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Prediction of the Reflood Phenomena with modifications in RELAP5/MOD3.1

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Abstract

Reflood model in RELAP5/MOD3.1 are modified to improve the unrealistic prediction results of the model. In the new method, the modified Zuber pool boiling critical heat flux (CHF) correlation is adopted. The reflood drop size is characterized by the use of $We = 1.5$ and the minimum drop size of 0.0007 m for $p^* \leq 0.025$. To describe the wall to vapor heat transfer at low pressure and low flow condition, the Webb-Chen correlation is utilized. The suggested method has been verified through the simulations of the Lehigh University rod bundle reflood tests. Through sensitivity study it is shown that the effect of drag coefficients is dominant in the reflood model. It is proved that the present modifications result in much more improved quench behavior and accurate wall and vapor temperature predictions.

1. Introduction

Under reflooding phase after a loss of coolant accident (LOCA) in nuclear power plants, complex thermal-hydraulic phenomena take place. Below the quench front, the heat is transferred from the rod bundle to the coolant by nucleate boiling. Near quench front, a number of tiny droplets are generated through the entrainment from continuous liquid surface. Up to some distance from the quench front, there exists dispersed flow film boiling. The understanding of reflood stage is important in large break LOCA analysis because it is usually predicted that the peak cladding temperatures (PCTs) occur during the reflood phase after LOCA.

In August 1988, USNRC issued a revised Emergency Core Cooling System rule entitled "Emergency Core Cooling System; Revision to Acceptance Criteria," which allows the use of best-estimate(BE) code for safety analysis provided that the uncertainties of the calculations are quantified and compared with acceptance limits contained in 10 CFR Part 50. Based on this revised rule, the best-estimate methodology may be applied to estimate the plant safety margin more realistically. To comply with the revised ECCS rule, it is very important to estimate the code capability and applicability to a certain phenomenon. Especially, it is one of the most important features in the safety analysis of LOCA to examine the appropriateness of the reflood model of a best-estimate code.

2. Previous Works

RELAP5 is a best-estimate analysis code, which is frequently used to analyze the trends of a real system of plant. RELAP5/MOD3.1 contains several unique features which are very helpful to simulate the ECCS performance after LOCA. For example, ECCMIX component is provided to describe the mixing phenomenon at the ECC water injection point. In addition, RELAP5/MOD3.1 provides reflood option and fine mesh rezoning scheme to describe the heat transfer in a transition region above which the core rods have not been rewet and below which they have. In this transition region, there exists a large axial variation in wall temperatures and heat fluxes that require a finer noding than is necessary for the normal temperature and heat flux calculations.

Many extensive analysis on the reflooding models of various versions of RELAP5 have been performed. M. Sencar and N. Aksan (1995) simulated the Lehigh University and PSI-NEPTUN bundle reflooding experiments with RELAP5/MOD2.5 and two versions of RELAP5/MOD3. From their results, it has been verified that both versions of RELAP5/MOD3 show unrealistic behavior such as continuous cooling of the nodes without clear turn-around temperature and no quenching phenomena.

Based on the above results, G. Th. Analytis (1995) modified several features which are closely related to the reflood model in RELAP5/MOD3. From the analyses of many separate-effect and integral-effect experiments, Analytis showed that the modified version of RELAP5/MOD3.1 was more physically sound than the frozen version.

At Korea Atomic Energy Research Institute (KAERI), the reflood model in RELAP5/MOD3.1 was analyzed extensively and several deficiencies in reflood model were identified during the assessment of FLECHT-SEASET series of experiments (1995). To remove these deficiencies from the code, the wall heat transfer packages were updated and time smoothing of wall vaporization and level tracking of transition flow were added in RELAP5/MOD3.1 reflood model. In addition, the droplet model for dispersed flow regime was modified.

Through the previous works by other researchers, the deficiencies of the reflood model in RELAP5/MOD3.1 have been well identified. In addition, many effective modification methods have been suggested. However, it seems that the theoretical backgrounds of some features in the modification methods are weak and sensitivity studies for modified terms should be provided.

3. Modifications of Reflood Model

3.1 Critical Heat Flux

Three important features in the frozen version of RELAP5/MOD3.1 reflood model are modified in the present study. One is the introduction of Zuber critical heat flux (CHF) correlation for low flow. Another is the modification of interfacial drag term for droplet flow. The other is the modification on the wall-to-vapor heat transfer correlation.

In RELAP5/MOD3.1, the appropriate prediction of CHF is very important because the heat transfer coefficient in transition boiling region is directly determined from the CHF value. In addition, the determination of heat transfer mode is closely related to the critical heat flux. Groeneveld look-up table, which is used in RELAP5/MOD3.1, has been found to show sudden changes in CHF values with respect to flow rate and quality at low pressure and low flow condition. Therefore, it is not suitable to be used at reflooding stage after LOCA. As suggested in the works at PSI and KAERI, the modified Zuber pool boiling CHF correlation is implemented in the present study when the mass flux is less than 150 kg/m^2s:

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

3.2 Interfacial Drag (Drop Size)

In RELAP5/MOD3.1, the size of reflood drops is evaluated from the Weber number criterion and limitation on the minimum drop size as a function of pressure:

$$D_{drop} = min\{D_H,\ max(D_{We},\ D_{min})\}. \tag{2}$$

With this method, D_{drop} is not allowed to be less than 0.0025 m for $p^* \le 0.025$, which is evidently false when it is compared with the results of FLECHT-SEASET experiment. The average droplet diameters measured in FLECHT-SEASET experiment are less than 0.0025 m (1.0 ~ 2.2 mm).

To correct the inappropriate droplet size at low pressure, some researchers suggested modified methods. G. Th. Analytis (1995) used the criterion of $We = 3$ and $D_{min} = 0.0015$ for $p^* \le 0.025$. In K-REM version of RELAP5/MOD3.1 developed at KAERI, the average droplet size for reflood is restricted between 0.2 mm and 2.0 mm according to FLECHT experiment results. However, their modifications were based on the engineering judgement. Therefore, the influence of flow parameters on the drop size could not be explained by the modified versions of the code.

Through the comparison and evaluation of many existing correlations and experimental data, it is found that the analytical trends of droplet size can be well reflected into the existing reflood drop size evaluation method if we choose appropriate Weber number for droplet breakup and the limiting droplet size below which no further breakup is allowed. The following method for the drop size in reflood is suggested based on the Weber number criterion and the limitation on the minimum drop size:

$$We = 1.5, \tag{3}$$

$$\begin{aligned} D_{min} &= 0.0007 \text{ for } p^* \le 0.025, \\ &= 0.0007 + (0.0002 - 0.0007)\cdot(4.4444)\cdot(p^* - 0.025) \\ &\quad \text{for } 0.025 < p^* < 0.25. \end{aligned}$$

3.3 Wall-to-Vapor Heat Transfer

To describe the wall-to-vapor heat transfer process, the Dittus-Boelter correlation is adopted in RELAP5/MOD3.1. And the heat transfer coefficients in transition boiling region are calculated both from Chen correlation and single phase vapor heat transfer correlation. In addition, the heat transfer coefficients in film boiling region are also evaluated from the Dittus-Boelter equation. Therefore, the accuracy of the wall-to-vapor heat transfer correlation is very important for the description of reflood phase because it directly affects the quench behavior and the accuracy of the predicted clad surface temperatures.

H.Y.Jeong and H.C. No (1996) analyzed the accuracies of many different single phase vapor heat transfer correlations and found that most existing correlations including Dittus-Boelter correlation are not suitable at low flow condition. This result can be caused by the inherent characteristics of the correlations. Most of the existing single phase vapor heat transfer correlations have been derived from the data of high pressure and high flow. Therefore, the applicability of these correlations to lower pressure and lower flow range can not be guaranteed.

For the description of the wall-to-vapor heat transfer at low pressure and low flow condition, the following correlation developed by Webb and Chen (1984) is implemented in RELAP5/MOD3.1:

$$h_{wc} = h_{mod-CSO}(1 + F_s) \cdot F_e. \tag{4}$$

It has been validated by H. Y. Jeong and H. C. No that the accuracy of this correlation is better than any other correlations at low pressure and low flow condition. Furthermore, the droplet turbulence effect is well incorporated in the correlation.

4. Results and Discussion

The effects of the modifications in the reflood model have been analyzed for the Lehigh University bottom reflood tests (D. G. Evans et al., 1983). The experiments were performed in a 3 × 3 rod bundle geometry to study the effect of flow parameters on the rewetting phenomena. The diameter of each rod was 9.5 *mm* and the pitch between the rods was 12.6 *mm*. The rewetting tests were conducted at atmospheric pressures for low mass and heat flux ranges.

The nodalization which is used for the simulations is shown in Fig. 1. The source of inlet subcooled water is modeled as a time-dependent volume (TMDPVOL 100). The measured inlet injection velocity is modeled by a time-dependent junction (TMDPJUN 105), which is connected to the test section of 1.22 *m* length. The test section is modeled as a pipe component (PIPE 200) which has 20 equal nodes of 0.061 *m*. The test section heater is modeled as a heat structure (HT-STR 1200). A single junction (SNGLJUN 205) is used to represent the outlet of the test section. Finally, another time-dependent volume (TMDPVOL 500) is connected by the single junction to simulate the mass sink. The power generated from the heater rod is given as a form of general table.

The effects of each modified model are analyzed in Fig. 2. As shown in the figure, the predictions by the frozen version of RELAP5/MOD3.1 show large difference from the experimental data, which implies that some features in the reflood model of the frozen version are not suitable. It is found that the introduction of the modified Zuber pool boiling CHF correlation results in not so much remarkable improvement in the prediction of surface temperature and quench time. The Webb-Chen single phase vapor heat transfer correlation results in slightly early quenching and underpredicts wall temperatures when it is compared with the frozen version. The modifications on the drag term show a remarkable effect on the quench behavior and temperature prediction. The whole effects of the modifications can be summarized as the accurate temperature prediction and improved quench behavior though there exists some premature quenching at very low mass flow.

As shown in Fig. 3, the experimental wall temperature can be predicted in reasonable accuracy with the modified version of RELAP5/MOD3.1. This is mostly due to the implementation of the realistic drag term in the reflood model. It is also notable that the predictions of quench time are improved clearly through the modification. The accurate prediction of quench time is very important in the analysis of LOCA because it is closely related to the behavior of the peak cladding temperature (PCT).

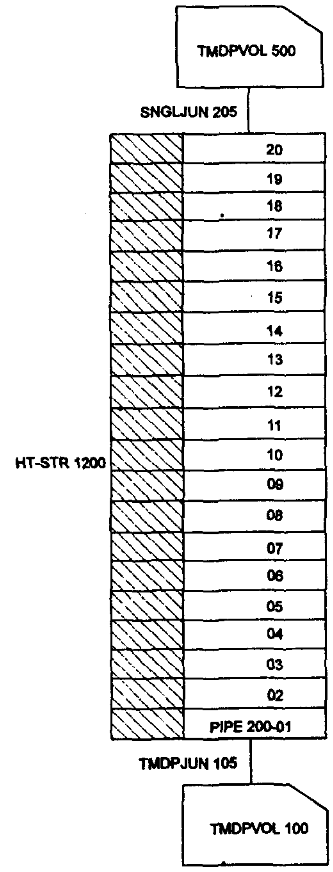

Fig. 1 **Nodalization scheme for the Lehigh University bottom reflood test**

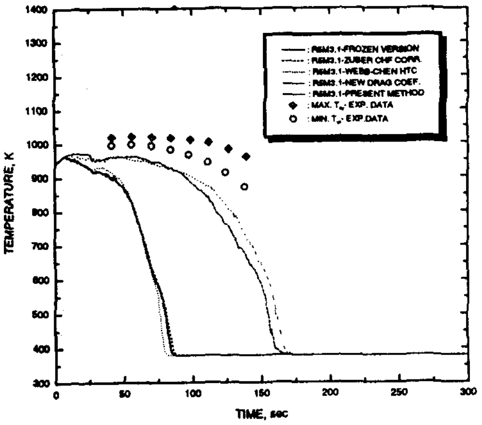

Fig. 2 **Wall temperature at 60 cm from the test section inlet for Lehigh University rod bundle test # 22.**

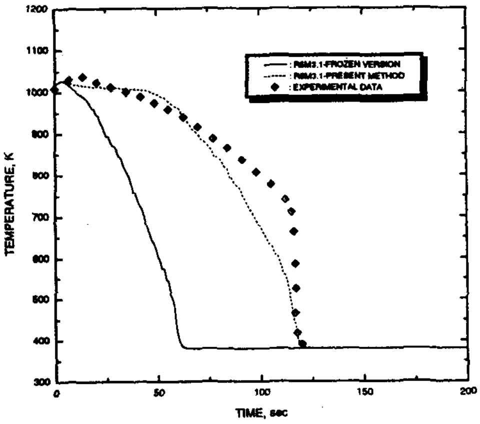

Fig. 3 **Wall temperature prediction at 30 cm from the test section inlet for Lehigh University rod bundle test # 20.**

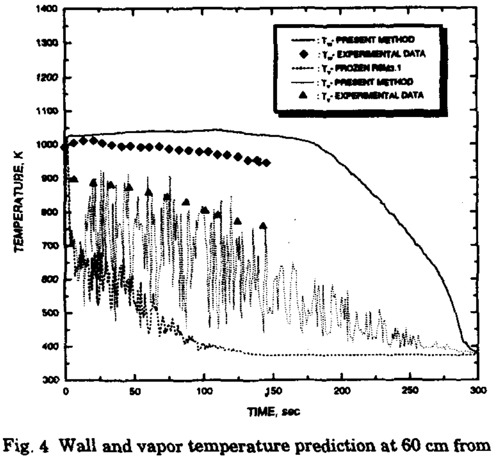

Fig. 4 **Wall and vapor temperature prediction at 60 cm from the test section inlet for Lehigh University test # 20.**

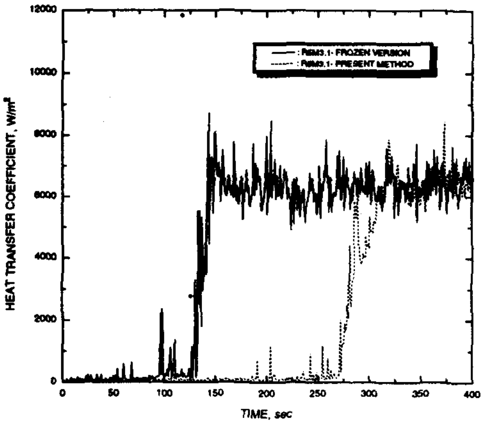

Fig. 5 Heat transfer coefficients at 60 cm from the test section inlet for Lehigh University rod bundle test # 20.

In Fig. 4, the predicted vapor temperatures by the present version are also given. Though the oscillatory behavior of the predicted vapor temperature is not consistent with the measured data, the predictions show much improved results when they are compared with those by the frozen version. Improvements in the prediction of vapor temperature and quench behavior are presumed to be due to the introduction of suitable wall to vapor heat transfer correlation.

The predictions of heat transfer coefficients for test numbers 20 with the frozen version and the modified version are compared in Fig. 5. The results of modified version show delayed quench behavior when they are compared with those of the frozen version.

In addition, it is found that the void fractions predicted with the modified version do not show deep vallies just after quenching, which is one of the improved features of the present work.

5. Conclusions

Through the present study, it is shown that the implementation of a realistic model for drag coefficients is essential for the prediction of reflood phenomena. It is verified that the criterion of $We = 1.5$ and the limiting drop size of 0.0007 m best describes the drop size existing at the situation of reflood. In addition, the Webb-Chen single phase vapor heat transfer correlation is incorporated into the heat transfer package to take into account the droplet turbulence effect and to remove the inherent inaccuracy of Dittus-Boelter equation at low flow region.

The modified version shows better accuracy in wall and vapor temperature predictions and more realistic quench behavior when it is compared with the reflood model of the frozen version of RELAP5/MOD3.1. However, it is also found that there still exist some factors of inaccuracy in the transition boiling heat transfer correlation.

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