Journal of the Korean Nuclear Society
Volume 26, Number 2, June 1994

Improvements to the RELAP5/MOD3 Reflood Model and Assessment

B.D. Chung, Y.J. Lee, C.E. Park, C.J. Choi, and T.S. Hwang
Korea Atomic Energy Research Institute
(Received January 17, 1994)

RELAP5 / MOD3 재관수 모델의 개선 및 평가

정법동 · 이영진 · 박찬억 · 최철진 · 황태석
한국원자력연구소
(1994. 1. 17 접수)

Abstract

Several improvements to the RELAP5/MOD3 reflood model have been made. These improvements were made to correct deficiencies in the reflood model identified by the assessment of the RELAP5/MOD3 code against FLECHT-SEASET experiments. The improvements consist of modification of reflood wall heat transfer package and adjusting the droplet size in dispersed flow regime. The time smoothing of wall vaporization and level tracking of transition flow are also added to eliminate the pressure spikes and level oscillation during reflood process. Assessment of the improved model against FLECHT-SEASET experimental data and application of LBLOCA analysis for plant shows that the deficiencies have been corrected.

요 약

FLECHT-SEASET 실험에 대한 RELAP5 / MOD3 평가시에 밝혀진 코드결함을 수정하기 위하여 RELAP5 / MOD3 재관수 모델을 개선하였다. 모델개선은 재관수 열전달 모델의 수정과 분산유동영역의 액적 크기의 조절을 통하여 이루어졌으며 재관수 계산시 발생되는 압력 spike와 수위진동 등의 결함을 개선하기 위하여 벽면비등모델의 time-smoothing과 천이 유동시의 level tracking모델도 첨가되었다. FLECHT-SEASET실험에 대한 개선모델의 검증과 발전소의 대형냉각재 상실 사고해석 응용에서 코드결함이 개선되었음을 알 수 있었다.

1. Introduction

The postulated loss-of-coolant accident(LOCA) of a pressurized water reactor has been the subject of intensive experimental and analytical studies in light water reactor. Many efforts are devoted to the investigation of thermodynamic behavior of reactor core and effectiveness of emergency core cooling system during reflood phase of LOCA. Recently the MOD3.1 version of RELAP5 [1] has been developed jointly by the NRC and a consortium of International Code Assessment and Application Program (ICAP). Although the emphasis of the RELAP5/MOD3.1 development was on large-break LOCAs, several deficiencies in reflood model were identified during the assessment of FLECHT-SEASET series of experiments [2]. The deficiencies are categorized as 1) High pressure spikes and oscillation during reflood 2) Delayed quenching 3) Incorrect void profile and vapor cooling in dispersed flow.

The purpose of this study is to present a new reflood model and its implementation in RELAP5/MOD3.1. A great deal of effort has been made to solve the above deficiencies, and the necessary model improvement and code modification has been carried out.

2. Improvement of Reflood Models

A boiling curve is used to govern the selection of heat transfer of reflood. In particular, the heat transfer regimes modeled are classified as single phase liquid convection, nucleate boiling, transition film boiling, film boiling and single phase vapor convection. Condensation heat transfer is also modeled, and the effects of noncondensable gases are modeled. The correlations of RELAP5/MOD3 were used for nucleate boiling (Chen correlation [3]) and single phase convection (Dittus-Boelter correlation). The correlations and selection logic for transition and film boiling mode are modified. Time smoothing of wall vaporization and level tracking of transition flow are also added to eliminate pressure spikes and level oscillation during reflood process. More detailed model descriptions are provided in the following section.

2.1. Wall Heat Transfer Package

The heat transfer package consists of a library of heat transfer correlations and selection logic algorithm similar to RELAP5/MOD3.1. For the normal heat structures, the correlation and logic algorithms are exactly the same as those installed in RELAP5/MOD3.1. However when the heat structures are flagged as reflood structure, some modification of correlations and logic algorithm are performed. The modified correlations used in each heat transfer regimes are detailed below.

2.1.1. Transition Boiling and Critical Heat Flux

In RELAP5, the transition boiling correlation is based on Chen transition boiling model [4] which is applicable to a dispersed flow regime. The model depends on the Critical Heat Flux (CHF) value and used to determine whether the film boiling occurs. Thus CHF correlation is important in determining the flow regime. The Groeneveld Look up table [5] was used to determine the CHF. Unfortunately, the value in the table was found to change suddenly with respect to flow and quality at low pressure and low flow condition. It may result in numerical instabilities or oscillation. Modified wall heat transfer package is based on the heat transfer logic developed on the basis of wall temperature.

The intersection of the nucleate boiling and transition boiling heat transfer regimes occurs at the CHF point. To provide for a continuous transition between regimes, the CHF point (q''_{CHF}, T_{CHF}) must be specified. The modified Zuber pool boiling CHF correlation [6] is chosen as a reasonable approximation of the maximum heat flux at the quench front:

$$q''_{CHF} =$$

$$(1-\alpha_g)(\pi/24)\ h_{fg}\ \rho_g{}^{0.5}\ [\ g\ \sigma\ (\rho_f-\rho_g)]^{0.25} \qquad (1)$$

To define the boiling curve, it is necessary to know the surface temperature at which CHF occurs. An iterative procedure is used to find the wall temperature at which the heat flux from Chen nucleate boiling correlation is equal to the critical heat flux. Thus,

$$q''_{CHEN}\ (T_{CHF}) = q''_{CHF} \qquad (2)$$

The transition boiling regime is bounded by the CHF point (below which the wall is continuously wetted and nucleate boiling exits) and the minimum stable film boiling point (above which the liquid cannot wet the wall and film boiling exits). The minimum stable film boiling temperature is called sometimes rewetting or quenching temperature. There are several correlations, e.g. Dix & Anderson [7], Murao [8], Berenson [9] and Henry [10] correlation. Good agreement between several FLECHT-SEASET data [11] and predicted rewetting temperature was obtained when a formulation of Henry correlation was used. Thus Henry correlation is incorporated in modified RELAP version to determine the minimum stable film boiling temperature and has following form:

$$T_{MIN} = T_{MIN,B} + \tag{3}$$

$$0.42(T_{MIN,B} - T_l)\ \{[(k\rho C_p)_l/(k\rho C_p)_w]^{0.5}\ [h_{fg}/C_{pw}(T_{MIN,B} - T_f)]\}^{0.6}$$

$$T_{MIN,B} = T_f + 0.127(\rho_v h_{fg}/k_v)\ [g(\rho_f - \rho_g)/(\rho_f + \rho_g)]^{2/3}$$

$$[\sigma/g(\rho_f - \rho_g)]^{1/2}\ [\mu_v/g(\rho_f - \rho_g)]^{1/3}$$

At present, there is no consensus on a correlation to use for the transition boiling regime. Modified version employs a simple interpolation scheme for heat transfer between CHF temperature and minimum film boiling temperature.

$$q''_{TRAN} = q''_{CHF} + (1 - \delta^2)\ q''_{FB} \tag{4}$$

, where δ is defined as $(T_W - T_{MIN})/(T_{CHF} - T_{MIN})$.

The above mentioned heat flux should be partitioned to the liquid and the vapor phase for two fluid model. Assuming that the heat transfer coefficient of vapor side does not change much, the energy partition of transition region can be estimated as follows.

$$h_g = h_{g,CHF} + (1 - \delta)\ h_{g,FB}$$

$$q''_g = h_g\ (T_w - T_g)$$

$$q''_f = q''_{TRAN} - q''_g \tag{5}$$

2.1.2. Film Boiling

Film boiling is described by heat transfer mechanisms that occur during several flow patterns, namely inverted annular flow, slug flow and dispersed flow. The wall-to-fluid heat transfer mechanisms are conduction across a vapor film blanket next to a heated wall, convection to flowing vapor and between the vapor and droplets, and radiation across the film to a continuous liquid blanket or dispersed mixture of liquid droplets and vapor.

The single phase vapor correlations become the model basis of the convection heat transfer in film boiling mode. However the presence of the droplet in steam flow provides a source of turbulence additional to that generated by wall shear, and this will enhance the steam convective heat transfer as deduced from steam-only experiments. Several investigators have looked at the effect of turbulence intensity on convective heat transfer in two-phase dispersed flows. Drucker et al. [12] proposed that the droplets will enhance turbulence in the flow; hence, heat transfer. The ratio of the two-phase-to-the-single-phase heat transfer coefficient φ can be written for entrained flow as

$$\varphi = h_{TP}/h_{SP} = 1 + 3.25[(1 - \alpha_g)Gr/Re^2]^{0.5} \tag{6}$$

where $(1-\alpha_g)$ represents the liquid fraction and Grashof number, Gr, and flow Reynolds number, Re, are based on steam properties and defined by

$$Gr = g(\rho_f - \rho_g)\rho_g D_H^3 / \mu_g^2 \tag{7}$$

and

$$Re = \rho_g V_g D_H / \mu_g \tag{8}$$

The above two phase enhancement effects are included in the convection term (Dittus Boelter Correlation) of the film boiling mode. Similar enhancement effects are included in other codes, COBRA-TF [13] and Westinghouse BART [14]. The correlations in RELAP5/MOD3 conduction (modified Bromley Correlation) and radiation model are deemed sufficiently accurate and are not changed.

2.2. Wall Vaporization Smoothing Model

In RELAP5/MOD3, there are two interphase mass transfer terms. One is a wall vaporization due to wall heat transfer and the other is a mass transfer arising from bulk exchange between the liquid and vapor spaces. The latter is treated as a partially implicit term, although the interfacial heat transfer coefficient is estimated explicitly. However the first term, wall vaporization, is treated as an explicit term in the mass and energy equation. This scheme was found to cause numerical oscillation. It is well known that a numerical underrelaxation can prevent this kind of oscillations.

Thus time smoothing of wall vaporization is implemented to a modified version as follows.

$$\Gamma_{w,n+1} = \eta\ \Gamma_{w,n} + (1-\ \eta)\ \Gamma_{w,n+1} \tag{9}$$

The underrelaxation factor is of the form, $\eta = \exp(-\Delta t/\tau)$, in order to obtain time-step(Δt) insensitive smoothing. For reflood case $\tau = 0.1$sec was selected because time constant for major transient phenomena is considered as longer than 0.1 second.

2.3. Water Level Tracking Model for Transition Flow

Such codes as RELAP5 code which use Eulerian coordinate system for the solution of the finite difference equation, cannot track the two phase mixture level unless systems were modelled with very fine nodalization. Although a fine mesh nodalization of reflood heat structure is provided to account for the axial conduction, the lack of level tracking results in incorrect heat transfer coefficient for a fine mesh heat structure in a given coarse mesh hydro-cell. This impact is more severe for the developing flow.

To circumvent this, a level tracking model is newly implemented in modified version for the calculation of the heat transfer coefficient of fine mesh heat structure. The variation of hydraulic parameters in a hydro-cell can be estimated with proper assumptions. One of the major parameters which govern the wall heat transfer is void fraction. It is assumed that the void fraction in a hydro-cell has a step change between upper and lower void fraction of hydro-cell, while other parameters remain constant. The model is coded as the following equation.

$$\begin{aligned} \alpha_g(z) &= \alpha_K \qquad \text{if} \quad 0 < z < z_{level} \\ &= \alpha_L \qquad \text{if} \quad z_{level} < z < 1 \end{aligned} \tag{10}$$

, where α_K means the void fraction of downstream volume, α_L is void fraction of upstream volume, and α_g is void fraction of given hydro-cell. The water level zlevel is defined as $(\alpha_g - \alpha_L)/(\alpha_K - \alpha_L)$. The above scheme is activated when $\alpha_K < 0.1$ and $0.1 < \alpha_g < 0.9$, and only one of the cells related to a reflood structure is applicable.

2.4. Droplet Model for Dispersed Flow Regime

In RELAP5/MOD3, the bubbly and mist flow regimes are both considered as dispersed flow. The dispersed bubbles or droplets can be assumed to be spherical particles with a size distribution following the Nukiyama-Tanasawa form [15]. The average diameter d_0 is obtained by assuming that $d_0 = (1/2)d_{max}$. The maximum diameter, d_{max}, is related to the critical Weber number, $We = d_{max}\ \rho_c\ (v_g - v_f)^2/\sigma$. The values for We are taken presently as 10.0 for bubbles and 0 for droplet. For reflood case, the value 12 was taken for droplet and average droplet size was restricted between 2.5mm and hydraulic diameter (10mm for typical PWR).

However estimated droplet size was too large comparing with the FLECHT-SEASET experiment and COBRA-TF estimations [16]. It may result in too much liquid accumulation downstream of the quench front and incorrect vapor cooling. In the modified version, there is no change in correlations for interfacial drag and heat transfer, but the average droplet size for reflood case is restricted between 0.2mm and 2.0mm. All interfacial surface area for mist flow regime were estimated based on the above droplet diameter.

3. Model Assessment and Code Verification

3.1. Assessment against FLECHT-SEASET test

Runs 31504, 31805, 31302, 31701 and 33338 from the 161-rod FLECHT-SEASET facility was used to assess the modified reflood model of RELAP5/MOD3.1 at various reflood rates and gravity driven reflood. Four forced feed reflood and one gravity feed reflood cases were selected for the assessment and shown in Table 1.

The test section was modeled using 20 uniform cells. Measured fluid conditions were used to define the conditions in the upper and lower time-dependent volumes, which represented the upper and lower plenums, respectively. The measured flow injection velocity was used to define the flow conditions at the time-dependent junction that connected the lower plenum and the pipe. The measured power, which decreased during the test period, was used as input to heat structures representing the rods.

The test section and heater rod models for gravity driven flood test are the same as the forced feed simulation except the downcomer and associated pipes are additionally modelled. The downcomer was modeled using 10 cells deemed sufficiently to give correct prediction of water level. The connecting pipes and valves are modeled also. The measured flow rate injected to the bottom of downcomer was used to define the conditions at the time dependent junction that connected to the bottom of downcomer.

The heatup and reflood phase of tests were simulated as a whole transient by using the measured heatup and decay power. The measured cladding temperatures before heatup were used as input to initial temperatures for each heat structures. The start time of water injection was used as input value also.

The experimental data for 161-rod FLECHT SEASET were chosen in ENCOUNTER Data Bank of USNRC. The sorted data for each test were used for the comparison of calculation results. Generally hydraulic cells in the model do not always have the same elevation as the measurement point. Thus calculation results are linearly interpolated for the comparison between calculation and experimental data. Assessments of forced feed and gravity feed test were performed based on the interpolated calculation results.

3.1.1. Forced Feed Test

On the reference test run 31504, with an injection velocity of 2.46cm/s (0.97 in./s), comparisons of averaged experiment data and calculated rod surface temperature histories are presented in Figure 1.

The predicted quenching behavior of original version illustrates the weakness in the reflood model. There are 200 second quenching tail at midplane. It is believed that the Chen transition boiling model yield values that are too small. In modified version, models for the quenching temperature (Modified Henry correlation) and CHF temperature are newly installed and the transition boiling heat transfer is determined by interpolating between the two point. The modification results in great improvement of code-predicted quenching behavior as shown in Figure 1.

Table 1. Assessment Matrix for FLECHT SEASET 161 Rod Test

Test Run Number	Pressure (Mpa)	Maximum Clad Temperature (K)	Flooding Rate (cm/sec)	Injected Liquid Temperature (K)
31504	0.28	1136	2.4	324
31805	0.28	1144	2.1	324
31302	0.28	1142	7.65	325
31701	0.28	1145	15.5	326
33338	0.28	1144	Gravity	325

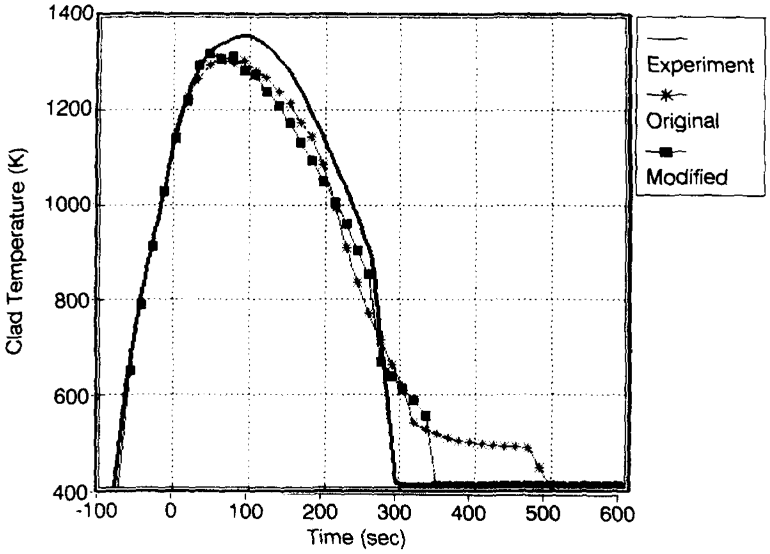

Fig. 1. Cladding Temperature Behavior at 72 in Core Elevation (FLECHT 31504)

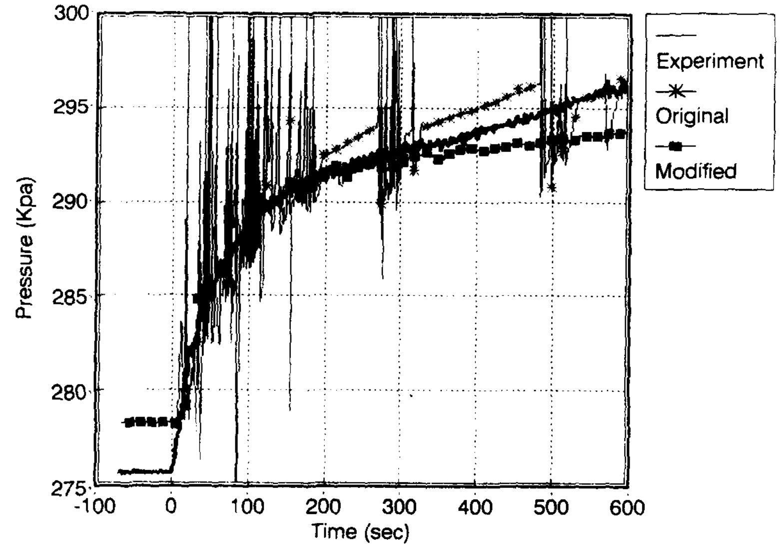

Fig. 2. Inlet Absolute Pressure Behavior(FLECHT 31504)

Comparison of inlet absolute pressure is presented in Figure 2. There are large pressure spikes in original version at the time of quenching of each heat structures. The combination of wall vaporization smoothing model and the level tracking model for the developing flow in modified version has remedied these deficiencies and pressure trends are predicted much better.

The calculated void fractions near the midplane (67 in.) is presented in Figure 3. It shows that there

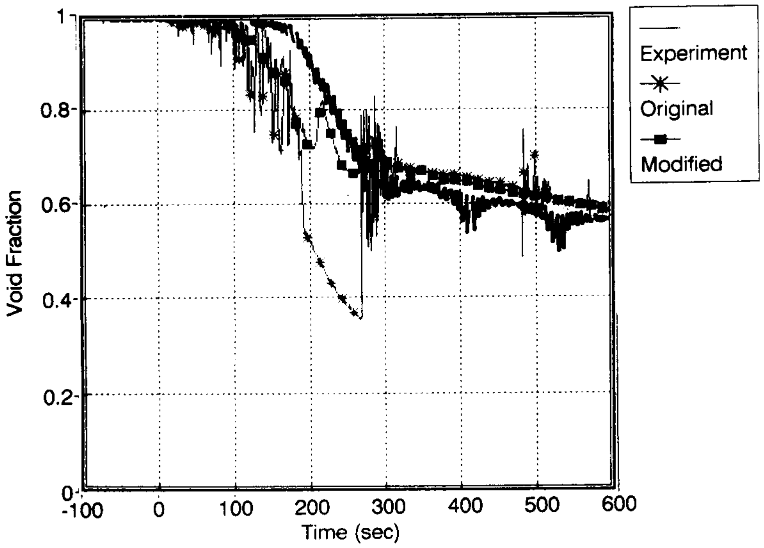

Fig. 3. Void Fraction Behavior at 72 in Core Elevation(FLECHT 31504)

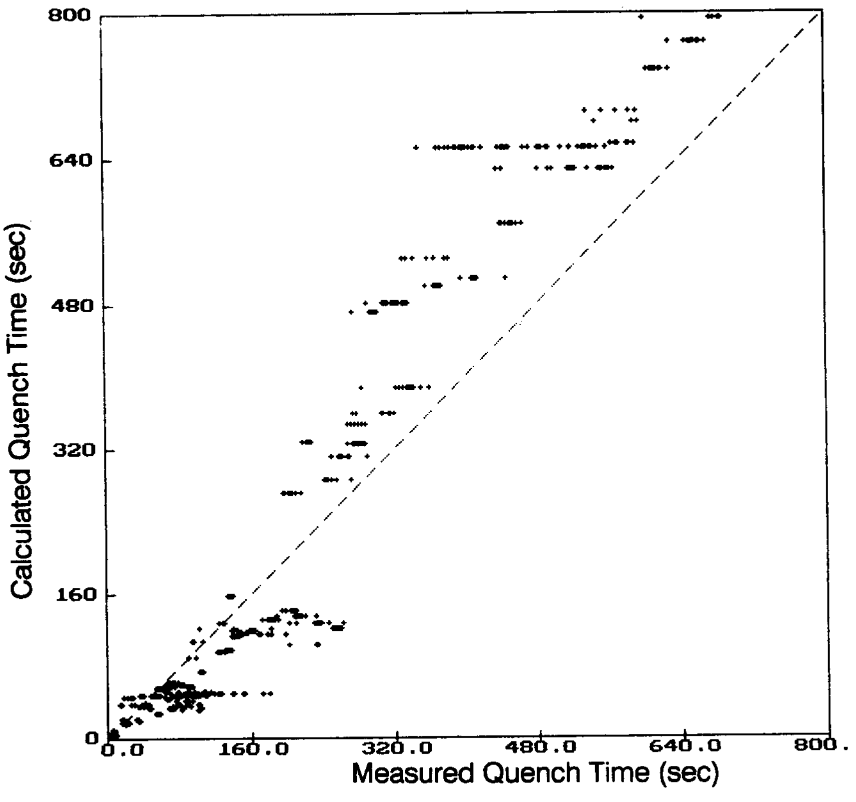

Fig. 4. Quenching Time Prediction of Original RELAP5/MOD3.1 Version

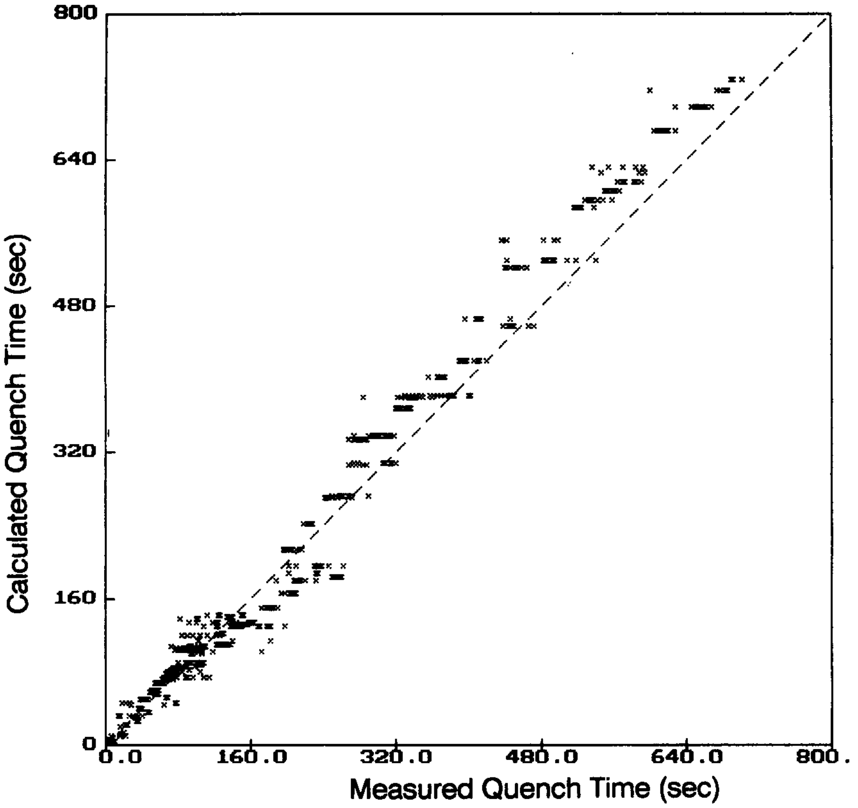

Fig. 5. Quenching Time Prediction of Modified RELAP5/MOD3.1 Version

is too much liquid accumulation at the downstream of quenching front. It may be caused by the low interfacial friction in dispersed flow regime predicted by the code. In modified version the maximum diameter of droplet size was restricted to be 2.0mm based on the FLECHT experimental observation. This restriction contributes to the increase in interfacial drag in dispersed flow regime and improvement of axial void profile. For high (Test Run 31701) and medium reflood injection test (Test Run 31302), the main characteristics are similar to reference case and hydraulic behaviors are much improved with the modified reflood model.

The determination of quenching time depends on the definition of quenching. In this report the quenching time was defined as the latest time when the clad temperature reaches 500K(~50K above the CHF temperature), because it is easy to compare the calculation result with test data through the simple definition. The calculated quenching time for 4 test runs are plotted in Figure 4 and 5, comparing with the experimental data.

Figure 4 shows that the original code predicts the early quenching in high liquid injection and delayed quenching in low liquid injection. The scattering of prediction is too large. It resulted from the weakness of transition boiling model and flow oscillation due to pressure spikes during reflood. These weaknesses are much improved in modified version and the predictions agree well with test data as shown in Figure 5.

3.1.2. Gravity Feed Test

Test run 33338 of gravity feed was selected for assessment because the test represents the more realistic reflood situation. The radial power distribution was accounted for in calculation and the rod surface temperature results from hot channel were presented in Figure 6.

The prediction of surface temperature is reasonable during the initial high reflood injection (~15 second). After the reduction of reflood rate, the test data shows a slight increase in temperature while the original code predicts continuous decrease and early quenching. The deviations become greater in the middle-to-upper elevation. This weakness of original version is probably due to the incorrect void fraction and steam velocity in test section. Unlike the forced reflood case, the liquid flow coming in the test section depends on the small pressure difference between the downcomer and the test section. If there are pressure spikes in calculation, these may affect the liquid injection velocity greatly. Figure 7 shows the calculation pressure spikes at test section inlet. With the help of wall vaporization smoothing in the modified version, these pressure spikes were diminished after the deduction of reflood rate. This contributes to the reduction of flow oscillation in test section and the correct prediction in rod surface temperature. The quenching behavior of surface temperature were also predicted well in the modified version due to the quenching temperature model.

3.2. Application of LBLOCA Analysis for Kori 3&4

Double ended cold leg break analysis for Kori 3 & 4 was performed using the modified version to verify the code predictability for overall LBLOCA phenomena. Results of peak clad temperature at midplane of core are presented in Figure 8 and compared with the original version of RELAP5. As shown in the figure, there is no change during the blowdown period because only the models related to reflood phenomena have been improved in modified version. During the reflood phase, the turn-around time of cladding temperature occurs too early in original version due to mainly the strong flow oscillations, while the

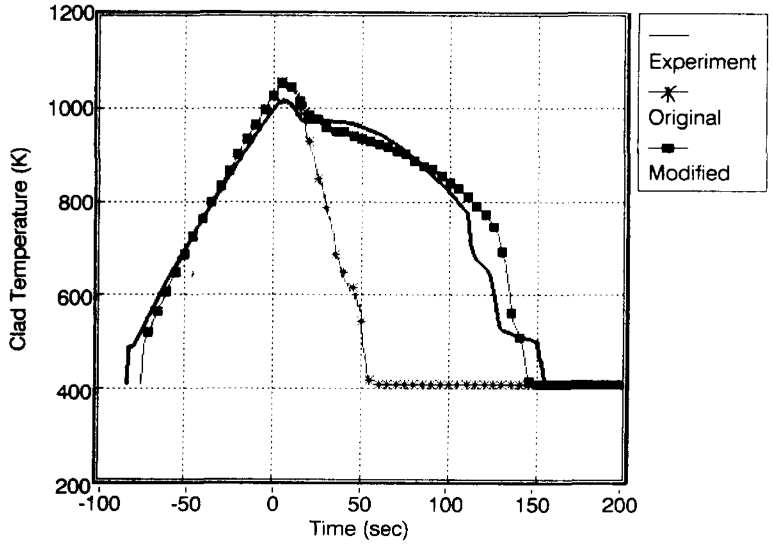

Fig. 6. Cladding Temperature Behavior at 96 In Core Elevation(FLECHT 33338)

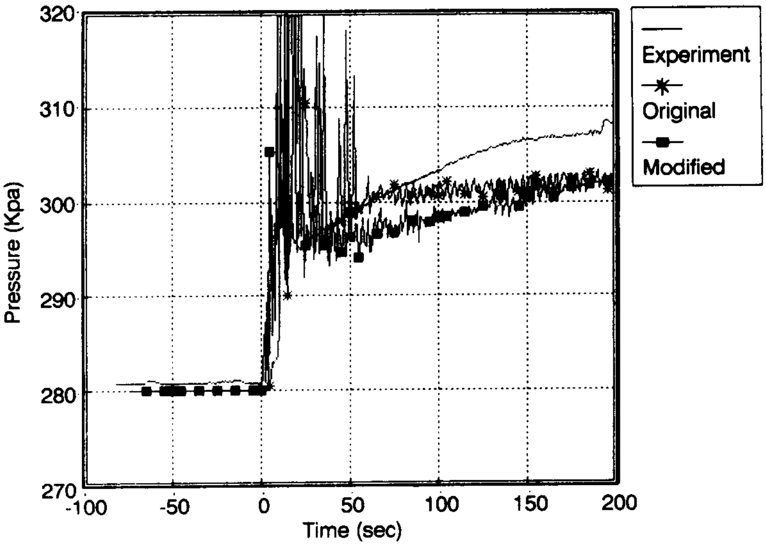

Fig. 7. Inlet Absolute Pressure Behavior(FLECHT 33338)

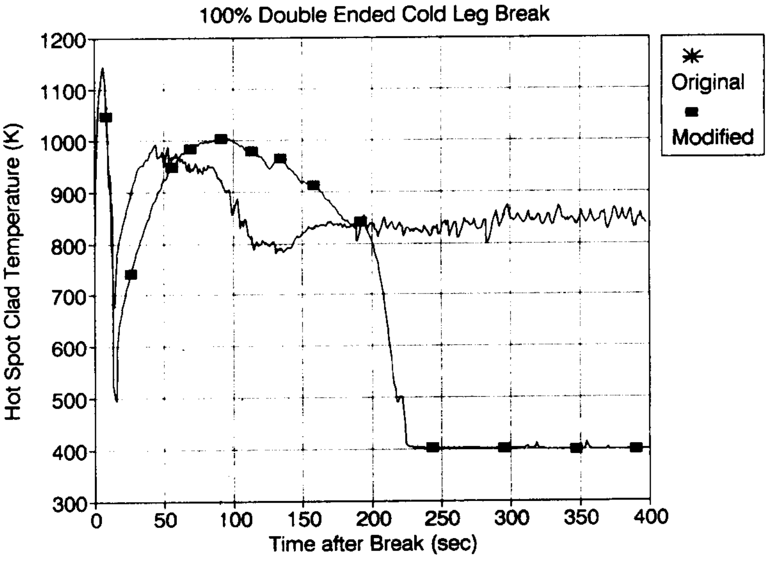

Fig. 8. Comparison of Predictions During LBLOCA Event of Kori 3 & 4

quenching of core does not occur due to the lack of quenching temperature model. In modified version, these deficiencies were corrected and predicted PCT behavior was considered as reasonable.

4. Conclusion

Assessment of original RELAP5/MOD3.1 code against the FLECHT SEASET series of experiments has identified some weakness of reflood model. The quenching of low reflood rate cases was delayed due to the lack of quenching temperature model and the shortcoming of Chen transition boiling model. Incorrect prediction of axial void profile and vapor cooling in dispersed flow resulted in increased cooling at the upper elevation. This was investigated to be caused by the incorrect prediction of droplet size and interfacial heat transfer. High pressure spikes during the reflood calculation resulted in the high steam flow oscillation and liquid carryover.

An effort had been made to improve the code with respect to the above weakness, and the necessary model for wall heat transfer package and numerical scheme had been modified. The weaknesses of RELAP5/MOD3.1 were much improved in modified version. The prediction of void profile and cladding temperature agreed better with test data. These improvements are more dramatic for gravity feed test. In the application of plant LBLOCA analysis, it can be concluded that the predictability of modified version for whole thermal hydraulic behavior was reasonable and suitable for use as best estimate code for LBLOCA.

Acknowledgement

Development of reflood model is based on the previous works for finding the deficiencies of RELAP5/MOD3. Acknowledgements are made of those who made significant contribution to the earlier reflood model assessment, in particular, J.S. Baek and W.J. Lee.

References

1. K.E. Carlson, et al., "RELAP5/MOD3 Code Manual, Volume 1, 2, 3, 4, and 5", NUREG/CR-5535, EGG-2596 (1990)
2. M.J. Loftus, et al., "PWR FLECHT SEASET Unblocked Bundle, Forced and Gravity Reflood Task Data Report", EPRI NP-1459, NUREG/CR-1532, WCAP-9699 (1981)
3. J.C. Chen, "A Correlation for Boiling Heat Transfer to Saturated Fluids in Convective Flow," Process Design and Development, 5, 322 (1966)
4. J.C. Chen, et al., "A Phenomenological Correlation for post-CHF Heat Transfer," NUREG-0237 (1977)
5. D.C. Groenveld, et al., "1986 AECL-UO Critical Heat Flux Lookup Table," Heat Transfer Engineering, 7, 1−2, 46 (1986)
6. N. Zuber, "The Hydraulics Crisis in Pool Boiling of Saturated and Subcooled Liquids," Part II, No. 27 in International Developments in Heat Transfer, International Heat Transfer Conference, Boulder, CO (1961)
7. G.E. Dix and G.M. Anderson, "Spray Cooling Heat Transfer in a BWR Fuel Bundle," ASME National Heat Transfer Conference (1976)
8. Y. Murao, "Correlation of Quench Phenomena for Bottom Flooding During Loss-of Coolant Accident," J. Nucl. Sci. Technol. 15, 12 (1978)
9. P.J. Berenson, "Film Boiling Heat Transfer from a Horizontal Surface," Trans. ASME, J. Heat Transfer, 83 (1961)
10. R.E. Henry, "A correlation for the Minimum Film Boiling Temperature," AIChE Symp. Ser., 7D (1974)
11. M.J. Loftus, et al., "PWR FLECHT SEASET: 161 Rod Bundle Flow Blockage Task Data Report,", EPRI NP-3268, NUREG/CR-3314, WCAP-10307 (1984)
12. M. Drucker, and V.K. Dhir, "Studies of Single and Two-Phase Heat Transfer in a Blocked Four-Rod Bundle," EPRI-NP 3485, Electric Power Research Institute (1984)
13. M.J. Thurgood et al., "COBRA/TRAC-A Thermal Hydraulic Code for Transient Analysis of Nuclear Vessels and Primary Coolant Systems", NUREG/CR-3046 (1983)
14. A.C. Spencer and M.Y. Young, "Mechanistic Model for the Best-Estimate Analysis of Reflood Transients (the BART Code)," HTD Volume 7,

19th National Heat Transfer Conference, Orlando, FL (1980)

15. G.B. Wallis, One Dimensional Two Phase Flow, New York, McGraw-Hill Book Company (1969)

16. C.Y. Paik, et al., "Analysis of FLECHT SEASET 163-Rod Blocked Bundle Data using COBRA-TF", EPRI-NP-4111, NUREG/CR-4166, WC-AP-10375 (1985)