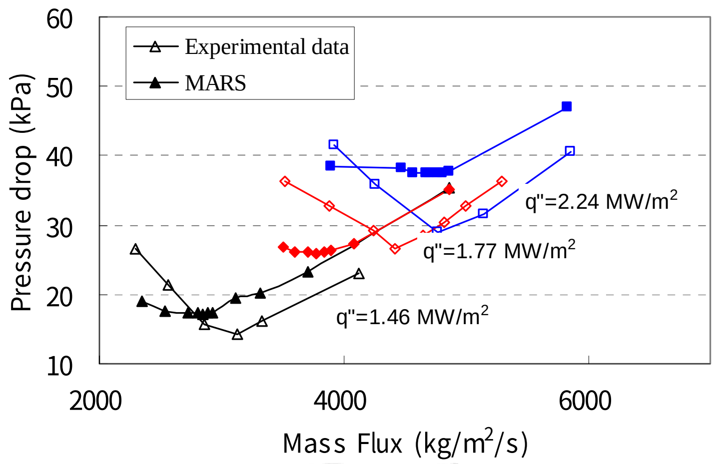


Fig. 18. Pressure drop versus the mass flux for hot cases

Table 6. Comparison of Test Data with the Predicted by MARS code

Heat Flux (mW/m^2)	Mass flux at OFI ($kg/m^2/s$)		Tin/Tout (℃)		Void at exit (%)	
	Exp.	MARS	Exp.	MARS	Exp.	MARS
5.3	7570	6882	45/-	45/201	20	48.7
7.4	10190	9672	45/-	45/200	30	46.6
9.4	13560	-	45/-	-	31.5	-

3.2.1.3 Comparison with the W&F Correlation

1) W&F Correlation for the minima in a pressure drop versus flow rate curve

Based on the experimental data, Whittle & Forgan suggested a correlation for the minima in the pressure drop versus flow rate curves for subcooled water flowing in narrow heated channels as below [11],

$$R = 0.697 + 0.00063\frac{Lh}{Dh} \qquad \textbf{for} \qquad 100 < \frac{Lh}{Dh} < 200$$

$$\text{Where,} \quad R = \frac{Tout - Tn}{Tsat - Tin}$$

For a round tube, it was suggested that a value of R equal to 0.95 of that given by the above equation.

2) Comparison results

The calculated results of the flow conditions at the OFI points for the F&W test and THTL test have been compared with the correlation for predicting the minimum flow rate conditions suggested by Whittle & Forgan. Figure 19 presents the predicted to measured ration of R values along with the ration of Lh/Dh. As shown in the figure, the prediction shows a good agreement to within ±5% for their data, but it overpredicts the THTL data for a higher pressure and narrower flow channels.

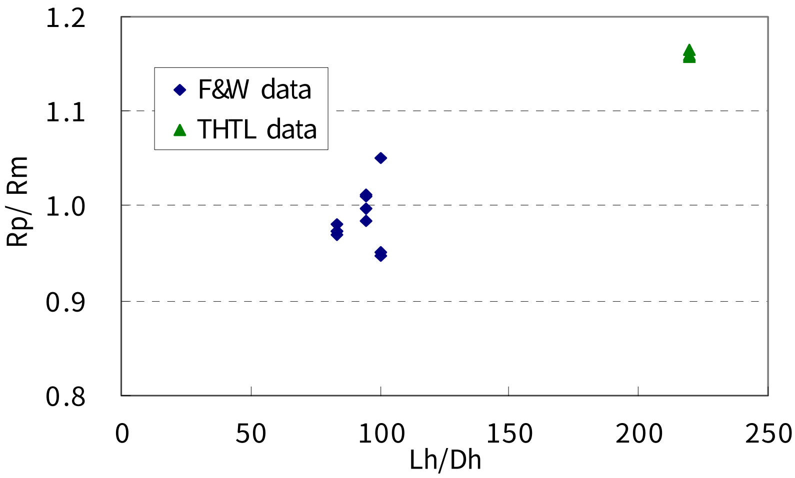


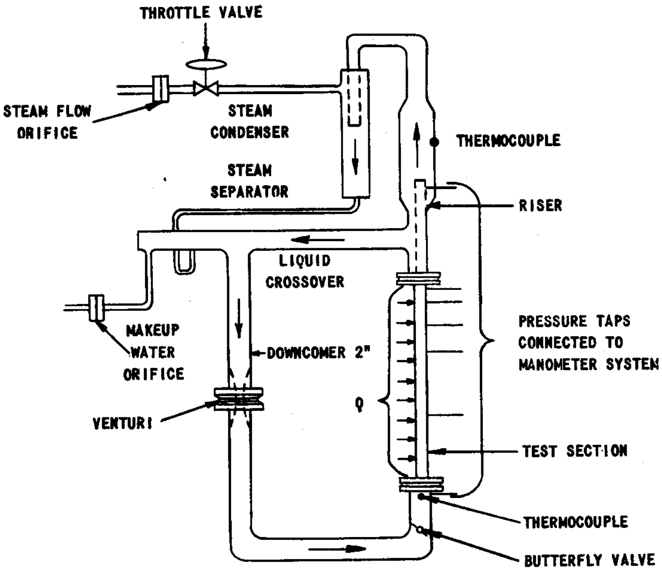
Fig. 19. Predicted to measured R ratio along with the Lh/Dh

3.2.2 Prediction of the Void Distribution

3.2.2.1 Simulation of the Marchaterre Experiment

1) Description of the Marchaterre experiment [15]

The Marchaterre experiment has been used for the assessment of the MARS code to be applied to the research reactor analysis. The test section was a rectangular channel of 6.35x50.8x1524 mm as shown in figure 20. The coolant in the flow channel is directly heated by an ac current through the walls, and the heat generation is uniform along the sectional length and around the periphery of the channel. The void fraction along the channel was measured by a gamma densitometer. The schematics of the test loop and test section are shown in figure 20. Detailed descriptions are found in reference [15].



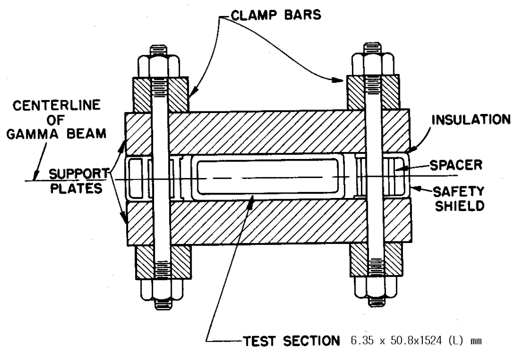


Fig. 20. Schematics of the test loop and test section

2) Nodalization and Simulation

The test section was simulated by the MARS code with a pipe component of 20 cells and the connected single and time dependent volumes at the top and bottom as shown in figure 21. A heat structure was attached to each cell of the pipe to model the heat generation in the test section. Even though the flow channel is heated from both sides, only one heated structure was modeled because the result of the void profile was the same as those of two heated structures with a 1/2 power each. The experimental conditions are specified with boundary conditions at the inlet and outlet. Ranges of the operating parameters for the 6 selected experimental data are given in table 7.

Table 7. Test conditions of selected data

Run #	Pressure (MPa)	Subcooling (K)	Velocity (m/s)	Heat Flux (kW/m^2)
155	1.124	6.94	0.9418	143.76
237	1.821	9.22	0.9053	167.95
296	4.230	6.64	1.8105	190.89
316	1.127	9.74	0.5700	119.46
165	4.211	12.06	1.0363	215.65
194	2.848	9.33	0.9997	167.16

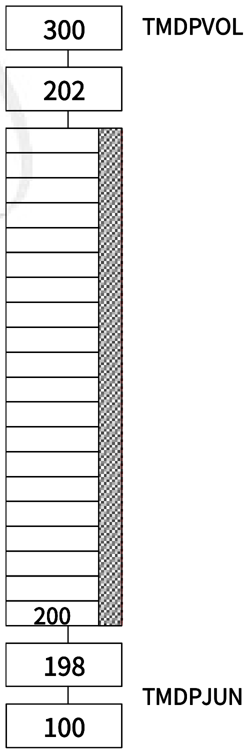
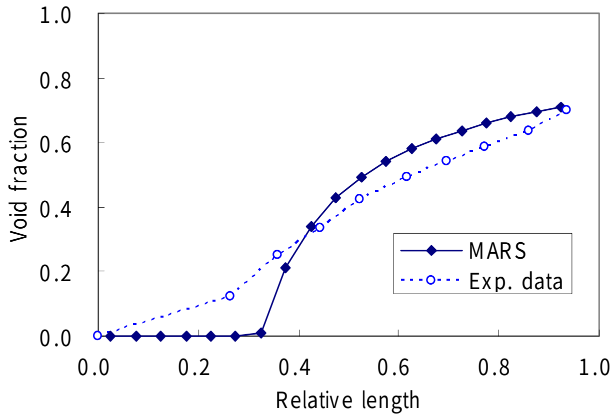


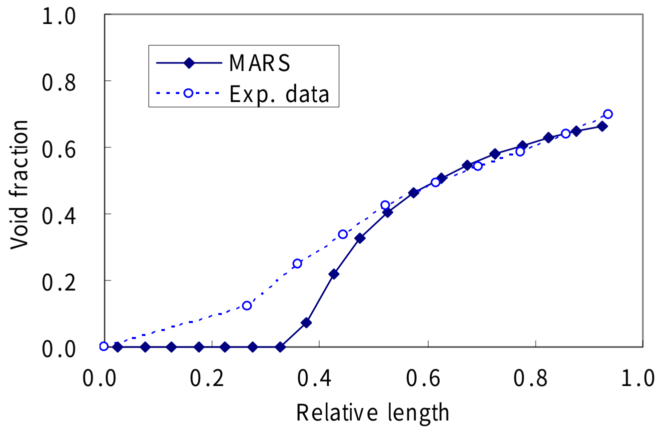
Fig. 21. Nodalization of test section

3) Simulation results

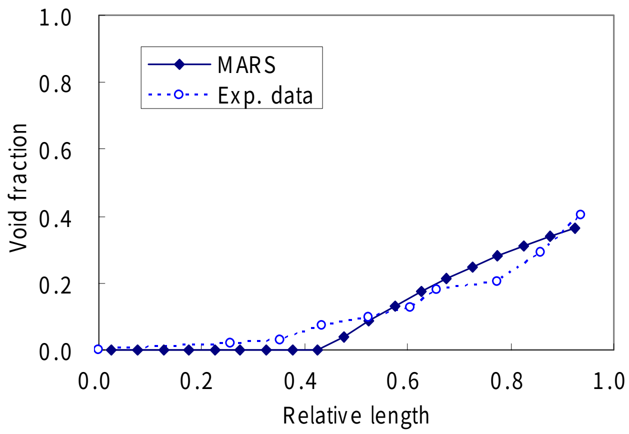
Simulation results for above 6 test data are presented in figure 22. As for the convective boundary condition for the heat transfer, an option for a standard heat transfer correlations, i.e., 100 as 3^{rd} data of the 1cccg501 card, was used instead of 102 which is specially developed for an ANS reactor application [16, 17]. The former results showed slightly higher void fractions than those of the latter [17]. Anyhow, it can be generally said from the figures that the calculated void is slightly under-predicted in the upstream part of the test section and shows a quite good agreement in the downstream of the test section at near and after the saturation temperature of the coolant. But one thing to be noted is that the predictions by the code are changing more steeply in the upstream part of the test section than the measured ones, i.e. in a range of around 0.1~0.4 of the void fraction.



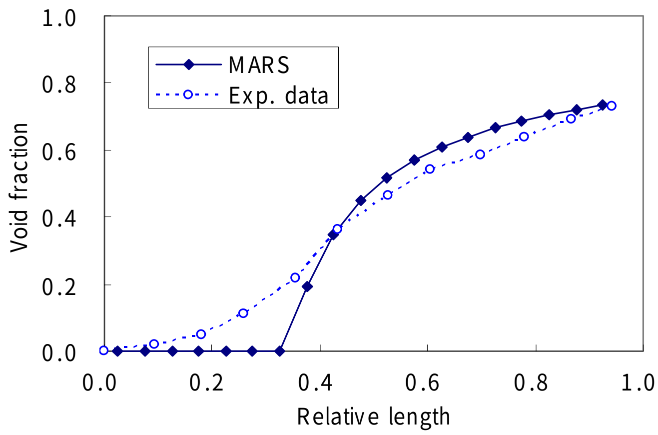
(a) Data 155 [P=1.124Mpa, V=0.94m/s]



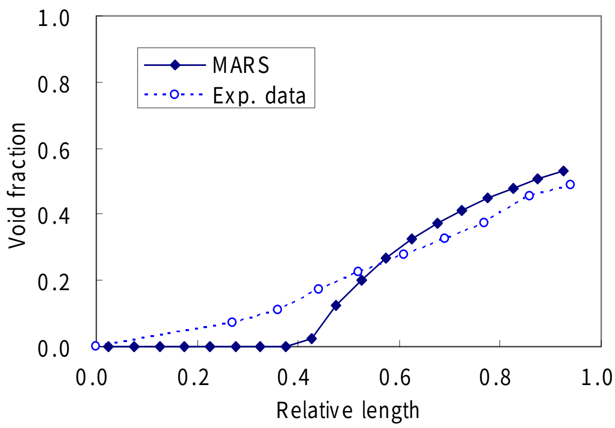
(b) Data 237 [P=1.182Mpa, 0.91m/s]



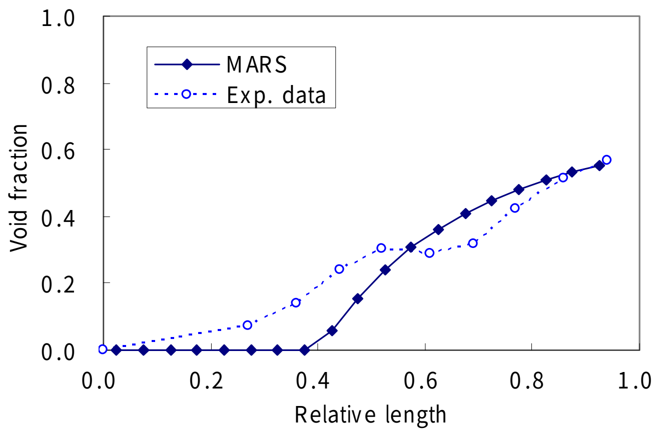
(c) Data 296 [P=4.230Mpa, V=1.81m/s]



(d) Data 316 [P=1.127Mpa, 0.57m/s]



(e) Data 165 [P=4.211Mpa, V=1.04m/s]



(f) Data 194 [P=2.848Mpa, 1.00m/s]

Fig. 22. Comparison of the calculated void profile with the measured one

3.2.3 Simulation of IEA-R1 Flow Transient

3.2.3.1 Nodalization and Modeling

Flow transient of Brazilian IEA-R1 reactor was simulated by MARS code. Figure 23 is the nodalization of IEA-R1 based on the information supplied by the IEA-R1 staff. The modeling and input has been prepared according to the components of MARS code. Pool outside was not considered in the model because it was not significant for these problems. The core was modeled with hot channel, average channel, and bypass flow channel with 19 axial nodes and the given peaking factors. Heat structures are attached to the hot and average channels. Core inlet flow rate and outlet pressure were used as boundary conditions. Coupling valve for establishing natural circulation is modeled with “CHKVLV” of MARS code.

3.2.3.1 Initial Conditions and Assumptions

The initial conditions used in this analysis are,

a. The reactor power is 5 MW. The axial power distribution was prepared from the data supplied by Brazilian IAEA CRP participant.
b. Total primary coolant flow rate is 681 m^3/h=187.3 kg/s.
c. Coolant inlet temperature was assumed to be 40℃.
d. Pressure B.C.was given at pool surface as TMDPVOL with atmospheric pressure.
e. The conductivity of all fuel is assumed as 35 W/m/K.

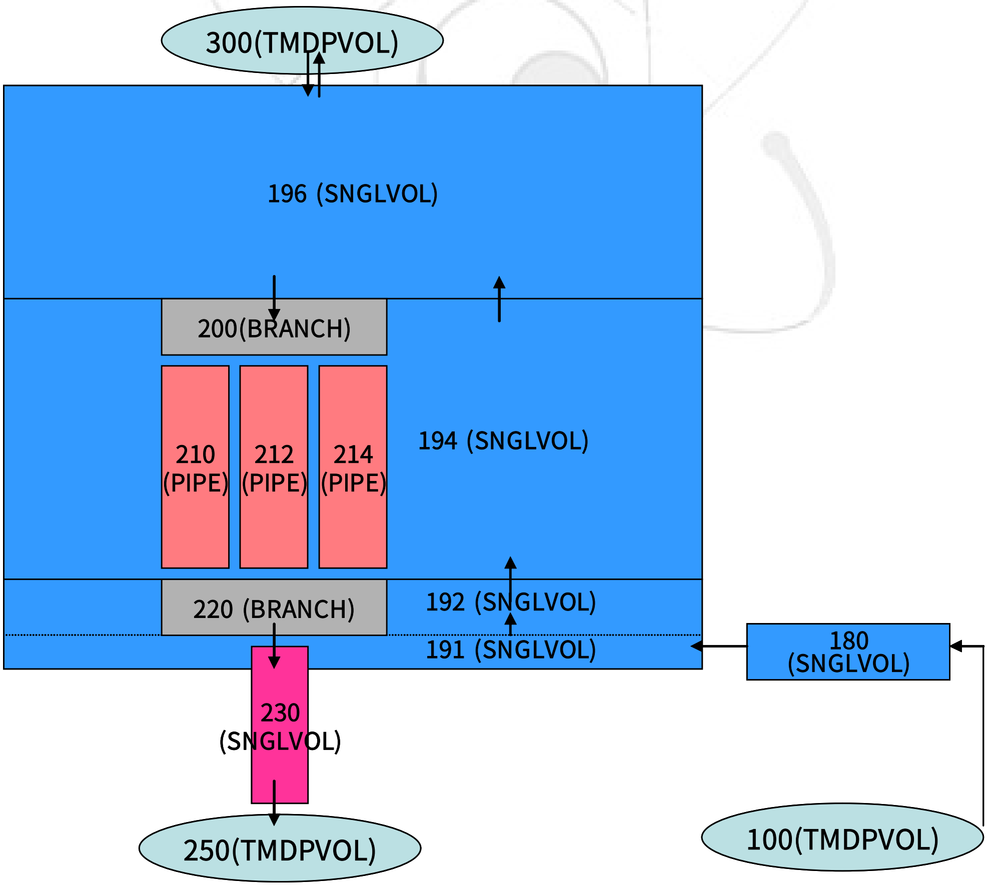
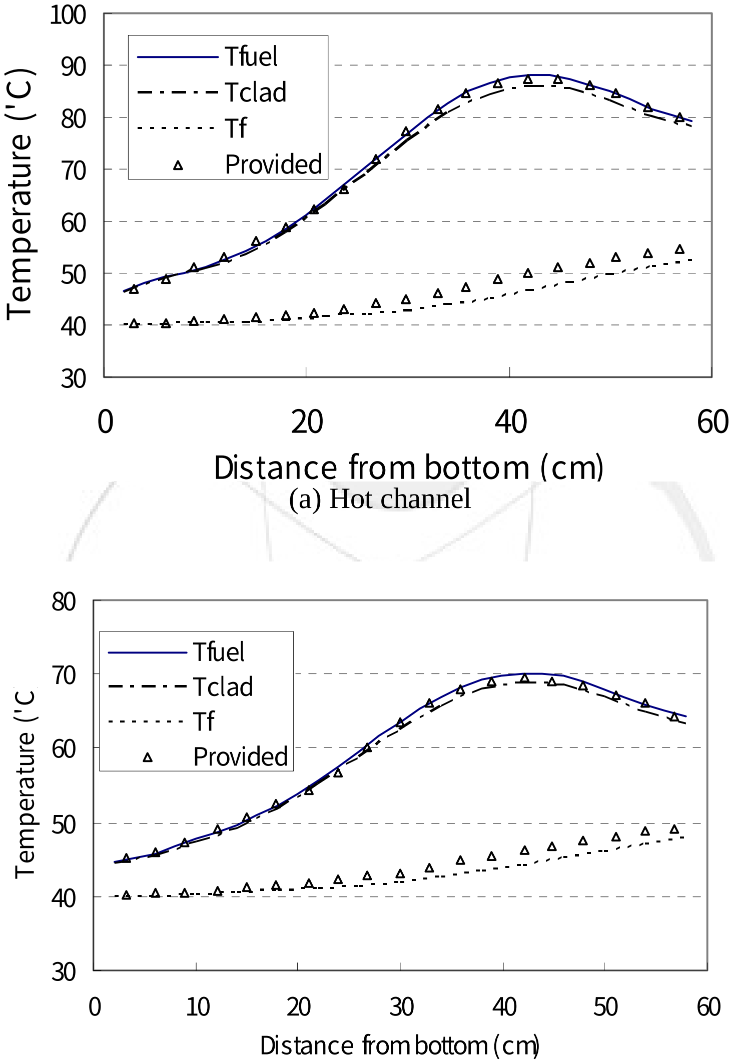


Fig. 23. Nodalization of IEA-R1 for MARS simulation

3.2.3.1 Steady State Simulation Results

With the conditions and modeling described previous, a steady state has been simulated and the results of the fuel and coolant temperatures were compared with those of measurement data. Figure 24 shows the comparison of MARS results with those provided by the IEA-R1 staff. The fuel and coolant temperatures calculated by MARS are quite close to those of data by supplier as shown in the figure. The difference of fuel temperature is less than 1 ^{o}C. Coolant exit temperature is comparatively large but less than 1.5 ^{o}C, but the hot channel coolant flow rates of calculation by MARS and the supplied data are quite same. So such difference may come from using different input and heat transfer correlation.



(a) Hot channel

(b) Average channel

Fig. 24. Comparison of the MARS results with those provided by supplier

3.2.3.2 Transient Simulation Results

Loss of flow transient due to the failure of pump was simulated. Instead of modeling primary cooling loop outside the pool, the variation of core flow was given as boundary condition. It was assumed that reactor protection system generated reactor trip signal at 90% of nominal flow and the reactor trip initiated 1 sec later due to trip delay. The coupling valve to establish natural circulation flow was assumed to be opened at 27 sec after pump failed. Figure 25 shows the variation of flow rate at various locations. It can be seen from the figure that the upward natural circulation flow was established stably after around 10 sec later opening of coupling valve. Temperature behaviors during the transient are shown in figure 26. Just after reactor trip, fuel and coolant temperatures drop rapidly and increase again when the coupling valve open and stabilized if natural circulation flow is fully established.

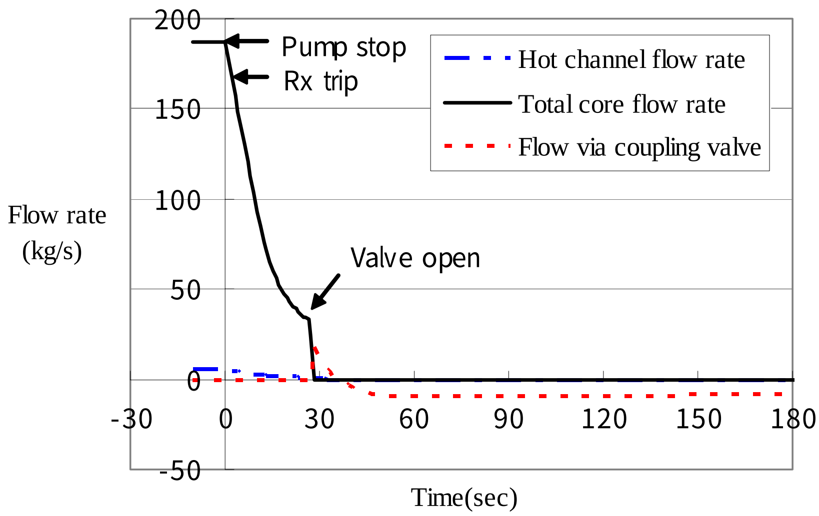


Fig. 25. Variation of flow rates at various locations

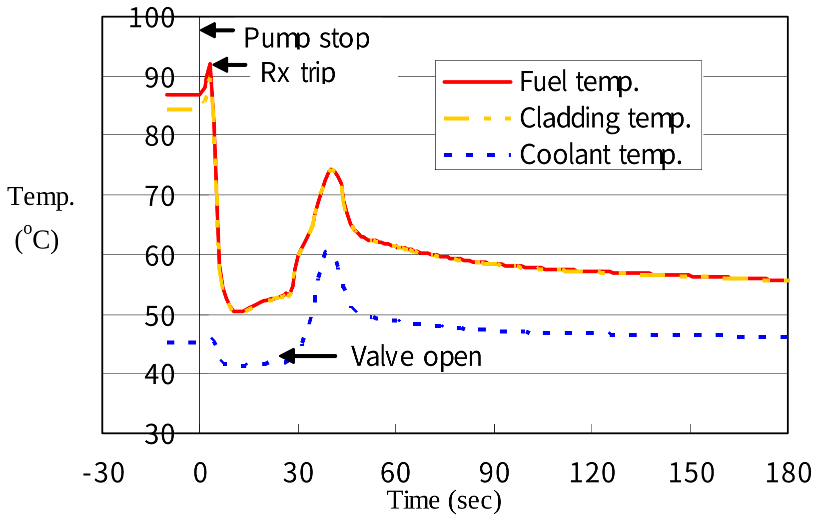


Fig. 26. Variation of fuel and coolant temperatures

3.2.4 Simulation of IAEA Benchmark Transients

The 10 MW reactor, SPERT, for the selected benchmark transients [10] is the same reactor model used for the neutronics benchmark computations in IAEA, TECDOC-233. Figure 27 is the nodalization for the following problems. Pool outside was not considered in the model because it was not significant for these problems. The core was modeled with hot and average channel with 21 axial nodes and the specified peaking factors. Core inlet flow rate and outlet pressure were used as boundary conditions.

3.2.4.1 Reactivity Insertion Transient

1) Event description

At an initial power of 1 watt, 1.5$ of reactivity is inserted into the critical reactor in 0.5 seconds. The trip setpoint of reactor safety system is actuated at 12 MW (120% of nominal power) with a time delay of 25 ms before the control rod insertion is initiated. A linear reactivity insertion of –10$ in 0.5 seconds was assumed at reactor trip.

2) Results

The simulation result for the above event is given in figure 28. The peak cladding temperature, which may be a most important parameter in this event, is depicted together with the results calculated by other organizations and codes in the figure. MARS-h gives a reasonable result of 166.4 ^{o}C, while others show 149.2 ~ 169.8 ^{o}C. Response of other parameters such as power and coolant temperature was similar with those by others in the reference 18.

3.2.4.2 Loss of Flow Transient

1) Event description

Fast loss of flow transient is occurred at the 10 MW steady state conditions. Core flow is reduced as $e^{-t/T}$ with T=1 second. Reactor trip is initiated at 85% of nominal flow with a 200 ms delay time before control rods insertion begins. A linear reactivity insertion of –10$ in 0.5 seconds was also assumed at reactor trip.

2) Results

The result of peak cladding temperature is compared with those predicted by other organization in figure 29. The second peak of the cladding temperature occurred during the flow reversal when the core flow changes from downward to upward direction for natural circulation. The MARS gives a reasonably good agreement with other results.

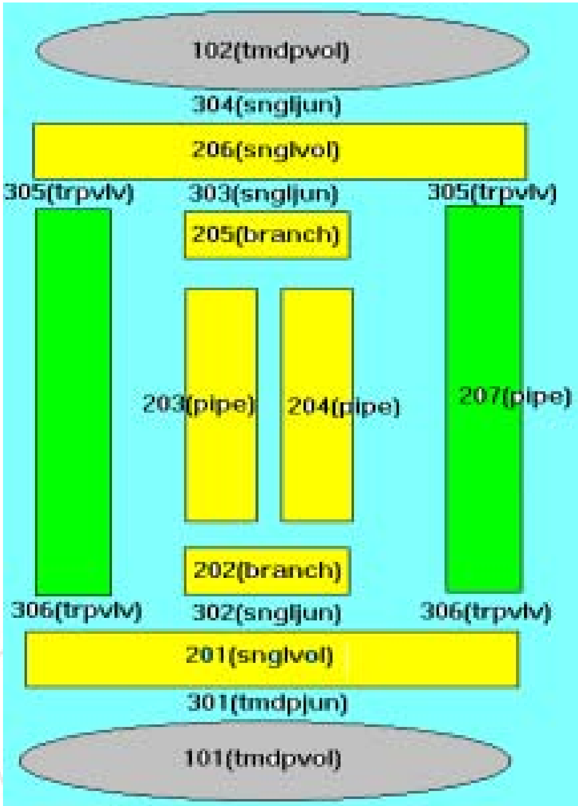


Fig. 27.. Nodalization of SPERT for MARS simulation

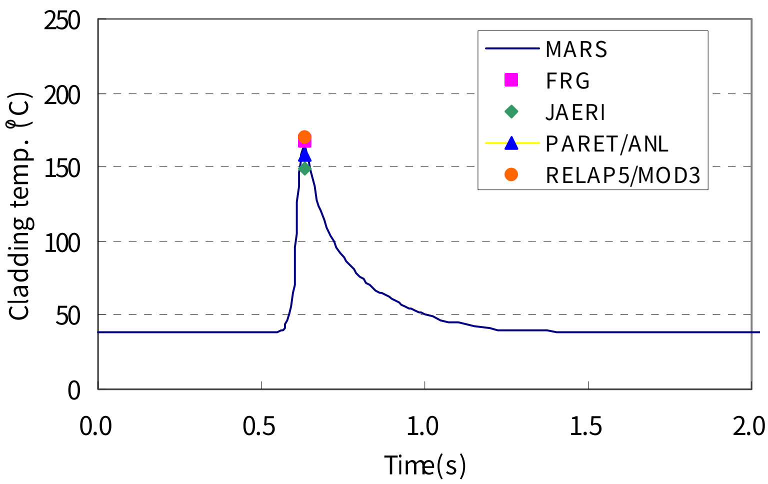


Fig. 28. Predicted peak cladding temperature at reactivity induced transient

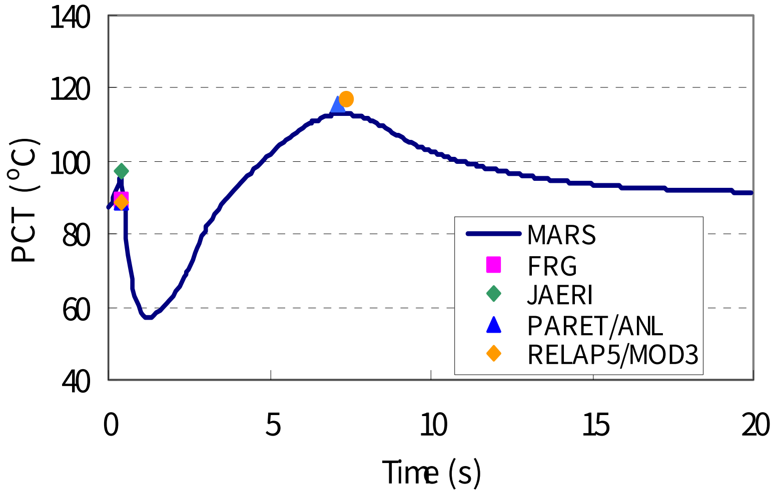


Fig. 29. Predicted peak cladding temperature at loss of flow transient

3.2.5. Summary

Some separate effect tests for the flow excursion characteristics and void distribution in a heated channel have been simulated by the MARS code in order to assess the applicability of the code to the analysis of research reactors. It is concluded from the calculation results that;

a) MARS code predicts reliably for the simulated cases and the agreements between the predicted and the measured flow rate at an OFI are within ±20%. .

b) MARS code has a tendency of under-predicting the flow rate at an OFI for narrower channels while it shows an over-prediction for wider flow channels.

c) Better results could be obtained as the modeling is close to the experimental condition.

d) More simulations are necessary for the MARS code to be applied to the RR with low pressure operating conditions, in particular, for the medium quality ranges at low pressure.

e) The void profile analyzed by the MARS code in this task shows a quite good agreement in the downstream of the test section at near and after the saturation temperature of the coolant, but slightly under-predicted in the upstream part of the test section.

f) From the simulation results for the Brazilian IEA-R1 and IAEA benchmark RR transients by MARS code, the MARS gives reasonably good agreements.

4. CONCLUDING REMARKS

MARS code developed for the transient analysis of power reactors was modified for applying to the analysis of the HANARO with finned rod type fuels which is operating at low pressure and low temperature conditions. The prediction capability of the code was assessed against the experimental data for the HANARO. From the assessment results, it can be said that the modified MARS code could be used for analyzing the thermal hydraulic transient of the HANARO. Some other simulations such as flow instability test and reactor transients were also done for the application of MARS code to RRs with plate type fuels. The results on the simulated cases show that the MARS code can be used to the transient analysis of RRs if carefully applied. In particular, an improvement on a void model seems to be necessary for dealing with the phenomena in high void conditions even though most of transients and accidents in RRs are terminated within single and subcooled conditions.

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KAERI/TR-3259/2006			

제목/부제	연구용 원자로 안전해석 적용을 위한 MARS 코드 검증 계산
연구책임자 및 부서명 (TR, AR인 경우 주저자)	박 철 / 하나로 운영부
연구자 및 부서명	김헌일, 임인철, 채희택 / 하나로 운영부

출 판 지	대 전	발행 기관	한국원자력연구소	발행년	2006. 10.
페 이 지	29 p.	도표	있음(V), 없음( )	크기	29x21 cm
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비밀여부	공개(V), 대외비( ), __ 급비밀		보고서 종류	기술 보고서	
연구위탁기관			계약 번호		
초록 (15-20줄내외)					

MARS 코드의 **하나로** 및 다른 연구용 원자로의 사고해석에 적용성 여부를 알아보기 위해 다음 자료에 대한 모사 계산을 수행하였다.

- **하나로** 설계 및 운전 자료
- 유동 불안정 및 기포 분포에 대한 기존 자료
- IAEA의 연구로 과도 시험 자료
- 브라질 IEA-R1 실험자료

핀이 달린 봉형 핵연료를 사용하는 **하나로**의 모사계산을 위해서 발전로의 과도해석을 위해 개발된 MARS 코드를 수정하여, **하나로** 실험자료와 비교하여 예측 성능을 평가하였다. 평가 결과, 수정된 MARS 코드는 하나로 열수력 과도해석에 적용할 수 있는 것으로 판단된다.

그리고 판형 핵연료를 사용하는 연구로의 적용성을 알아보기 위해 유동 불안정 및 연구로 과도 상태에 대한 모사 계산도 수행되었다. 이 경우는 MARS 코드를 수정하지 않고 계산하였다. 계산 결과에서 MARS 코드는 연구용 원자로 과도해석에 주의를 기울여 사용 가능한 것으로 나타났다. 다만, 기포가 많은 조건의 현상 분석에는 기포 모델의 개선이 일부 필요한 것으로 보인다.

주제명키워드 (10단어내외)	연구용 원자로, MARS 코드, 판형 핵연료, 봉형 핵연료, 하나로, 안전해석, 코드 검증 계산

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Main author and Department	Cheol Park / HANARO Management Div.
Co-Researcher and Department	H.Kim, H.T Chae, I.C. Lim /HANARO Management Div.

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Abstract(15-20 Lines)

In order to investigate the applicability of MARS code to the accident analysis of the HANARO and other RRs, the following test data were simulated.

- ☐ Test data of the HANARO design and operation
- ☐ Test data of flow instability and void fraction from published documents
- ☐ IAEA RR transient data in TECDOC-643
- ☐ Brazilian IEA-R1 experimental data

For the simulation of the HANARO data with finned rod type fuels at low pressure and low temperature conditions, MARS code, developed for the transient analysis of power reactors, was modified. Its prediction capability was assessed against the experimental data for the HANARO. From the assessment results, it can be said that the modified MARS code could be used for analyzing the thermal hydraulic transient of the HANARO.

Some other simulations such as flow instability test and reactor transients were also done for the application of MARS code to RRs with plate type fuels. In the simulation for these cases, no modification was made. The results of simulated cases show that the MARS code can be used to the transient analysis of RRs with careful considerations. In particular, it seems that an improvement on a void model may be necessary for dealing with the phenomena in high void conditions.

Subject Keywords (About 10 words)	research reactor, MARS, plate fuel, rod type fuel, HANARO, safety analysis, code validation