Code Evaluation on the Conservative Critical Flow Models in SPACE3.0

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1. Introduction

The nuclear thermal hydraulic system code known as SPACE (Safety and Performance Analysis CodE) code was approved by Korea nuclear regulator and its license version (SPACE3.0) was released at the beginning of 2017. At the same time, the SBLOCA (Small Break Loss of Coolant Accident) evaluation methodology for the APR1400 (Advanced Power Reactor 1400) using the SPACE3.0 code was also approved. The goal of this methodology is to set up a conservative evaluation methodology in accordance with Appendix K of 10CFR50 [1].

In this study, the critical flow model among various conservative models in the methodology is evaluated to validate its conservatism using some SETs. The SBLOCA evaluation methodology adopts the combined HF-Moody critical flow model [2] to predict the discharge flow conservatively. The Moody critical flow model [3] for a conservative prediction under the two-phase condition has been implemented as a look-up table with the Henry-Fauske critical flow Model [4] for the subcooled liquid condition in the SPACE3.0 code.

2. Conservative Critical Flow Model in SPACE3.0

The critical flow model of the SPACE3.0 code is developed based on the Ransom-Trapp (RT) model. However, the Moody model is also implemented into the SPACE3.0 code to meet the two-phase discharge flow requirement of Appendix K.

Regarding the application of the Moody model, the stagnation condition (p_o, h_o) is derived from the cell center immediately upstream of the exit plane. The stagnation enthalpy can be calculated from the cell center properties as [3].

$$h_0 = \left(h_f + \frac{v_f^2}{2}\right)(1-x) + \left(h_g + \frac{v_g^2}{2}\right)x \tag{1}$$

where the local enthalpies(h), fluid velocities(v) and flow quality(x) are evaluated under an equilibrium condition at the cell center. By assuming an isentropic process, the stagnation pressure can then be obtained from the local entropy as defined by the cell center properties and the stagnation enthalpy derived through the steam table iteration:

$$P_o = P_o(h_o, s(h, P)) \tag{2}$$

The Henry-Fauske model is used for the subcooled liquid condition in conjunction with the Moody model. The discharge flow by this model is also expressed using the stagnation pressure and enthalpy in the SPACE3.0 code. Figure 1 presents the discharge flow under both the pressure and enthalpy conditions. This is provided as a look-up table in the SPACE3.0 code.

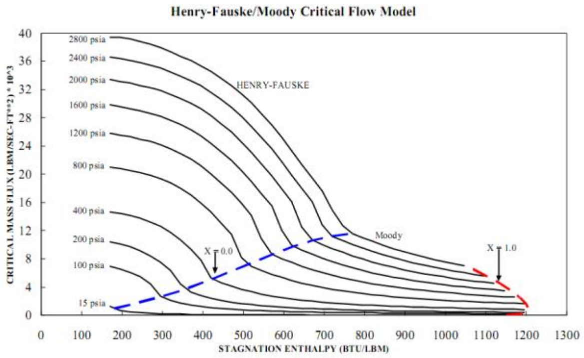

Fig. 1 Critical flow for the combined HF-Moody model in the SPACE3.0 Code

3. Code Assessment

In this section, the HF-Moody model implemented in the SPACE3.0 code is assessed against Marviken test no.15 and the Edward pipe blowdown test compared with both test data and the best-estimate model, Ransom-Trapp.

3.1 Evaluation for Marviken test no.15

Marviken facility, which is reactor-sized, consists of a pressurized vessel containing steam and water under high pressure, an exhaust pipe placed at the vessel bottom, and a convergent nozzle capping the pipe [5]. Test initiates when the nozzle is suddenly opened, after which the pressures, temperatures and densities at various sections are measured during the subsequent blowdown. One of representative tests of the Marviken program, no.15 test is used to assess the implementation of the HF-Moody model. The break was connected to the bottom of a large pressure vessel. The pressure vessel was 5.2m in diameter and 24.6m tall. The vessel initially contained regions of subcooled liquid, saturated liquid and a steam dome. Table 1 shows the boundary conditions for the chosen test.

Table 1 : Boundary conditions for Marviken test No.15

Parameters	Values
Initial upper press. (MPa)	5.04
Subcooling at bottom of vessel (℃)	31
Initial min. temp. (℃)	233
Vessel initial level (m)	19.93
Nozzle L/D (m)	3.6

The pressure vessel is modeled with a PIPE component with a discharge pipe. To simulate the boundary conditions, the TFBC (Temporal Face Boundary Condition) is introduced in SPACE3.0 code. The state conditions as a function of time or some time-advanced quantity are entered as a table, with time or the time-advanced quantity as the independent or search variable. The choking option is assigned only at the outlet of discharge pipe. A discharge coefficient of 1.0 is used as the default.

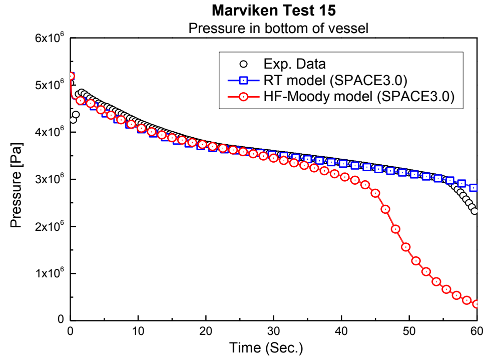

Fig. 2 Comparisons of pressure behaviors

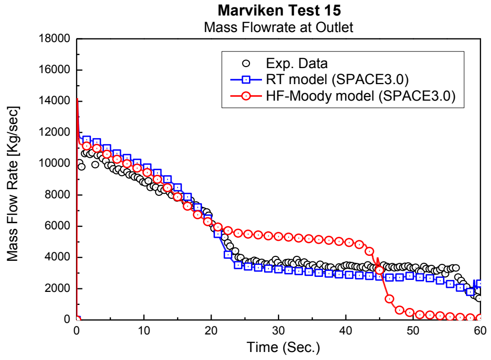

Fig. 3 Comparisons of break flow behaviors

As a result of the calculation of Test no. 15, figures 2 and 3 show the pressure and break flow between experimental data and the two types of SPACE3.0 critical flow models. The water in the pressure vessel of Test no. 15 has a subcooling temperature of 31℃. It is initially discharged as subcooled liquid for an extended period of time. It becomes a two-phase fluid after approximately 18 seconds or is discharged as a quasi-equilibrium two-phase fluid at close to 22~25 seconds. The transition regime for a critical flow between a subcooled fluid and a two-phase fluid is predicted.

As shown in figures 2 and 3, the behavior of the SPACE3.0 with the RT model is in very good agreement with the experimental data. In the case of the HF-Moody model, the pressure is under-predicted from about 25 seconds because the discharge flow is calculated as high in the saturated regime. As a result, the time discharging the steam appears much more quickly.

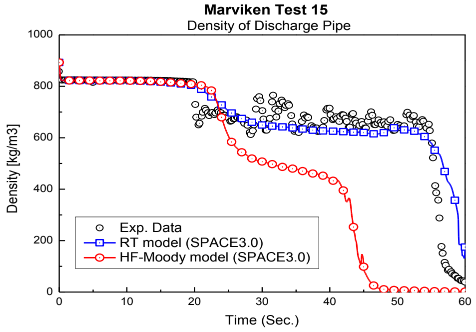

Fig. 4 Comparison of density behaviors

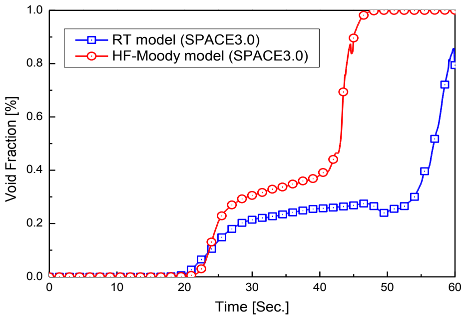

Fig. 5 Comparison of void fraction behaviors

Also, the HF-Moody model clearly predicts a higher value than the RT model, ranging from 3,000 kg/sec to 6,000 kg/sec. This range, which appears from approximately 20 to 45 seconds, is considered as the two-phase fluid regime and is calculated by the Moody model. This is confirmed in the density and void behavior shown in figures 4 and 5. The divisions of the flow regimes in the critical flow model for the SPACE3.0 code are determined as follows by the void fraction.

- When $a_g = 0$: Single-phase fluid regime
- When $a_g \le 1.0\text{x}10^{-5}$: Subcooled fluid regime
- When $1.0\text{x}10^{-5} < a_g \le 0.1$: Subcooled fluid and two-phase flow transition regime
- When $0.1 < a_g \le 0.9$: Two-phase flow regime
- When $0.9 < a_g \le 0.99$: Two-phase flow and pure steam transition regime
- When $a_g > 0.99$: Gas and pure steam regime

When the void fraction exceeds 0.1, as shown in figure 5, it is noted that a two-phase fluid is discharged between 20 and 45 seconds. Thus the conservative approach of the implemented Moody model in a two-phase discharge flow is demonstrated.

3.2 Evaluation for Edward Pipe blowdown test

As another evaluation result in this section, the conservative aspects of the implemented model are assessed using the Edward Pipe test [6]. The Edward pipe test is used to verify blowdown behavior, including the flashing phenomenon. This test was designed to simulate sudden depressurization of a simple horizontal pipe. The heat loss at the pipe wall is not included in this calculation. SPACE nodalization of the Edward pipe test with a boundary condition is shown in figure 6. To simulate the boundary conditions, a TFBC component such as Marviken modeling is used. The choking option is assigned only at the outlet of the TFBC face (No. 005). A discharge coefficient of 1.0 is used as the default.

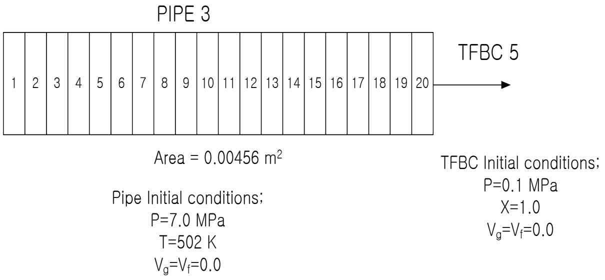

Fig. 6 Nodalization of the Edward pipe test

Figures 7 and 8 present both the SPACE3.0 code and test data of the pressure and void fraction of a cell at the middle part (1.64m, cell no 8 of the PIPE component) of the test section. In comparison with the SPACE3.0 RT model and test data, the SPACE3.0 HF-Moody model is highly under-predicted for pressure and void fraction.

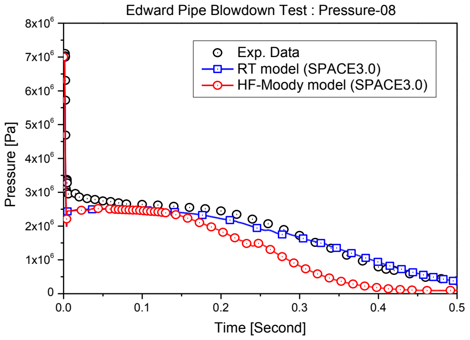

Fig. 7 Pressure behaviors for the Edward pipe

As observed in the Marviken evaluation, the behaviors vary between the two models in the SPACE3.0 code when the void fraction exceeds 0.1. These figures show that the conservative aspects of the implemented Moody model in a two-phase discharged flow are suitably demonstrated.

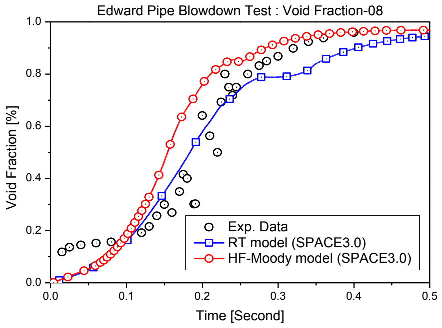

Fig. 8. Void behaviors in the middle of the test section

3. Conclusions and Further works

The SBLOCA evaluation methodology licensed using the SPACE3.0 was developed in accordance with Appendix K of 10CFR50.

In this paper, the combined HF-Moody critical flow model of Appendix K models is assessed for a conservative predictability of the discharge flow. To do this, SETs data such as Marviken test and Edward Pipe test are utilized and compared with the realistic model of the SPACE3.0. The results show that the HF-Moody model predicts conservatively both experimental data and RT model under a two-phase condition. Therefore, we could confirm the conservatism of the implemented critical flow model.

Further analyses will be presented for the model sensitivity through the variation of discharge coefficient.

REFERENCES

[1] USNRC, 1987, Compendium of ECCS research
[2] SPACE3.0 Code Manual, 2017
[3] F. J. Moody "Maximum flow rate of a single component, two-phase mixture", Journal of Heat Transfer, Trans. American Society of Mechanical Engineer, 87, No.1, February, 1965.
[4] R. E. Henry and H.K. Fasuke, "The two-phase critical flow of one-component mixure in nozzles, orifices, and short tube," Trans, ASME, J. Heat Transfer, Vol. 93, pp.179-187, 1971.
[5] Marviken Full-Scale Critical-Flow Tests, EPRI-NP-2370, 1982.
[6] A. R. Edwards and F.P. O'Brien, "Studies of Phenomena connected with the depressurization of water reactor," Journal of the British Nuclear Energy Society, pp 125-135, 1970