Assessment of SPACE for FLECHT-SEASET reflood experiments using criterion for minimum film boiling point based on wall temperature at node interface

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1. Introduction

The transition between film boiling and transition boiling regimes is the important phenomenon at a reflooding phase in loss of coolant accidents. This transition determines the timing and the temperature for a quenching. The wrong evaluation on the quenching time and temperature leads to inconsistent results for consequences of reflood experiments. Typically, in a thermal-hydraulic system code, a minimum film boiling (MFB) point model determines the collapse of the film boiling based on the center temperature of a node. In this paper, we found that the system code has possibility to sustain the film boiling regime longer than the real phenomenon. This comes from its coarser mesh size than that of a computational fluid dynamics code. Although several system codes such as SPACE, RELAP5, and COBRA-TF [1, 2] employed a fine mesh rezoning technique, the node size is still large as a few or a few tens of millimeters. To obtain accurate result with a so-called practical node size, we applied the transition criterion at a node interface.

2. Quench front propagation

2.1. Behavior of quench front

During the reflood phase, a quench front is formed on the fuel rod surface. Near the quench front, the heat transfer and the temperature of the rod drastically varies with axial locations. To catch all the changes on flow regimes and the temperature distribution, the mesh should be refined enough. However, the refinement for the node size of a system code often encounters large computational efforts or numerical instabilities for the parameters.

To address the anticipated problem with a coarse mesh, we described the behavior of the quench front with the nodes as shown in Fig. 1.

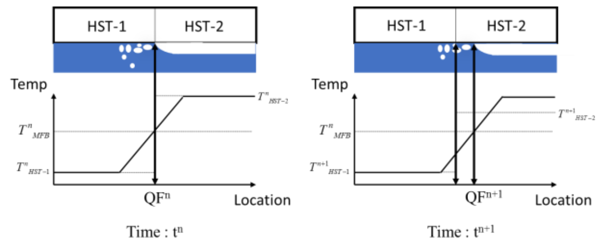

Fig. 1. The description for the anticipated difference between the real phenomenon and the code simulation.

We assume the initial situation that the quench front (QF) is located at the middle of the heat structure 1 and 2 (HST-1, HST-2) in the system code. The solid lines in graphs are the actual temperature distribution at each time. The wall temperature on the quench front is $T^n{}_{MFB}$ at the time t^n. The temperatures of each node are expressed as $T^n{}_{HST-1}$ and $T^n{}_{HST-2}$. In the next time, t^{n+1}, the quench front will propagate to the surface of HST-2 as QF^{n+1} in reality. However, the code has possibility to keep the film boiling at HST-2 due to a small timestep or a coarse node size. This delay of the temperature drop at the certain heat structure successively affects to the quenching of the downstream at the fuel rod.

To resolve this issue, we simply applied the criterion for the MFB temperature at the node interface, instead of the node center. For example, with Fig. 1, the current system code sustains the film boiling in HST-2 at the time t^{n+1}. However, the state of HST-2 becomes the transition boiling with the modified one at the time t^{n+1}, since the interface temperature of HST-1 and HST-2 is lower than $T^{n+1}{}_{MFB}$. Unlike the original method, this modification can cause the faster collapse of the film boiling than the actual phenomenon. So we performed the node sensitivity as following sections.

2.2. Node sensitivity without rod power

To check the effect of the original and modified method, we constructed the code input with 3 heat structures as illustrated in Fig 2.

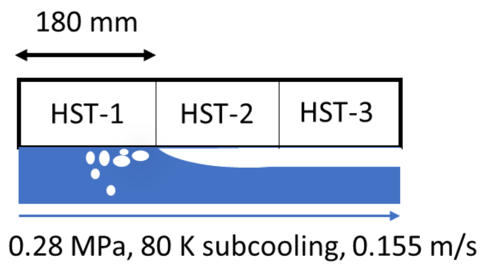

Fig. 2. Nodalization and initial conditions for sensitivity study.

The conditions and geometry are from FLECHT-SEASET 31701, which has been largely used to evaluate the prediction capability of system codes for the reflood. For this section, the experimental rod power was not applied and the initial location of quench front is at the interface of HST-1 and HST-2. We varied the node size in HST-2 and HST-3 from 0.6 mm to 20 mm.

As depicted in Fig. 3 and 4, the calculation results of the temperature and the accumulated heat transfer were saturated with the mesh size of 0.6 mm for both of the original and modified method. It is definite that there is no difference between two methods when we can simulate with the sufficiently small node size.

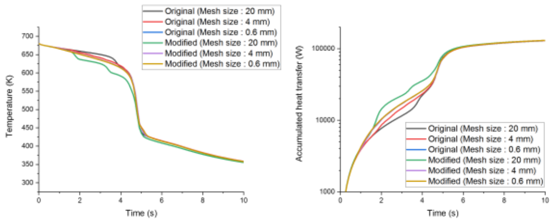

Fig. 3. Temperature and accumulated heat transfer of HST-2 without rod power.

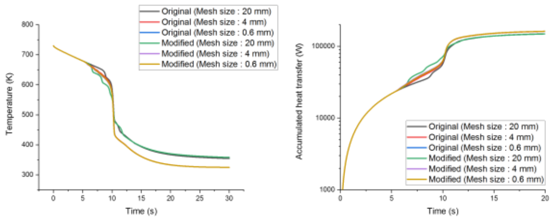

Fig. 4. Temperature and accumulated heat transfer of HST-3 without rod power.

The interesting part is that the modified method gave more accurate results than those from the original one in the presence of the coarse mesh size (4 mm). For the accumulated heat transfer of HST-2, the average deviations between the results from the original method and the saturated results are respectively 4.65% and 1.47% for mesh sizes of 20 mm and 4 mm. The same comparison with the modified method yields 5.10% and 0.84% for each mesh size (20 mm and 4 mm). For the heat transfer of HST-3 with the node size of 4 mm, the average deviations with the modified results (0.46 %) also showed better agreements than those with the original method (2.79 %).

2.3. Node sensitivity with rod power

For this time, the experimental rod power was considered. However, in this case, the saturated results were not observed as shown in Fig. 5 and 6. The temperatures of the heat structures increased unphysically with the smaller mesh size than 0.6 mm.

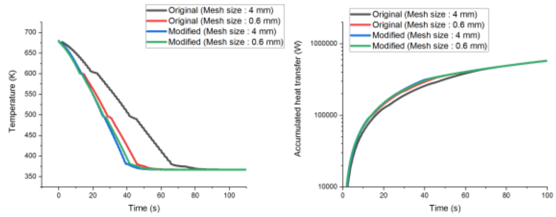

Fig. 5. Temperature and accumulated heat transfer of HST-2 with rod power.

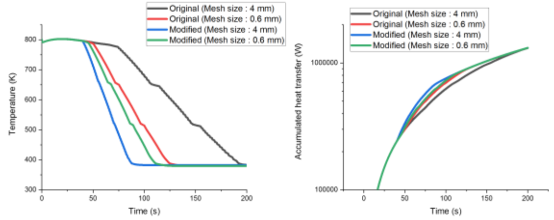

Fig. 6. Temperature and accumulated heat transfer of HST-3 with rod power.

Since the saturated results are not available, let us assume that the average value of the results from the original and modified method is the accurate one. For the results of HST-2, the average deviation between the accurate one with the original method is 8.44 % for the node size of 4 mm. For the same node size, the average discrepancy between the accurate one and the modified method is 1.47 %. For the average deviation of HST-3, the modified method showed better results as 3.27 % compared to 5.84 % for the original method.

Summing up the results from section 2.2 and 2.3, the modified method is more numerically accurate than the original method with the node of a medium-coarse size (~ a few mm scale).

3. Assessment of SPACE for FLECHT-SEASET reflood tests with original and modified method

3.1. FLECHT-SEASET

FLECHT-SEASET (Full-Length Emergency Core Heat Transfer – Separate Effects and System Effects Test) was performed to provide the heat transfer and two-phase flow data with a PWR rod bundle geometry for postulated conditions of reflooding, core boiloff, and natural circulation [3]. The detail specifications of the facility, experimental conditions and results were documented in the literature [4]. We selected 3 tests (31504, 31302, 31701) which have different operating flow velocity (2.4, 7.65, 15.5 cm/s). The axial length of the rod bundle is 12 ft (3.66 m). The other parameters are almost same such as the rod peak power (2.3 kW/m), the operating pressure (0.28 MPa), and the water subcooling (~ 80 K). The nodalization of SPACE is described as Fig. 7. The mesh size is 2.0 mm for all simulations.

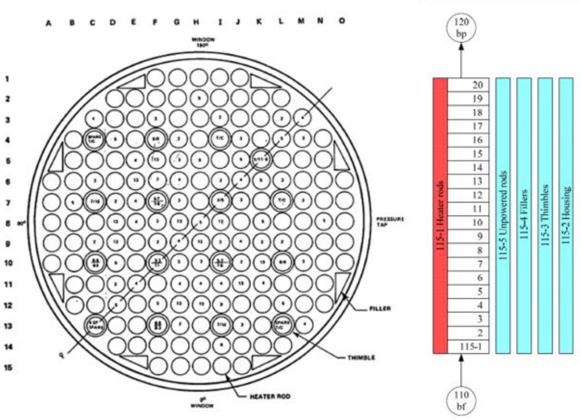

Fig. 7. Cross-section and SPACE nodalization for FLECHT-SEASET [3, 5].

3.2. Selection of minimum film boiling temperature model

The default option for the MFB temperature in SPACE 3.2 is Carbajo model [6]. Nishio et al. [7] classified the MFB temperature from a propagative collapse and a coherent collapse of the film boiling. Ohtake and Koizumi [8] found that the quenching velocities of the propagative collapse well agreed with the MFB temperature from the coherent collapse obtained from Nishio et al. [7]. So we included the variation for the MFB point model. As described in Table I, we changed MFB point model and the method for the transition criterion. We will compare the wall temperatures for axial locations of 1 ft, 2 ft, 6 ft, 10 ft, and 11.5 ft.

Table I: Assessment matrix

Index	Minimum film boiling point model	Position of transition criterion
00	Carbajo	Node center
01	Carbajo	Node interface
10	Nishio et al.	Node center
11	Nishio et al.	Node interface

3.3. Qualitative and quantitative analysis

Before the discussion on the results, notice that the results of the index 01 and 11 are likely to be accurate results of the index 00 and 10 for the numerical aspect, respectively. As shown in Fig. 8, the rod surface temperatures were plotted for test 31701. At the axial location of 1 ft, the tendency of the experimental data agreed well with the cases of using MFB model from Nishio et al.. For the location of 11.5 ft, the calculation results from the index 0x (i.e. index 00 and 01) showed the rapid temperature drop, while those from the index 1x (i.e. index 10 and 11) underestimated the film boiling heat transfer. For axial locations of 2 ft and 6 ft, the results from the index 00 showed the good agreement. However, there is a possibility that the early quenching of 1 ft and 11.5 ft resulted in good agreements with temperatures of 2 ft and 10 ft in coincidence. In other words, if the results from index 0x are corrected as the experimental data at 1ft and 11.5 ft, the temperature drops of 2 ft and 10 ft are delayed and lose its current prediction accuracy.

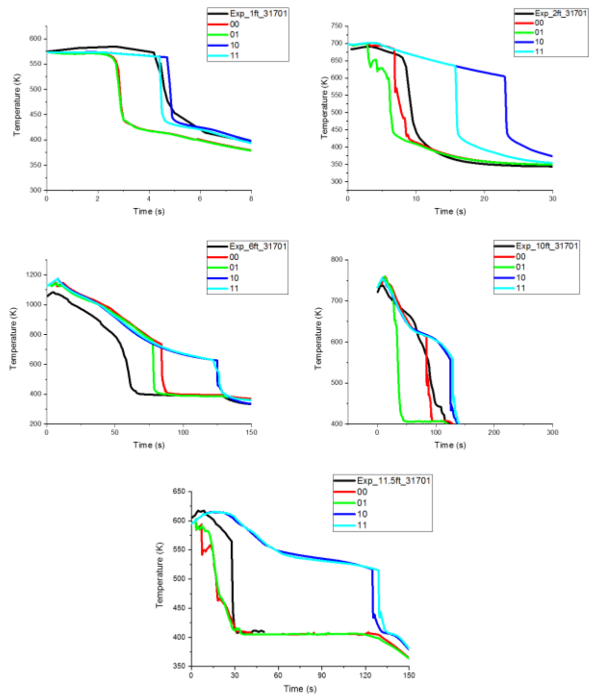

Fig. 8. The rod surface temperature of test 31701 along axial location.

To compare the prediction accuracies in a quantitative way, we used FFTBM (Fast Fourier Transform Based Method). AA (Average Amplitude) is the indicator of the prediction accuracy, which the lower value means better agreement with experimental data. In Table II, we tabulated the average value of AA results from test 31504, 31302 and 31701. The typical value for AA meaning the good agreement is known as 0.3.

Table II: Average AA results by FFTBM

Lo\Index	00	01	10	11
1 ft	0.19	0.18	0.17	0.12
2 ft	0.21	0.25	0.32	0.31
6 ft	0.28	0.27	0.27	0.27
10 ft	0.21	0.26	0.25	0.23
11.5 ft	0.33	0.32	0.42	0.42

Again, notice that the results from the index x1 are more accurate than the index x0 in terms of the numerical accuracy, as we mentioned in section 2. For the bottom location (1 ft), the use of Nishio et al. MFB model and the node interface showed the best accuracy.

For the top location (11.5 ft), all the cases did not agreed well with experiments. For 2 ft and 10 ft data, the original code (index 00) showed the best agreement. However, this good accuracy would be achieved from the combination of early quenching of the bottom and top locations and the numerical results by the coarse mesh size. In terms of the better prediction for overall locations, it is necessary to improve the prediction capability for the top location by investigating the appropriate model for the dispersed flow film boiling or entrainment and deposition for the droplet.

4. Conclusions

The transition criterion between the film boiling and transition boiling was applied at the node interface, instead of the node center. For the coarse mesh size about a few mm, the modified method showed numerically better results than those of the original method. We assessed the representative reflood experiments with the different MFB model and method for the transition criterion. For the bottom location, the results from the changes of two parameters showed the best agreement. For the top location, no results agreed well with experimental data. For middle locations (2 ft, 6ft, 10 ft), the original code estimated the results well. However, for middle locations, this currently good accuracy may be achieved from the numerical problem by the original method with the coarse mesh and the early quenching of the bottom and the top.

Acknowledgement

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