Journal of the Korean Nuclear Society
Volume 34, Number 5, pp.455~467, October, 2002

Modifications and Assessment of RELAP5/MOD3.2 for HANARO Thermal-Hydraulic Safety Analyses

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(Received March 19, 2002)

Abstract

RELAP5/MOD3.2 was modified to perform the thermal-hydraulic safety analysis for HANARO transients. Several aspects of RELAP5/MOD3.2 were modified or replaced by new features to properly simulate the unique HANARO characteristics such as the finned fuel element, the cooling mechanisms by both plate type heat exchanger and the natural circulation. Especially, the heat transfer packages were modified to be more appropriate for the safety analysis and the heat transfer models were developed for the plate type heat exchanger as well as natural circulation through the pool water. This modified version of RELAP5/MOD3.2 is renamed as RELAP5/HANARO. The thermal-hydraulic simulations of the single fuel pin test and plate type heat exchanger were performed to assess the realistic predicting capabilities of RELAP5/HANARO and compared with experimental results and manufacturer's data in this paper. In addition, the natural circulation experiment using the scaled bundle was simulated to validate the capability of RELAP5/HANARO. The simulation results show almost similar trend with experimental data. Therefore, it is proved that RELAP5/HANARO has a confidence to use for the safety analyses of HANARO.

Key Words : RELAP5/MOD3.2, HANARO, heat transfer correlations, plate type heat exchanger, natural circulation

1. Introduction

HANARO (High-flux Advanced Neutron Application Reactor) is an upward flowing light water cooled, heavy water reflected, open-chimney-in-pool type research reactor with maximum thermal power of 30 MWth. At normal operation, the core heat is removed by forced convection flow through two pumps and two heat exchangers. During reactor shutdown, the decay heat is removed by the natural circulation through the primary cooling system along with the same path as the forced convection flow or by a gravity driven recirculating flow via the flap valves inside the pool.

It becomes necessary to have a reliable system analysis code applicable to HANARO which operates under the low pressure and low temperature conditions. RELAP5/MOD3.2 was chosen as the basic tool of the thermal-hydraulic transient analysis code for HANARO safety analyses. Since RELAP5/MOD3.2 [1] was developed primarily for the system transients of light water reactors (LWRs) which operates under the high pressure and high temperature conditions, the direct application of this code to HANARO safety analysis may lead to some undesirable results due to lack of detail modeling capabilities under the low pressure and low temperature conditions. The heat transfer package was found to be the major part having vital influences on the code calculation results [2]. The heat transfer package consists of empirical correlations developed under certain conditions, that is, applicable ranges, beyond which the erroneous results may be. Thus, some of heat transfer models of RELAP5/MOD3.2 should be replaced by the new correlations applicable to the HANARO operation condition. The main objectives of the present study are to replace a new heat transfer package appropriate for the safety analysis of HANARO and to assess the newly developed heat transfer models suitable for the plate type heat exchanger and the natural circulation important features to HANARO transient analysis.

Major modifications were made to the package of heat transfer correlations appropriate for HANARO applications since it significantly affects the calculation results. The built-in heat transfer correlations were replaced with those developed, based on the experimental data and the operating conditions for the finned fuel elements. The heat transfer models associated with plate type heat exchanger and the natural circulation were developed to enable this code applicable to HANARO [3,4]. The heat exchanger model was developed to reproduce the data of the heat transfer rate and the pressure drop given by manufacturer since both the heat transfer rate and pressure drop characteristics for the plate type heat exchanger used in HANARO are quite different from those of the shell and tube type heat exchanger used in nuclear power plants. The natural circulation model was developed to simulate the core cooling capability in the pool. These modified heat transfer correlations and newly developed both the plate type heat exchanger and natural circulation models are implemented to the modified code together with steam table having proper range for the HANARO operation condition. This modified version of RELAP5/MOD3.2 is renamed as RELAP5/HANARO.

The modification of RELAP5/MOD3.2 necessitates assessment and validation of RELAP5/HANARO. The validation of RELAP5/HANARO was carried out to assess its capability to demonstrate the thermal-hydraulic behavior of HANARO transients in physically more reasonable and predictable way [5]. RELAP5/HANARO was tested through the single fuel pin test heat transfer experiment and plate type heat exchanger model. The simulation of natural circulation experiment using the scaled fuel bundle was also performed to evaluate the core cooling capability in the pool.

2. Modifications of Heat Transfer Packages for HANARO

Following discussions present the correlations used to calculate the heat transfer for a specific heat transfer regime. For each regime, detailed descriptions of the correlations for HANARO are provided. The heat transfer package originally modeled in the RELAP5/MOD3.2 was reviewed in view of HANARO applicability. Then, the heat transfer package applicable to HANARO was proposed and discussed.

2.1. Heat Transfer Correlations for Single-Phase Flow

HANARO is designed to be cooled by the single-phase liquid at normal operation. The heat transfer package of RELAP5/HANARO includes the single-phase correlations for forced laminar and turbulent convection for liquid and vapor.

2.1.1. Laminar Flow

The model applied to the fully developed laminar flow for liquid and vapor is an exact solution in a tube with constant wall temperature and constant thermal properties. The solution is in the form [6] as

$$h_{lam} = 3.656\left(\frac{k}{D_e}\right), \qquad (1)$$

where k is evaluated at the bulk fluid temperature.

2.1.2. Turbulent Flow

For the turbulent region, the Dittus-Boelter correlation is implemented in the RELAP5/HANARO to describe the forced turbulent convection of liquid and vapor flows for the application to HANARO analysis [7]. The turbulent heat transfer correlation for HANARO finned fuel element is written as

$$h_{turb} = 0.009388\left(\frac{k_f}{D_e}\right)Re_f^{0.9109}\,Pr_f^{0.536}, \qquad (2)$$

where the terms with subscript "f" are evaluated the physical properties at the film (near wall) fluid temperature defined as $(T_w+T_b)/2$. Since neither the constant wall temperature nor the constant heat flux condition can exactly reflect the HANARO reactor conditions, the lower value of the heat transfer coefficient is selected for the conservatism.

2.2. Heat Transfer Correlations for Two-Phase Flow

RELAP5/MOD3.2 can estimate temperature distribution of HANARO finned fuel element. It is, however, limited to use the single-phase forced convection. The Chen correlation was modified for the onset of nucleate boiling (ONB), which defines the boundary between single-phase forced convection and partial subcooled boiling, and subcooled nucleate boiling correlations applicable to the HANARO safety analysis. The bases of the model are the same as those for saturated nucleate boiling but with modifications. The Chen correlation is implemented to cover the region of the subcooled nucleate boiling heat transfer in the finned fuel element.

2.2.1. Nucleate Boiling Heat Transfer Correlations

The heat transfer coefficients in the transition boiling region are calculated from both the Chen correlation and single-phase liquid heat transfer correlation, i.e., Dittus-Boelter correlation. The present study extends the original Chen formulation to improve its predicting capability at the low pressure and low temperature characteristics. The Chen correlation [6] for turbulent internal flow is selected for saturated nucleate boiling. It bases on the mechanistic heat transfer model, which consists of the heat transfer due to turbulent forced convection of liquid flow, h_{mac}, and the heat transfer due to nucleate boiling, h_{mic}. It takes the form as

$$h = h_{mac} + h_{mic}, \qquad (3)$$

or

$$q'' = h_c \cdot (T_w - T_b) + h_{NCB} \cdot (T_w - T_{sat}). \quad (4)$$

The convective heat transfer term is expressed as the Dittus-Boelter correlation multiplied by the F factor, which represents the increase of convective heat transfer by void generation in the boundary layer. The same models in the previous section are incorporated into the HANARO application.

$$h_c = 0.009388\left(\frac{k_f}{D_e}\right) Re_f^{0.9109}\, Pr_f^{0.536} \cdot F. \quad (5)$$

The Chen F factor was modified to F′ to improve the smoothness of F, which forms

$F' = F - 0.2(T_{sat} - T_f)(F - 1) \quad T_{sat} > T_f \geq (T_{sat} - 5)$
$F' = 1.0 \quad T_f < (T_{sat} - 5).$

The nucleate boiling heat transfer term, h_{NCB}, is expressed by the correlation of Forster and Zuber with an addition of an S_f factor as

$$h_{NCB} = 0.00122\left(\frac{k_f^{0.79}\, c_{p_f}^{0.45}\, \rho_f^{0.49}}{\sigma^{0.5}\, \mu_f^{0.29}\, h_{fg}^{0.24}\, \rho_g^{0.24}}\right) \Delta T_{sat}^{0.24}\, \Delta P_{sat}^{0.75} \cdot S_f, \quad (6)$$

where S_f is the suppression factor. The S_f factor is expressed analytically as follows

$$S = \begin{bmatrix} \left(1+0.12\left(Re\times10^{-4}\right)^{1.14}\right)^{-1}, & Re < 32.5\times10^4 \\ \left(1+0.42\left(Re\times10^{-4}\right)^{0.78}\right)^{-1}, & 32.5\times10^4 \leq Re \leq 70\times10^4 \\ 0.1, & Re \geq 70\times10^4 \end{bmatrix}.$$

2.2.2. The ONB Correlation

The ONB occurs when the wall temperature exceeds the saturation temperature and bubbles start to form on the heated surface from nucleation sites. The correlation of ONB is very important in the safety analysis of low pressure pool-type research reactor like the HANARO. The ONB correlation added for HANARO type fuel element [8] is expressed as

$$T_{w,ONB} = T_s + \left(\frac{8\sigma_s\, T_{s,K}\, v_{fg}\, h_{sp}}{h_{fg}\, k_s}\right) \left[1.07397\times10^5\, Re_f^{-0.77995}\, Pr_f^{-2.65827}\left(\frac{c_{p,s}\Delta T_{sub}}{h_{fg}}\right)^{0.212271}\right], \quad (7)$$

where the terms with subscript "f" are evaluated at the film (near wall) fluid temperature.

2.2.3. Subcooled Nucleate Boiling Heat Transfer Correlation

Subcooled boiling is the dominant heat transfer model for HANARO during transient conditions. For the description of the subcooled boiling model, the following correlation was developed for the subcooled boiling region from the heat transfer experimental data for HANARO finned fuel elements. The subcooled boiling correlation [9] is expressed as

$$h_{sb} = h_{sp}\left(1 + \Psi \cdot \Delta T\right), \quad (8)$$

where,

$$\Psi = 1.38\times10^5 \cdot Bo_m^{0.5} \cdot \left(1+Re_b\right)^{-0.877} \cdot Pr_b^{-0.713} \cdot \left(\frac{\rho_f}{\rho_g}\right)^{-0.069} \cdot \left(\frac{D_h}{D_{sh}}\right)^{1.847}$$

$$\Delta T = \begin{bmatrix} \dfrac{T_w - T_{w,ONB}}{T_w - T_b}, & T_w \geq T_{w,ONB} \\ 0.0, & T_w \leq T_{w,ONB} \end{bmatrix}.$$

2.3. The Correlations for CHF

The appropriate prediction of CHF is very important because the heat transfer coefficient in the transition boiling is directly determined from the CHF value. The Groeneveld lookup table was adopted to determine the CHF in RELAP5/MOD3.2. However, it was found to show sudden changes in CHF values with respect to flow rate and quality at low pressure and low flow conditions. The CHF correlation for HANARO was developed using the data from the heat transfer experiment of the single fuel pin. This methodology was verified through the comparison of the predicted subchannel velocity distribution with the experimental result and the comparison of the CHF prediction by the code with the limited number of the bundle CHF data.

2.3.1. High Flow Rate CHF Correlation

The CHF data for the HANARO type fuel taken from the single fuel pin test heat transfer experiment performed at Whiteshell Nuclear Research Establishment (WNRE) in Canada and those for the aluminum rod were employed in the development of the CHF correlation. A CHF correlation for the unfinned heated rod was developed first, and then the fin effect was taken into account later by introducing a modeling parameter of the fin. To apply the CHF correlation developed in this way to the thermal-hydraulic design and safety analysis of HANARO, the effects of the difference between the single fuel rod and the rod bundle in geometry, especially, a cold wall, and non-uniform axial power distribution on the CHF were considered.

For more than 200 kg/m^2-sec of mass flux, G, the newly developed CHF correlation [10] for HANARO finned fuel element at high flow condition is used as

$$q''_{CHF-H} = 1.81722\times10^{-2}\,Re^{0.454741}\,(1-\chi_e)^{7.06122}\left(\frac{\rho_f}{\rho_g}\right)^{-0.0015188}\left(\frac{8}{D_e}\right)^{1/3}\left(\frac{P_{ht}}{P_{ba}}\right)^{0.6}.$$

2.3.2. Low Flow Rate CHF Correlation

The modified Zuber CHF correlation was developed analytically for horizontal pool boiling of a saturated liquid on a flat plate. This CHF correlation is implemented in the present study when the mass flux is less than 100 kg/m^2-sec. The correlation is the form as

$$q''_{CHF-Z} = (1-\alpha_g)\left(\frac{\pi}{24}\right)h_{fg}\,\rho_g^{0.5}\left[g\,\sigma(\rho_f-\rho_g)\right]^{0.25}. \quad (10)$$

If $100 < G < 200$ kg/m^2-sec, a linear interpolation with mass flux was performed, with the q''_{CHF} values obtained from the CHF at low flow rate and high flow rate. The functional relationship for the interpolation is as follows

$$q''_{CHF} = q''_{CHF-Z} + \left(\frac{G-100}{100}\right)\left(q''_{CHF-H} - q''_{CHF-Z}\right). \quad (11)$$

2.4. The Correlations of Plate Type Heat Exchanger

The plate type heat exchanger is chosen as the primary cooling heat exchanger. Since the pressure drop and heat transfer characteristics as well as the geometric configuration of the coolant path of this component are quite different from those of the usual tube shaped hydrodynamic volume, it is virtually impossible to describe this plate-type heat exchanger behavior using the conventional heat transfer and pressure drop correlations. Due to these reasons, new heat transfer correlations are implemented to the RELAP5/HANARO to represent the heat transfer characteristics of the plate type heat exchanger. The new correlations are expressed as

$$\begin{aligned} h &= 0.1302\left(\frac{k}{D_e}\right)Re^{0.721}\,Pr^{0.4}, \qquad Re \ge 290 \\ h &= 0.85\left(\frac{k}{D_e}\right)Re^{0.39}\,Pr^{0.4}, \qquad Re < 290. \end{aligned} \quad (12)$$

One problem involved in using these correlations is that the equivalent heated diameter is not known for this plate type heat exchanger. In order to compensate the difference between the equivalent hydraulic diameter and the equivalent heated diameter in the calculation of the heat transfer coefficient, a set of the correlation factors corresponding to (D_h/D_e) are multiplied to the above correlations.

3. Development of Simulation Models for HANARO

3.1. Single Fuel Pin Test Model

The single fuel pin test was performed using the electrically heated fuel element simulator (FES) enclosed in a glass tube, which simulated the hydraulic characteristics of the finned fuel element in a single flow channel [11,12]. This test was to develop the new correlations indigenous to the heat transfer characteristics of HANARO finned fuel element both for single-phase and two-phase conditions. The heat transfer is further improved by forcing coolant to flow upward over the finned fuel surfaces at high subcooling and high mass flux conditions during normal operation. The finned fuel element is modeled as a bare cylindrical rod without fins. The single fuel element is axially divided into two heat structures to see the axial temperature variation during transients. Eight radial mesh intervals are used in each heat structures; six for fuel, two for the cladding. The fin effect on the heat transfer and pressure drop in the fuel channels is considered via only using the equivalent heated and hydraulic diameters. The heat flux is based on the bare rod diameter. The RELAP5/HANARO nodalization for single fuel pin test simulation is shown in Figure 1.

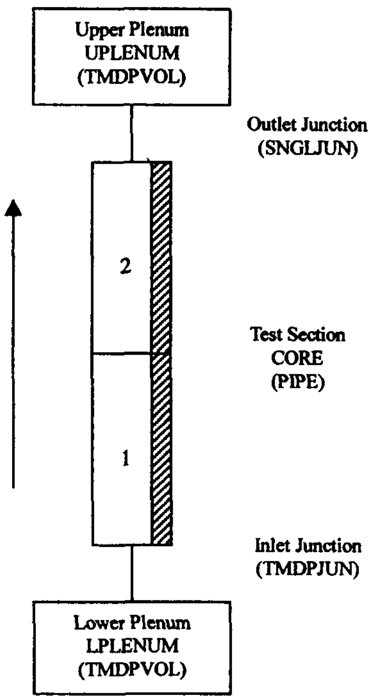

Fig. 1. Calculational Model for Single Fuel Pin Heat Transfer Experiment

3.2. Plate Type Heat Exchanger Model

The simulation model of the HANARO heat exchanger is completed for the system heat structure, as depicted in Figure 2. For the plate type heat exchanger, the primary and secondary sides modeled by parallel plates are coupled to the heat structures located in-between. The plate type heat exchanger is modeled as the above mentioned model using 12 volumes and 12 heat structures in such a way that the steady state characteristics supplied by the manufacturer may be reproduced. The secondary cooling system is modeled as time dependent boundary conditions for the simplicity of the analysis. The pressure differences between the inlet and outlet are imposed by using time dependent volume of RELAP5/MOD3.2 and the established flows by the pressure difference are calculated.

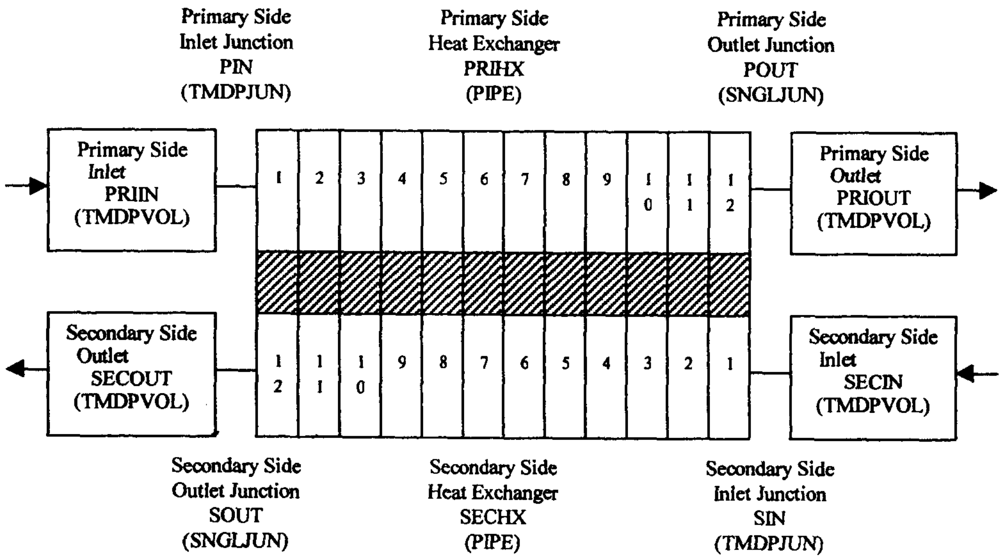

Fig. 2. Calculational Model for HANARO Plate Type Heat Exchangers

3.3. Natural Circulation Model

The natural circulation through pool is the principal cooling mechanism during shutdown condition. The natural circulation test is designed to demonstrate the general behavior of the HANARO reactor where all of the coolant flows through the bypass line into the inlet plenum. Shortly after reactor shutdown, the primary pump on HANARO will be turned off to facilitate fuel and/or target changes. Under this condition, the decay heat from the core will be removed to the pool by natural circulation. It is assumed that there is no flow through the primary circuit, and that all of the cooling water for the core has to flow the pool through the bypass line into the inlet plenum. The question then arises of how much decay heat can be removed from the core by natural circulation.

A natural circulation experiment with a scaled single heated bundle was performed to simulate natural convection decay heat conditions in a large tank simulating the pool [13,14]. This bundle is an 18-element hexagonal array with nominal flat

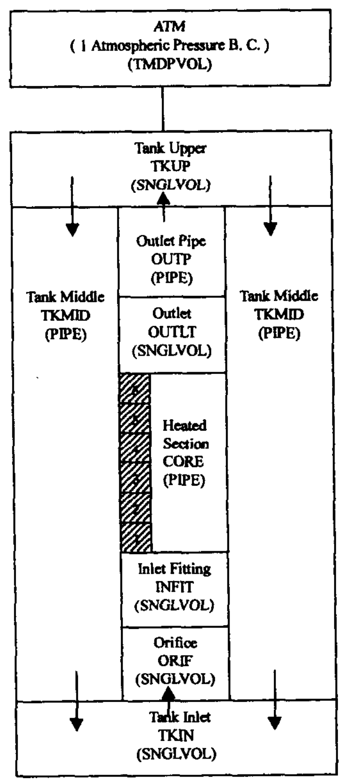

Fig. 3. Simulation Model for Natural Circulation Experiment

radial and cosine axial heat flux profiles. The pool is modeled into two parts, one for above the chimney and the other for below the chimney. The coolant piping is not modeled as heat structure since the heat transfer to the atmosphere across this piping is very small and can be negligible due to low coolant temperature. The water pool surface is connected to the time dependent volume which represents the atmosphere. The simulation model of the natural circulation experiment is shown in Figure 3.

4. Results and Discussion

Several thermal-hydraulic simulations were performed using the RELAP5/HANARO to validate whether the modified heat transfer package, the developed models associated with the plate type heat exchanger, and the natural circulation are working well as intended. The purpose of these various simulations is to assess the predicting capabilities of RELAP5/HANARO under the transient conditions in HANARO.

4.1. Heat Transfer of Single Fuel Pin Test

In HANARO, the heat removal from the core is enhanced by adding fins to the fuel rod surfaces. The modified heat transfer package is used to perform the code validation against the single fuel

Table 1. Summary of Input Data and Calculated Results for Single Fuel Pin Heat Transfer Experiments

Case No.	Power (W)	Flow Rate (kg/sec)	Pressure (kPa)	T_{bulk} (°C)	$T_{sh,m}$(1) (°C)	$T_{sh,p}$(2)(°C) RELAP5/ HANARO	RELAP5/ MOD3.2	P/M(3) Ratio
T01	12000	0.501	130.00	79.14	106.00	107.66	119.35	1.016
T02	20000	0.988	161.50	32.93	65.90	67.28	91.88	1.021
T03	35130	1.091	168.50	81.24	127.50	123.84	142.99	0.971
T04	7183	0.303	124.45	67.07	91.94	95.80	109.06	1.042
T05	4903	0.217	127.87	94.53	114.01	115.75	119.17	1.015
T06	19516	0.386	332.48	97.89	144.63	147.97	158.60	1.023
T07	35000	0.779	326.00	95.47	146.50	146.07	164.43	0.997
T08	35000	0.965	157.50	85.18	129.60	125.56	144.64	0.969
T09	10635	0.105	122.75	82.68	121.36	128.67	129.63	1.060
T10	41912	0.968	150.88	90.08	133.59	134.12	155.40	1.004
T11	31321	0.386	322.47	100.68	150.73	159.74	171.54	1.060
T12	42377	0.565	328.15	102.82	149.90	161.92	178.51	1.080
T13	6000	0.107	118.00	84.54	119.30	117.38	120.74	0.984
T14	6000	0.107	118.00	97.34	119.30	128.30	129.21	1.075
T15	35100	0.965	158.00	95.78	132.76	131.41	150.12	0.990
T16	86303	0.750	227.84	43.52	151.86	155.99	185.67	1.027

Note 1: (1) Maximum Measured Temperature of Fuel Element Sheath
(2) Maximum Predicted Temperature of Fuel Element Sheath
(3) Ratio of Predicted (RELAP5/HANARO) to Measured Temperatures

Note 2: Case No. T01 - T04 from Single-Phase Data
Case No. T05 - T08 from ONB Data
Case No. T09 - T12 from OSV Data
Case No. T13 - T16 from Two-Phase Data

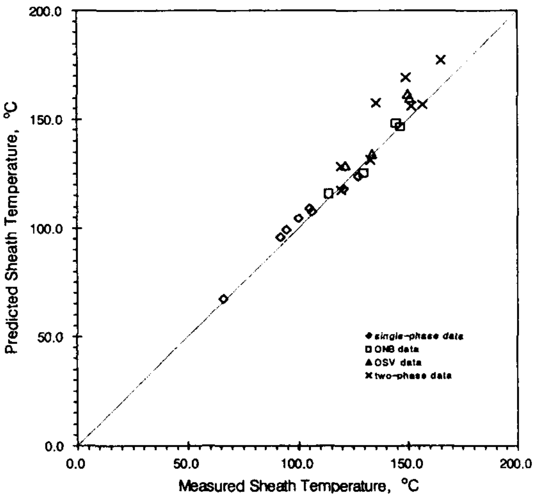

Fig. 4. Comparison of Predicted to Measured Sheath Temperatures

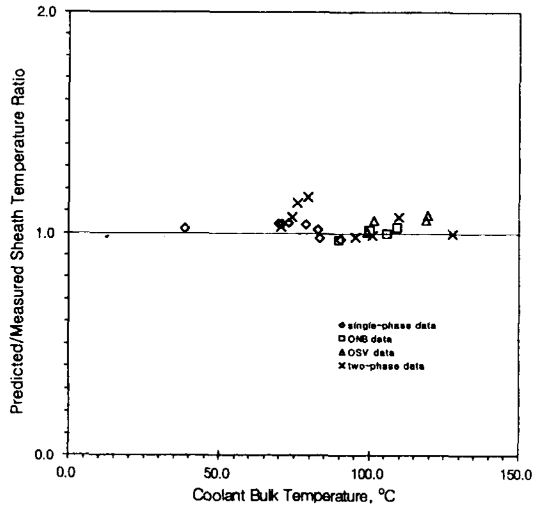

Fig. 5. Comparison of Predicted to Measured Sheath Temperatures with Coolant Bulk Temperature Changes

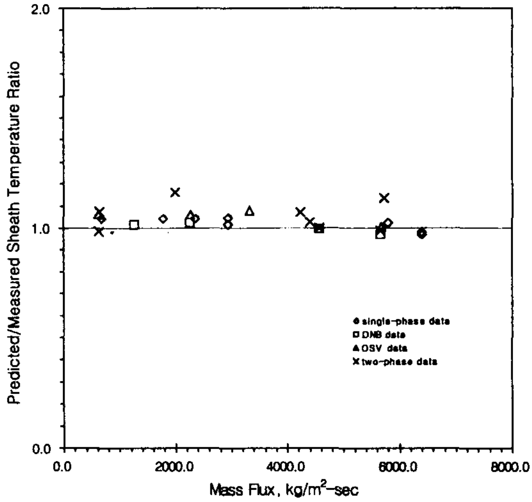

Fig. 6. Comparison of Predicted to Measured Sheath Temperatures Ratio with Mass Flux Changes

pin test whether the newly selected heat transfer correlations are correctly implemented and work as intended. The emphasis of this simulation is placed the validation of the hydraulic and heat transfer characteristics of the finned fuel element, which has eight longitudinal fins attached on the sheath surface. These fins are to enhance the convective heat transfer to coolant and to reinforce the mechanical strength of the fuel element.

Based on single fuel pin heat transfer experiment covering a wide range of the input data, which include the single-phase, ONB, onset of significant void (OSV), and two-phase data obtained at the AECL, the representative 16 cases are chosen and applied to the input for the newly developed code. After the application of RELAP5/HANARO to the representative 16 cases, the fuel surface temperature profile is turned out to be almost identical regardless of the heat transfer regime. The assessment results of the single fuel pin test showed generally good agreement with the experimental data for several flow conditions, but the results simulated by the RELAP5/HANARO are overpredicted within 5% as listed in details in Table 1 and depicted in Figure 4 through 6. It can be confirmed whether there is enough conservatism in the fuel surface temperature prediction by comparing with experimental data.

In addition, the simulation results for the single fuel pin test with both the RELAP5/MOD3.2 and RELAP5/HANARO codes are compared in this paper. The fuel surface temperatures predicted by the RELAP5/MOD3.2 show a large difference from the RELAP5/HANARO results that the RELAP5/MOD3.2 heat transfer package choice gives the higher temperatures.

4.2. Simulation of Plate Type Heat Exchanger

The thermal-hydraulic performance of the plate type heat exchanger was tested and proven to coincide with the performance data provided by the manufacturer. The plate type heat exchanger performance data provided by the manufacturer was reproduced by input data such as the manipulated flow area, hydraulic diameter and junction loss coefficient. Even if the geometric dimension and configuration are somewhat different from the actual heat exchanger, this kind of model is accepted as long as the model that heat exchanger has the same performance as the actual heat exchanger.

The simulation results of both codes are provided in Table 2 and 3. As can be observed, the results of simulations made very little difference in the pressure drop, but the RELAP5/HANARO was found to predict the higher heat transfer rates than those predicted by the RELAP5/MOD3.2. The calculated values were compared with manufacturer's data. The pressure drop characteristics and heat transfer performances of the model were compared with those of the manufacturer-supplied information and the discrepancies were found to overpredict by about 5% and 1%, respectively. RELAP5/HANARO showed a tendency of underprediction for the pressure drop at low flow condition of HANARO. The discrepancy is judged not to be serious in the simulation of the overall system transient and the calculated values are conservative.

4.3. Natural Circulation Experiment

The simulations for the natural circulation behavior were performed by using the RELAP5/HANARO. The purpose of this simulation is to assess the predicting cooling capability of RELAP5/HANARO under the natural circulation

Table 2. Comparison of Designed to Simulated Pressure Drop with Flow Rate Changes

Data Point	Flow Rate (kg/sec)	Pressure Drop (Pa)		
		Designed	Simulated	
			RELAP5/ HANARO	RELAP5/ MOD3.2
1	3.0	24.0	27.0	27.0
2	5.0	50.0	51.0	50.0
3	7.0	78.0	79.0	77.0
4	9.0	108.0	111.0	108.0
5	10.0	126.0	128.0	127.0
6	11.0	149.0	147.0	151.0
7	13.0	196.0	187.0	191.0
8	15.0	247.0	231.0	228.0
9	390.0	84400.0	85757.0	85740.0
10	420.0	99360.0	99205.0	99274.0

Table 3. Comparison of Designed to Simulated Heat Transfer Rates with Flow Rate Changes

Data Point	Flow Rate (kg/sec)		Temperature (℃)		Heat Transfer Rate (kW)		
			T_{in}	T_{out}	Designed	Simulated	
						RELAP5/ HANARO	RELAP5/ MOD3.2
1	PCS*	390.0	44.2	35.0	14000.0	14013.6	11922.7
	SCS**	420.0	32.0	40.0			
2	PCS	9.0	43.6	34.5	420.0	420.6	387.7
	SCS	15.0	32.0	38.7			
3	PCS	7.0	43.6	32.4	327.0	327.5	278.2
	SCS	10.0	32.0	39.8			
4	PCS	5.0	43.6	32.4	234.0	234.9	231.5
	SCS	10.0	32.0	37.6			

* : Primary Cooling System
** : Secondary Cooling System

Table 4. Comparison of Measured to Calculated Mass Flow Rates and Core Outlet Temperatures with Natural Circulation Experiments

Power (kW)	Mass Flow Rate (kg/m^2-sec)		Core Outlet Temperature (℃)	
	Test	Calculation	Test	Calculation
9.5	0.062	0.061	60.4	62.5
19.0	0.090	0.082	73.9	80.2
28.5	0.113	0.098	84.3	94.3
38.0	0.135	0.106	90.6	101.1

condition in HANARO. The results show that RELAP5/HANARO gives reasonable predictions for the flow rate and the coolant temperature during natural circulation condition and has a confidence to simulate natural circulation in HANARO.

The simulation results for each power level are given in Table 4. These are the averaged temperatures and the calculated flow. The calculated flow was obtained from the heat balance assuming single-phase fluid at the inlet and outlet thermocouples. This flow was used to obtain the pressure loss across the inlet orifice. The average void in the bundle was then calculated from this inlet orifice pressure drop by equating it to the gravity head assuming homogeneous flow. The simulation results of the mass flow rate and core outlet temperature are represented in Figures 7 and 8. The simulation results of the natural circulation are similar to the experimental data, even though minor discrepancies of the flow between the experiment and the prediction are identified due to the use of the constant local geometric pressure loss coefficients (e.g., inlet endplate, spacers, etc.) which can be estimated at each power level. Also some factors of inaccuracy

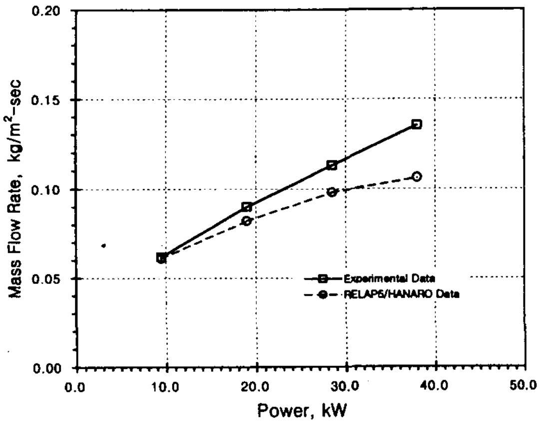

Fig. 7. Comparison of Calculated to Measured Mass Flow Rate with Power Changes

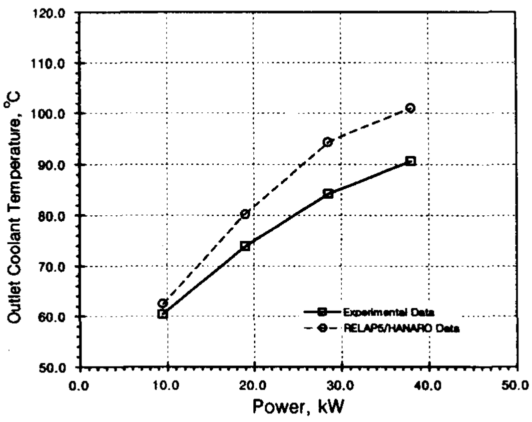

Fig. 8. Comparison of Calculated to Measured Outlet Coolant Temperatures with Power Changes

still exist in the natural circulation simulation. However, these differences are insignificant and conservatively acceptable in thermal-hydraulics. The mass flow rates are underpredicted less than 10%, otherwise the core outlet temperatures are overpredicted by about 4%.

5. Conclusions

A reliable system analysis code applicable to HANARO which operates under low pressure and low temperature conditions, RELAP5/HANARO, was developed from the RELAP5/MOD3.2 to perform safety and accident analyses. Many aspects of RELAP5/MOD3.2 were either modified or replaced by new features to be able to simulate the HANARO characteristics such as the finned fuel element, plate type heat exchanger, and natural circulation in the pool.

The proposed new models provide reasonable calculational capability through the use of applicable thermal-hydraulic models to describe the safety and analysis for HANARO. The robust simulation capability of RELAP5/HANARO is shown through various simulations of the thermal-hydraulic behaviors for HANARO. All of the simulation results are in reasonably good agreement with the transients considered. From comparisons of the RELAP5/HANARO predicted results with experimental data, RELAP5/HANARO comprises the unique characteristics of HANARO and it is capable of simulating well the thermal-hydraulic behavior under the postulated transient conditions of HANARO.

Nomenclature

D_e	equivalent diameter
D_h	hydraulic diameter
h	heat transfer coefficient
k	thermal conductivity
Pr	Prandtl number
P_{ba}	bare element heated perimeter
P_{ht}	fuel element heated perimeter with fins
q''	heat flux
Re	Reynolds number

Greek

χ_e	equilibrium quality
ρ	density
ρ_f / ρ_g	ratio of liquid to vapor density

Subscripts

f film property or liquid phase
g vapor phase
w fuel surface
s saturated property
b bulk temperature

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