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Incorporation of Henry-Fauske Critical Flow Model into TRAC-PF1

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Abstract

Henry-Fauske critical flow model was incorporated into TRAC-PF1 to correct some errors in the original TRAC-PF1 critical flow model. Henry-Fauske model was numerically implemented and tested against steady-state steam-water experimental data. The model was incorporated into TRAC-PF1 and code assessment against Marviken Critical Flow Tests 15 and 24 was carried out. Calculations using RELAP5/MOD3 were also made for comparison. Ten cases were calculated for each test and sensitivity study on nodalization as well as critical flow model was performed. Stand-alone numerical model test and code assessment were done for verification and validation of code modification. Calculation results show that the modified version of TRAC-PF1 has a capability to model critical flow correctly in various conditions.

I. Introduction

The TRAC-PF1 code[1] is investigated and assessed against experimental data to identify the area which would be improved at KNFC. As a series of this kind of efforts, code assessment[2] against FLECHT-SEASET test had been done before. In this study, critical flow model in TRAC-PF1 was investigated.

When the velocity of the fluid is equal to the sonic velocity of that fluid, the resulting mass flow is limited or choked. This phenomenon is also known as critical flow. During critical flow, fluid conditions in downstream of the choking plane cannot physically be transmitted upstream, since this information can be transmitted at no greater than the sonic velocity of the fluid. Thus, only the upstream conditions influence the flow at a choked point in the system.

The models in single-phase flow are simple because the sonic velocity and critical mass flux are related directly and simply. However, two-phase critical flow is more complex. The homogeneous equilibrium model (HEM) is the simplest analytical model that can be postulated. For fixed stagnation (upstream reservoir) conditions, the critical flow rate is obtained by assuming the fluid entropy remains constant and finding the downstream pressure for which mass flux exhibits a maximum.

Moody[3] considered the available data for blowdown in long pipes. Moody points out that although homogeneous theory using reservoir conditions provides a good prediction of critical flow rates, it provides a poor prediction of pressure at the exit of the blowdown pipe. He developed critical flow model for use with exit conditions, and based on high slip ratios at the exit. Burnell[4] previously recognized the existence of a metastable state in the flow of flashing water through nozzles and hypothesized that water surface tension retarded the formation of vapor bubbles, thus causing the water to be superheated. He developed a semi-empirical method for predicting the flow of flashing water through short nozzles. Henry and Fauske[5] developed a model for critical flow in nozzles and short tubes, which allows for nonequilibrium effects and considers a two-phase mixture upstream of the break.

The TRAC-PF1 momentum equation has no sonic limiting; thus, a separate equation must be used when critical flow is calculated to occur. In TRAC-PF1, the following method is used:

If an estimated momentum equation is less than the critical flow based on upstream conditions, calculate the flow using the momentum equation. Otherwise, calculate the flow using the critical flow criteria.

There are two separate models in TRAC-PF1, one for subcooled-flow choking and the other for two-phase-flow choking. For single-phase liquid, a simple model is used and the velocity at the throat is calculated as minimum between the two of sonic velocity and velocity obtained from the Bernoulli's equation. The two-phase critical flow model in TRAC-PF1 originally was developed by Ransom and Trapp[6] using the characteristic analysis approach. According to Ref. [7], there was an effort to correct some of the deeply rooted errors in TRAC-PF1 in the course of development of TRAC-PF1/MOD1. To eliminate this kind of error in critical flow model of TRAC-PF1, Henry-Fauske critical flow model is incorporated into TRAC-PF1 in this study so that the modified version of TRAC-PF1 can be used to predict the critical flow conditions.

II. Henry-Fauske Critical Flow Model

The Henry-Fauske critical flow model has been used for flow regimes that occur during nuclear reactor transients, from subcooled to superheated upstream stagnation conditions. The expansion of the vapor in the low quality region is treated as nonequilibrium. The derivation of the Henry-Fauske critical flow model begins with a complete, general expression for steady-state, one-dimensional continuity and momentum equations for one-component, two-phase flow. At critical flow, the mass flow rate exhibits a maximum with respect to the throat pressure. Thus, the expression for the critical flow rate is given as;

$$G_c^2 = \left\{ k \left[[1 + x(k-1)] x \frac{dv_g}{dP} + \left[v_g \{1 + 2x(k-1)\} + kv_l \{2(x-1) + k(1-2x)\} \right] \frac{dx}{dP} \right. \right.$$
$$\left. \left. + k[1 + x(k-2) - x^2(k-1)] \frac{dv_l}{dP} + x(1-x)\left(kv_l - \frac{v_g}{k} \right) \frac{dk}{dP} \right]^{-1} \right\}_t$$

where k is vapor/liquid slip ratio defined by $k = u_g/u_l$.

The assumptions used to simplify this model are: 1. Slip between phases is negligible; 2. Interphasic heat and mass transfer during expansion are small; 3. The liquid phase is incompressible; 4. The vapor phase expands at the throat in a polytropic manner to account for the small interphasic heat transfer. After defining the equilibrium quality in terms of entropy, assuming the vapor as a real gas following a polytropic process, and assuming that mass transfer at the choking plane is dominated by the liquid phase, the following expression for critical mass flux is obtained.

$$G_c^2 = \left[\frac{x_0 v_g}{nP} + (v_g - v_{l0}) \left\{ \frac{(1-x_0)N}{s_{gE} - s_{lE}} \frac{ds_{lE}}{dP} - \frac{x_0 c_{pg} (1/n - 1/\gamma)}{P(s_{g0} - s_{l0})} \right\} \right]_t^{-1}$$

The equation for the critical flow rate is coupled with the momentum equation describing the overall pressure history to obtain a solution in terms of the stagnation conditions. The two-phase momentum equation can be integrated between the stagnation and throat location to give

$$(1-x_0)v_{l0}(P_0-P_t)+\frac{x_0\gamma}{\gamma-1}\left[P_0v_{g0}-P_tv_{gt}\right]=\frac{\left[(1-x_0)v_{l0}+x_0v_{gt}\right]^2}{2}G_c^2$$

Substitution of equation for the critical flow rate enables one to rearrange the above equation and express it more compactly as a transcendental form. For given stagnation conditions of P_0 and x_0, the transcendental expression for the critical pressure ratio can be solved. This solution implicitly involves the critical flow rate. Therefore, a solution of the above equation yields predictions of both the critical pressure ratio and flow rate.

III. Numerical Implementation of Henry-Fauske Model and Incorporation into TRAC-PF1

Henry-Fauske model is numerically implemented for incorporation of the model into TRAC-PF1. As the first step, a stand-alone routine for Henry-Fauske model was built up. The stand-alone program of Henry-Fauske critical flow model is tested against experimental steam-water results and Henry-Fauske model calculation result given in Ref. [5]. The verification is made for various stagnation conditions, and the largest difference between the original Henry-Fauske model and numerically implemented model in this study occurs at high stagnation pressure, which is about 3 %. This discrepancy may be due to the difference in solution method for the transcendental equation. However, in general sense, it can be concluded that the Henry-Fauske model is numerically implemented correctly. Then, the numerically implemented Henry-Fauske model is incorporated into TRAC-PF1. Code assessment of the modified code against some experimental test data was made to confirm that Henry-Fauske model works well.

IV. Code Assessment against Marviken Tests 15 and 24

The Marviken Full Scale Critical Flow Tests[8] were conducted by discharging water and mixtures from a full sized reactor vessel through a large diameter pipe that supplied the flow to the test nozzle and mounted on the bottom of a vessel. The major components of the facility are the pressure vessel, the discharge pipe, the test nozzle and rupture disc assemblies, and the containment and exhaust pipes The nozzles ranged from 166 to 1809 mm in length and from 200 to 500 mm in diameter, which have similarity to the pipe of broken loop at large break LOCA in nuclear power plant. Tests 15 through 27 were conducted using a constant diameter test nozzle section of 500 mm and length to diameter ratio (L/D) of 0.3 to 3.6 to provide full-scale critical flow data at LBLOCA for operational nuclear power plants. For the tests 15 and 24, the dimensions of the test nozzle section are summarized in Table 1.

TRAC-PF1 code assessment against Marviken tests 15 and 24 has been made using both original critical flow model and Henry-Fauske model. In addition to these TRAC calculations, the calculations using RELAP5/MOD3.2.1.2 were carried out for comparison.

The nodalization of Marviken facility consists of a vessel, a discharge pipe including nozzle, and containment, as shown in Figure 1. A nozzle is modeled with various numbers of nodes ranging from no nozzle modeling to three nodes modeling for analyzing sensitivity on nodalization. Ten cases were calculated for Marviken test 15 and 24, respectively. The classification of cases is presented in Table 2.

The calculation results are presented in Figures 2 through 6 with experimental data. Figures 2 and 3 show results from sensitivity analysis on nodalization, and Figures 4 to 6 show results from critical flow model sensitivity study. Four sensitivity studies on nozzle modeling have been performed for each test, according to selection of the code and critical flow model used. However, only the results from sensitivity on nozzle modeling with TRAC-PF1 and Henry-Fauske critical flow model are presented in this paper. Calculation results from cases 1 through 3 in Table 2 were used for sensitivity study.

Calculation results shown in Figures 2 and 3 can be divided into two categories depending on nozzle modeling. Category 1 is the cases of no or one node nozzle modeling, and category 2 is the cases of multiple nodes nozzle modeling. The difference between the two categories is whether upstream junction area is comparable to or much greater than that of break junction. In general, the behaviors are similar, but the results from category 1 cases show better agreement with experimental data.

Calculation results shown in Figures 4 to 6 are from sensitivity analysis on critical flow model with one node nozzle modeling and no nozzle modeling for Test 15 and 24, respectively. One exception is the case with the original TRAC-PF1 code for Test 15. Calculation result showed unreasonable behavior during subcooled choking period in this case, and thus the case with two nodes modeling was used instead.

As shown in Figures 4 and 6, RELAP5/MOD3 is not sensitive to critical flow model during subcooled choking period, while TRAC-PF1 shows difference in initial peak in mass flow rate. Insensitivity of RELAP5/MOD3 during subcooled choking period is due to the fact that choking criterion is not met for most time steps during this period. The difference in mass flow rate is apparent after inception of two-phase choking. Since the transition period, during which rapid decrease in mass flow rate is shown after inception of two-phase choking, is shorter for Henry-Fauske model, it results in higher mass flow rate than original critical flow model during two-phase choking period. There is unreasonable peak in mass flow rate around 50 seconds with Henry-Fauske model in RELAP5/MOD3 for Marviken test 15 which is a test with large L/D nozzle. Even, the calculation failed to run for Marviken test 24 having small L/D with RELAP5/MOD3.

The experimental data on void fraction in Figure 5, shows that the two-phase choking begins to occur about 20 seconds after transient. The inception time of two-phase choking shows good agreement with experimental data in case of TRAC-PF1 with Henry-Fauske model and RELAP5/MOD3, while it is delayed in case of the original TRAC-PF1 code. During the two-phase choking period, Henry-Fauske model overestimates the void fraction regardless of nozzle modeling and codes used.

V. Conclusion

Henry-Fauske critical flow model is incorporated into TRAC-PF1 and tested against steady-state steam-water test data and Marviken tests 15 and 24. From the calculation results and sensitivity analysis, the followings are found:

- The Henry-Fauske model is implemented correctly since it predicts critical flow with a reasonable accuracy.
- TRAC-PF1 gives better calculation result with no nozzle modeling or one node modeling rather than with multiple node nozzle modeling.
- TRAC-PF1 with Henry-Fauske model produces more stable results than the original TRAC-PF1 code and RELAP5/MOD3 with Henry-Fauske model.

Thus, it is concluded that Henry-Fauske model is incorporated into TRAC-PF1 satisfactorily and the modified version of TRAC-PF1 has a capability to model critical flow correctly in various conditions.

References

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Table 1. Dimensions of Test Nozzles

Test Number	D (mm)	L (mm)	L/D
15	500	1809	3.6
24	500	166	0.3

Table 2. Classification of Cases

Case No.	Code used	Critical flow model	Nozzle modeling	
			Test 15	Test 24
1	TRAC-PF1	Henry-Fauske	One node	No modeling
2	TRAC-PF1	Henry-Fauske	Two nodes	One node
3	TRAC-PF1	Henry-Fauske	Three node	Two nodes
4	TRAC-PF1	Original	One node	No modeling
5	TRAC-PF1	Original	Two nodes	One node
6	TRAC-PF1	Original	Three nodes	Two nodes
7	RELAP5/MOD3	Henry-Fauske	One node	No modeling
8	RELAP5/MOD3	Henry-Fauske	Three nodes	One node
9	RELAP5/MOD3	Original	One node	No modeling
10	RELAP5/MOD3	Original	Three nodes	One node

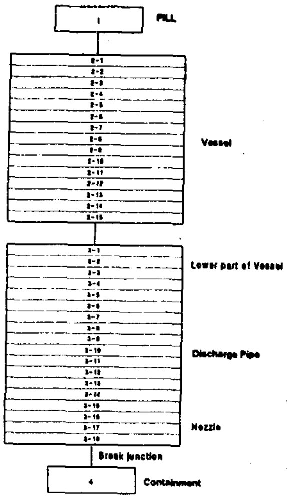

Figure 1. Noding diagram of Marviken Facility for TRAC code

MARVIKEN TEST 15

TRAC-PF1 with Henry-Fauske model

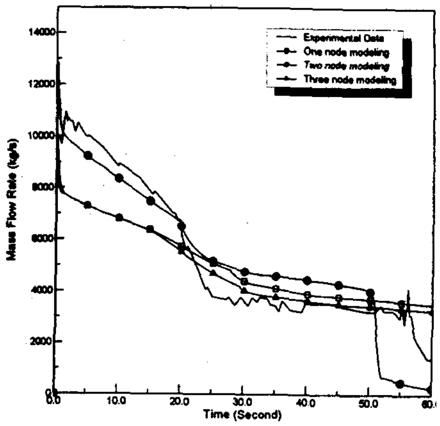

Figure 2. Sensitivity on nozzle modeling with TRAC-PF1 Henry-Fauske model against Marviken test 15

MARVIKEN TEST 24

TRAC-PF1 with Henry-Fauske model

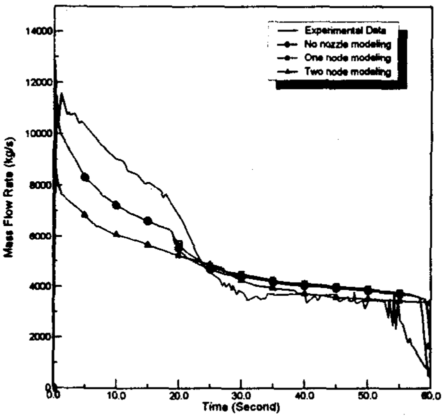

Figure 3. Sensitivity on nozzle modeling with TRAC-PF1 Henry-Fauske model against Marviken test 24

MARVIKEN TEST 15

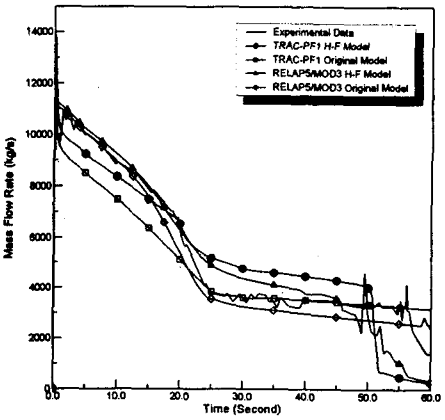

Figure 4. Comparison of critical flow model against Marviken test 15 (Mass flow rate)

MARVIKEN TEST 15

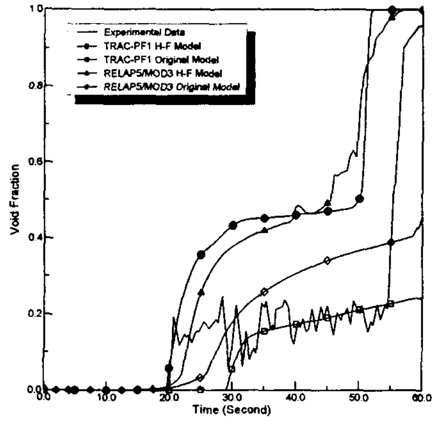

Figure 5. Comparison of critical flow model against Marviken test 15 (Void fraction)

MARVIKEN TEST 24

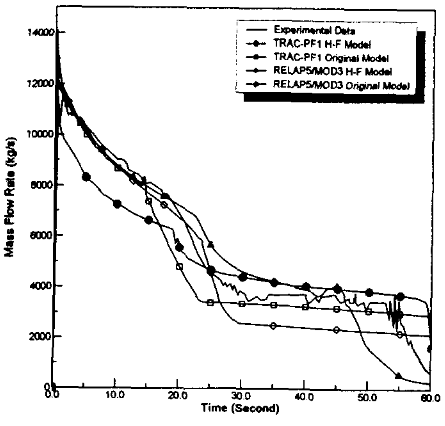

Figure 6. Comparison of critical flow model against Marviken test 24