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Thermal Fluid Mixing Behavior during Medium Break LOCA in Evaluation of Pressurized Thermal Shock

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Abstract

Thermal fluid mixing behavior during a postulated medium-size hot leg break loss of coolant accident is analyzed for the international comparative assessment study on pressurized thermal shock (PTS-ICAS) proposed by OECD-NEA. The applicability of RELAP5 code to analyze the thermal fluid mixing behavior is evaluated through a simple modeling relevant to the problem constraints. Based on the calculation result, the onset of thermal stratification is investigated using Theofanous's empirical correlation. Sensitivity calculations using a fine node model and crossflow model are also performed to evaluate the modeling capability on multi-dimensional characteristics related to thermal fluid mixing.

I. Introduction

The thermal-hydraulic mixing between cold high pressure injection (HPSI) water and hot fluid in downcomer of reactor pressure vessel (RPV) has been one of the major issues in assessment of the pressurized thermal shock (PTS) risk, which was required in the regulatory guide on PTS [1]. The previous experience indicated that the difference greater than 40 °F in reactor coolant system (RCS) overcooling could be obtained between the case using one-dimensional code and one using a detailed mixing analysis code [2]. Such a difference due to thermal fluid stratification could be experienced during small break loss of coolant accident (SBLOCA) in pressurized water reactor (PWR). Therefore, a reliable analytical method has been required to evaluate whether the cooling behavior in downcomer of RPV could be affected by HPSI thermal fluid stratification or not.

The medium-size break LOCA was, in itself, less severe sequence than SBLOCA in PTS concern, since it may have a faster RCS depressurization. However, the thermal-hydraulic mixing analysis in this medium-size LOCA could be difficult sequence since the complex thermal-hydraulic phenomena such as break flow, phase separation, steam-water mixing and condensation, hot-cold water mixing and stratification, etc., may be involved. Based on this concern, an international comparative assessment study on PTS (PTS-ICAS) was proposed by OECD-NEA to assess the capability of analytical model on thermal mixing prediction [3].

The present study, as a preliminary analysis, aims to evaluate the modeling capability of one-dimensional code, RELAP5 [4] on thermal fluid mixing behavior. The code has been widely used in global system thermal-hydraulic behavior during PTS sequences [2]. To this purpose, a simple modeling relevant to the PTS-ICAS problem constraints was developed. Based on the calculation result, the onset of thermal stratification is investigated using Theofanous's empirical correlation [5]. Sensitivity calculations using a fine node model and crossflow model are also performed to evaluate the modeling capability on multi-dimensional characteristics related to thermal fluid mixing.

Ⅱ. PTS-ICAS Problem Description

The thermal-hydraulic mixing problem of PTS-ICAS is to find out the transient of fluid temperature and local heat transfer coefficients in downcomer for a postulated 200 cm^2 hot leg break accident in a postulated reactor system whose geometry is identical to one of the UPTF (Upper Plenum Test Facility) experiment facility. The UPTF was a facility representing the typical KWU type 4-loop pressurized water reactor (PWR) with one-to-one volume scale. The RPV has an outer diameter of 5.37 m and has connections with four cold legs and hot legs, each of which has ECCS (emergency core cooling system) nozzle.

The medium size break was assumed at zero seconds with simultaneous reactor coolant pump stop. The problem specifies the HPSI and LPSI occurred after 100 seconds and 750 seconds into transient, respectively. Provided are, as constraints, the global downcomer pressure up to 5000 seconds, the global downcomer fluid temperature and fluid-to-downcomer wall heat transfer coefficient up to 300 seconds, and the downcomer water level up to 5000 seconds. The ECCS injection flow rate and temperature were given as functions of time. Also hot leg injection was allowed to be neglected by its less impact on downcomer fluid temperature.

Ⅲ. Modeling Description

As mentioned previous, RELAP5/MOD3.2 code was used to calculate the thermal-hydraulic mixing in PTS-ICAS task. The RELAP5 model for the UPTF was illustrated in Figure 1. The model consisted of 19 hydrodynamic volumes and 21 junctions. The RPV wall was simulated by six heat structures with six meshes in radial direction. The present model, as a minimum, includes the RPV, one hot leg and one cold leg (lumping four hot legs and cold legs), break, and ECCS. Due to the limited information, the boundary conditions for the RELAP5 calculation relevant to the problem constraints could not be uniquely specified, especially in flow conditions at cold leg upstream and hot leg downstream. Through some preliminary calculations, the boundary conditions were set with some artificial assumptions as follows:

1) The constraint showed that heat transfer coefficient was initially 19,000 W/m^2K and dropped to few hundreds W/m^2K in 150 seconds. Thus the initial loop flow rate was assumed to be 6140 kg/sec, which was corresponded to the given initial heat transfer coefficient. The insulation condition was assumed for outer wall of RPV.
2) A postulated pump was modeled to be with the previous flow condition. The pump was set to stop at 100 seconds.
3) The constraint on downcomer pressure was specified at hot leg.
4) The downcomer water level behavior was specified as a problem constraint; however, it is difficult to impose as a boundary condition in RELAP5 calculation. Thus the level will be calculated by the code in the present model.
5) The break was assumed to be open completely at 200 seconds, and the discharge coefficient was selected to be 0.2, which results in the calculation results as close to the water level constraint.

Ⅳ. Result and Discussion

1. Base Calculation

Based on the simple modeling scheme described above, a RELAP5 steady state calculation was performed to initial condition over the system. The calculated condition indicated the RCS pressure of 16 MPa, fluid temperature at downcomer of 570 K, which were close to the problem constraints.

A base case transient from this steady state condition was calculated up to 5000 seconds. In this analysis, the result up to 1500 seconds is discussed, because the transient after 1500 seconds did not show the further change in thermal-hydraulic behavior.

Figure 2 shows a comparison of the downcomer pressure between the calculation and the constraint. The calculated pressure behavior was well agreed to the constraint except two-phase period from 120 to 750 seconds. The deviation beginning from 120 seconds was due to early steam migration from upper part of the upper plenum into the hot leg and break, which was a typical phenomena in hot leg break case. The reason for such an early steam migration can be regarded as uncertainty in break flow. Currently, the accuracy of the predicted break flow cannot be evaluated because any constraint on the break flow was not specified. This deviation may have impact on flow stagnation and flow thermal stratification.

Figure 3 shows a comparison of the averaged heat transfer coefficient at downcomer fluid-to-wall between the calculation and the constraint. Compared to the constraint, the calculated data showed the minimum heat transfer occurred at 100 seconds and oscillations after 300 seconds due to steam condensation. The overall behavior was well agreed to the constraint. The predicted heat transfer coefficient was less than 10 KW/K-m^2 during HPSI period and less than 3 KW/K-m^2 during LPSI period, respectively.

Figure 4 shows downcomer level behavior. The water level decreased until 100 seconds by break flow and increased slightly by HPSI water. Up to 750 seconds, the level shows an oscillatory behavior due to steam condensation and then the level was recovered to 2 m elevation. The calculation result was relatively close to the constraint, however a deviation was found, which may be due to the break flow behavior in the same way as pressure behavior.

Figure 5 shows a comparison of fluid temperatures at the various elevation of the downcomer. The calculated cooling behavior was well-agreed to the problem constraint up to 300 seconds although there was some underestimation. An overall downcomer fluid cooling was calculated from 570 K to 300 K during 1500 seconds.

The current calculation result indicated the fluid temperatures were almost similar at various elevations during the periods from 0 to 200 seconds and after 800 seconds. It indicated that there was no fluid stratification during both periods.

The variation of temperature during HPSI period (120 to 750 seconds) could be regarded as thermal fluid stratification and the maximum temperature gradient was to be 45 K. However, as mentioned previously, the downcomer fluid was in two phase mixture and not in fully-stagnant state during the period. Therefore, it was still questionable whether the code predicted the stratification reasonable or not.

To evaluate the onset of thermal fluid stratification, the empirical correlation proposed by Theofanous [5] can be used as follows:

$$\frac{Q_L}{Q_{HPI}} \leq Fr_{HPI,CL}^{-5/7} - 1 \tag{1}$$

, where Q_L and Q_{HPI} denote volumetric flow rates at cold leg and HPSI, respectively. And Froude number can be defined as follows:

$$Fr_{HPI,CL} = \frac{Q_{HPI}}{A_{CL}} \left\{ gD_{CL} \frac{(\rho_{HPI} - \rho_L)}{\rho_{HPI}} \right\}^{-1/2} \tag{2}$$

Figure 6 shows a comparison of Froude number calculated by Eq.(2) and the Eq.(1) as a function of flow ratio. The upper part of the curve of Eq. (1) represents the not-stratified area. It can be obviously stated that there were two groups of data points not stratified, i.e., LPSI period and initial phase with high flow ratio. The remaining data points indicated there was a partially stratified period, i.e., the two phase period during HPSI. This analysis result was agreed to the current RELAP5 calculation in qualitative manner. The applicability of Eq.(1) to the two-phase condition with steam condensation was questionable, since the Eq.(1) was derived from the single-phase fluid mixing test in small scale.

2. Sensitivity Study

As mentioned previously, sensitivity calculations using a fine node model and crossflow model were also performed to evaluate the modeling capability on multi-dimensional characteristics related to thermal fluid mixing. The selected cases in this study included a case of 16 volumes for downcomer (denoted by 16x1); and a case of two channels each discretized with 16 volumes and 16 crossflow junctions between two channels (16x2).

Figures 7 and 8 shows comparisons of downcomer fluid temperatures at - 0.5 m and - 2.0 m elevations between base case and two sensitivity cases, respectively. Overall cooling behavior was almost identical for three cases. This result indicated that the overall mixing and cooling behavior were not affected by the current modeling schemes to consider the fine node effect and the multi-dimensional mixing characteristics. The current calculation showed a strong crossflow between volumes, which resulted in complete mixing between both volumes. It was known as one of the code model deficiencies [6], and the code improvement was required.

V. Conclusions

The thermal fluid mixing problem during a postulated medium size LOCA at hot leg proposed as PTS-ICAS was analyzed, which was an important part of the PTS risk assessment. From the present preliminary analysis result, the following conclusions are obtained :

1) A simple RELAP5 modeling scheme was developed relevant to the PTS-ICAS problem constraints, which could provide a thermal-hydraulic behavior reasonable to the medium size hot leg break.
2) The current preliminary result shows an overall downcomer fluid cooling from 570 K to 300 K during 1500 seconds, and heat transfer coefficient less than 10 KW/K-m^2 during HPSI period and less than 3 KW/K-m^2 during LPSI period, respectively.
3) It was believed that thermal fluid stratification did not occurred for both initial phase and LPSI phase, which was supported by Theofanous's stratification criteria.
4) The current modeling scheme to consider multi-dimensional mixing characteristics has no effect on thermal mixing behavior. It needed the further investigation using the improved code.

References

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[5] H.P. Nourbakhsh and T.G. Theofanous, *"A Criterion for Predicting Thermal Stratification Due to High Pressure Injection in a Circulating Reactor Loop,"* Technical Note, Nuclear Science and Engineering, 94, 77-79(1986).

[6] Gary Johnsen, *RELAP5 Developmental Status, Presented at the Ninth CAMP Meeting*, LANL, Oct. 1996

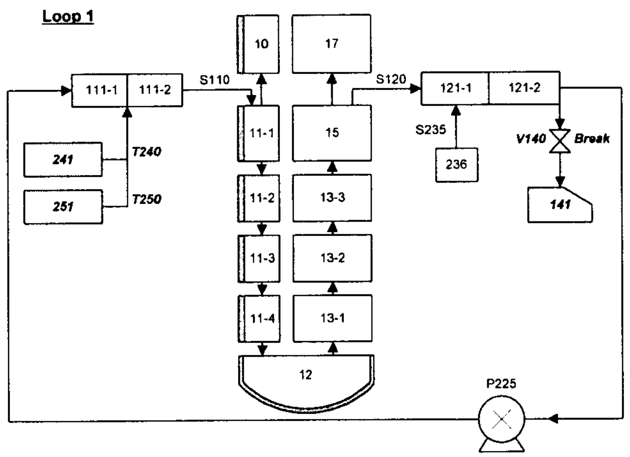

Figure 1 RELAP5 Nodalization of UPTF Facility for Thermal-Hydraulic Mixing Task

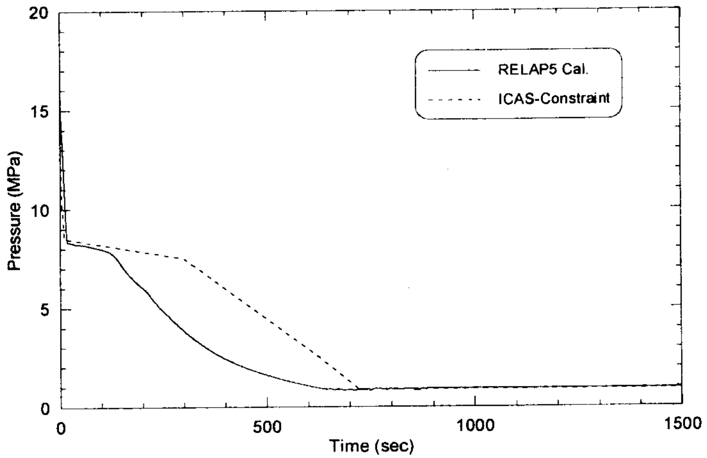

Figure 2 Downcomer Pressure

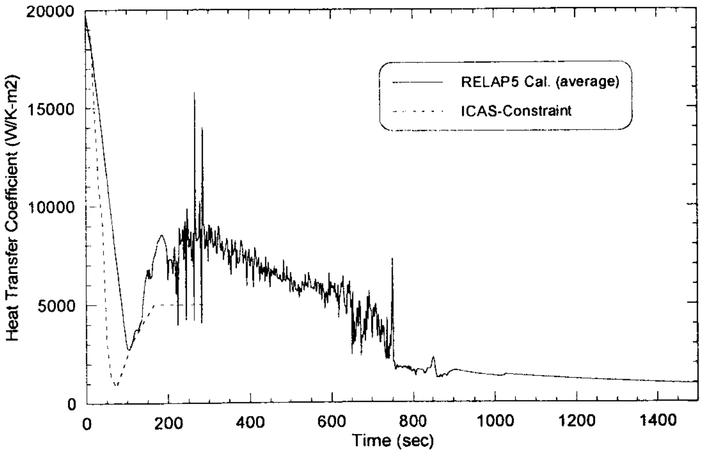

Figure 3 Heat Transfer Coefficient

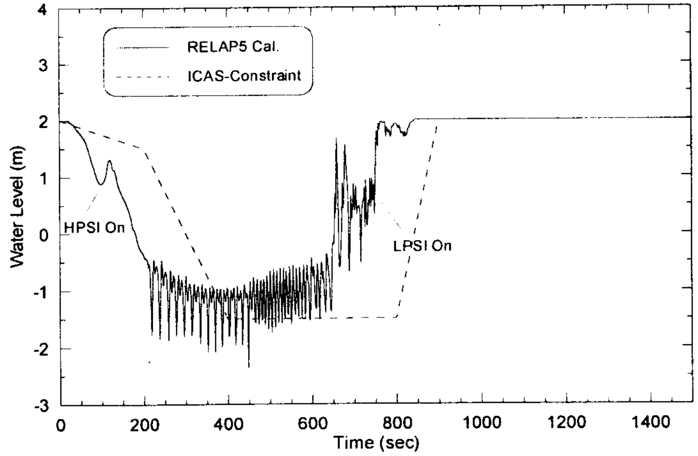

Figure 4 Downcomer Water Level

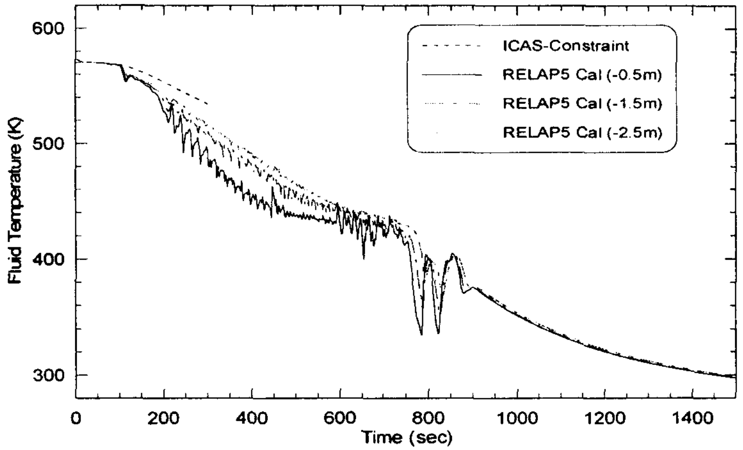

Figure 5 Comparison of Downcomer Fluid Temperature

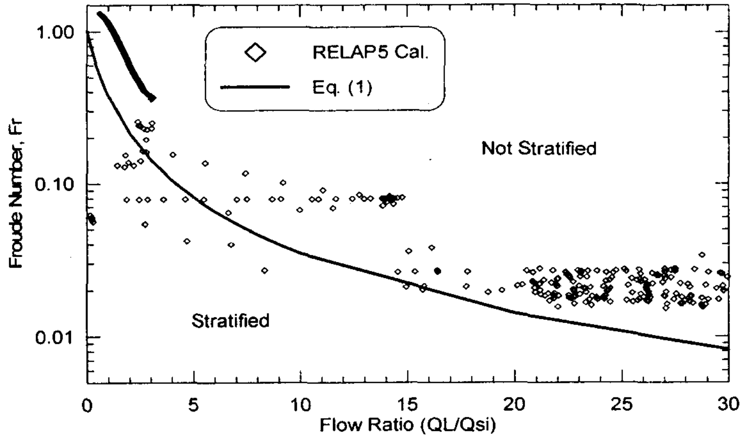

Figure 6 Comparison of Fr and QL/Qsi

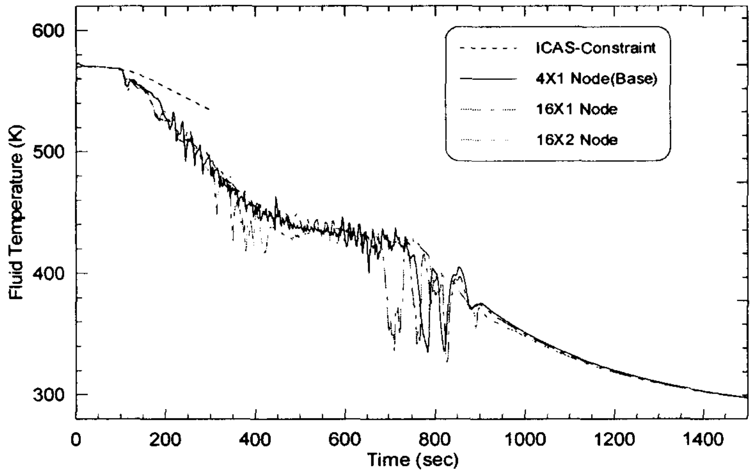

Figure 7 Comparison of Downcomer Fluid Temperature at -0.5m elevation

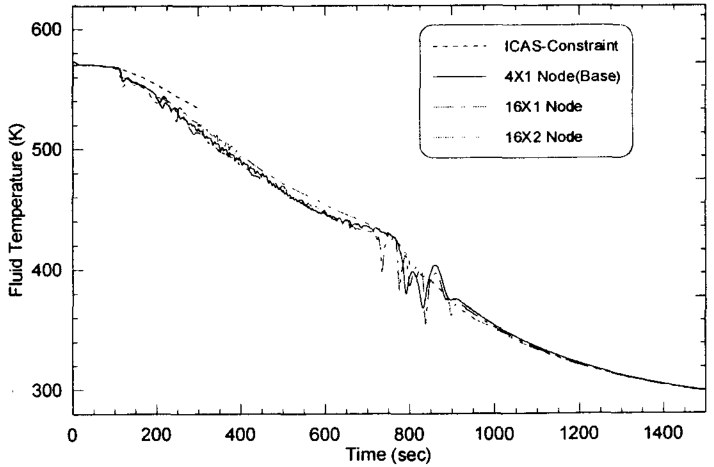

Figure 8 Comparison of Downcomer Fluid Temperature at -2.0m elevation