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# Predictions of the Marviken Subcooled Critical Mass Flux Using the Critical Flow Scaling Parameters

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## ABSTRACT

A total of 386 critical flow data points from 19 runs of 27 runs in the Marviken Test were selected and compared with the predictions by the correlations based on the critical flow scaling parameters. The results show that the critical mass flux in the very large diameter pipe can be also characterized by two scaling parameters such as discharge coefficient and dimensionless subcooling ($C_{d,ref}$ and $\Delta T^*_{sub}$). The agreement between the measured data and the predictions are excellent.

## 1. Introduction

Predicting the critical discharge rate is very important in analyzing the consequences of a LOCA on a nuclear reactor. Such analysis requires that the flow rate from several pipes, which may be as large as 1,000 *mm* in diameter, be known.

There are a large number of critical flow models with varying approaches and assumptions regarding the flow evolution. In order to quantify the validity of several of the more widely used critical flow models, Elias et al. tested ten different critical flow models against an extensive set of qualified data [1]. The results show that existing models are inadequate to predict the Marviken Test [2] data which is the only large diameter critical flow data. The analytic and fitted models have not provided the well-centered predictions. Two-fluid models such as Elias-Chambre model and complete drift flux model were unsuccessful to predict the Marviken experiment. Attempts to predict the Marviken experiment with Richter model have only been partly successful. This situation is surprising since an earlier analysis [3] showed fair to good success using this model with the Marviken data. The exact reason for this situation has not been found.

The study of Elias et al. also shows the comparison of Marviken data with TRAC-PF1/MOD1. The experimental runs were 12, 13, 15-19, 21, 22, 25 and the statistical comparison to experiment is as follows; the mean errors run from 0.03 to 0.31 and the standard deviations are 0.03 to 0.64. In addition, TRAC nearly always underpredicts the Marviken data. This situation indicates to us that direct best estimate calculations of large break situations are unreliable and therefore, we need more reliable and accurate critical flow models for large diameter pipes.

Recently, Park developed two scaling parameters for geometry and initial conditions in critical two-phase flow of subcooled water [4] and applied his model to wide range of geometries and initial conditions to validate the model [5,6]. Since his model is reliable, simple to use, and successfully predicted the critical mass fluxes in various geometries, it is meaningful to test it against the very large diameter critical flow data.

This paper compares the Marviken Test data with the predictions by the correlations based on the critical flow scaling parameters. A total of 386 subcooled critical flow data points from 19 runs of 27 runs in the Marviken Test were selected and compared. It is shown that the critical mass flux in the very large diameter pipe can be also characterized by two scaling parameters.

## 2. Correlations Based on the Scaling Parameters

Park developed two-phase critical flow rate model using two scaling parameters for geometry and initial conditions [4]. Discharge coefficient of 20 °*C* water ($C_{d,ref}$) at given pressure condition is known as scaling parameter for geometries. Scaling parameter for initial conditions is assumed to be dimensionless subcooling ($\Delta T^*_{sub}$). Dimensionless subcooling is defined as; $\Delta T^*_{sub} = \Delta T_{sub} / (T_{sat} - T_{ref})$, where subscript " *ref* " refers to the values at 20 °*C*.

The critical mass flow rate can be calculated as a function of $C_{d,ref}$ and $\Delta T^*_{sub}$ as following [5,6];

For $L/D \geq 10$ with $L \geq 40$ *mm*, and $D \geq 300$ *mm* with $L/D \geq 1$

$$G_c = (C_d)_{ref} \left\{2\,\rho\,(P_o - P_b)\right\}^{0.5}_{ref} \left[ 1 - \frac{15.2}{1 + \exp\left\{(\Delta T^*_{sub} + 0.578)/0.188\right\}} \right] \tag{1}$$

For $L/D < 10$ with $D < 15$ *mm*, and $D \geq 300$ *mm* with $L/D < 1$

$$G_c = (C_d)_{ref} \left[2\,\rho\,(P_o - P_b)\right]^{0.5}_{ref} \left[ 1 - \frac{0.88}{1 + \exp\left\{(\Delta T^*_{sub} - 0.03)/0.162\right\}} \right] \tag{2}$$

where, $P_b$ is the initial back pressure of the receiving reservoir.

## 3. Predictions of Marviken Critical Flow Rates

The Marviken critical flow tests are among the few experiments to provide two-phase critical flow data at large scale and the first to test nozzle sizes up to 509 *mm*. A total of 27 tests were carried out. The parameter which were varied included the nozzle diameter, the nozzle length, and the initial subcooling of the water in the pressure vessel. The nozzles tested had rounded entrances followed by nominally 200, 300, or 500 *mm* constant diameter test sections from 166 to 1,809 *mm* in length. The test matrix of the Marviken Program is shown in Table 1. All the test except Run-05 were initiated with a stagnation pressure of 5.0 *MPa*.

Table 1. Marviken Critical Flow Program Test Matrix

| Diameter (*mm*) | Length (*mm*) | *L/D* | Run No. Used in Test | Run No. Used in Comparison |
|---|---|---|---|---|
| 200 | 590 | 3.0 | 13,14 | 13 |
| 300 | 290 | 1.0 | 6,7 | 6,7 |
| 300 | 511 | 1.7 | 25,26 | 26 |
| 300 | 895 | 3.0 | 1,2,12 | 1,2,12 |
| 300 | 1,116 | 3.7 | 17,18,19 | 17,18 |
| 500 | 166 | 0.33 | 23,24 | 24 |
| 500 | 730 | 1.5 | 20,21,22,27 | 21,22,27 |
| 500 | 1,809 | 3.6 | 15,16 | 15,16 |
| 509 | 1,589 | 3.1 | 3,4,5,8,9,10,11 | 3,5,8,11 |

There was extensive and redundant instrumentation in the Marviken test facility. Although it is not easy to pick a set of consistent measurements which can be used to define a set of inlet stagnation conditions, the discharge pipe inlet conditions specified by pressure sensor 001M106 and temperature sensor 001M402 have been taken as initial conditions. In addition, mass flow rates calculated using both the pitot-static and inventory method have been used for comparison.

At least one test run for each geometry has been calculated and compared with the data. The test run numbers selected for comparison are shown in Table 1. The value of $C_{d,ref}$ for each test run was not obtainable from the Marviken Program. Instead, $C_{d,ref}$ of given test run was obtained by matching their highly subcooled data to the prediction. Then the calculated discharge coefficient was assumed to be constant throughout the test. Since, during a test, the variation of mass flux and stagnation pressure were not large, it is believed that the variation of the discharge coefficient is not large.

The model predictions on the selected Marviken tests are shown in Figures 1 to 7. These figures are arranged to first show the 500 mm diameter tests (Figures 1 - 3), then 300 *mm* diameter tests (Figures 4 - 6), and 200 *mm* diameter test (Figure 7) is followed. All the model predictions ends when the fluid temperature approaches the saturation temperature corresponding to the stagnation pressure. Comparisons between the model predictions and the test data show that, for subcooled conditions, the model predictions are in good agreement with data while the agreement is somewhat poor for low subcooled conditions. The mean error and standard deviation are 0.01 and 0.06, respectively (Figure 8).

The comparison shows that mass fluxes calculated by Eq. 1 are lower than the experimental results by approximately 20 % for the lower subcooled condition in Tests 7 and 24. However, Eq. 2 developed for very short length tube (20 *mm*) with large $L/D$ ratio ($L/D = 20$) predicts the mass fluxes in these geometries very well (Figures 3 and 6). This result suggests that Eq. 1 may not be used for very small $L/D$ geometries with larger diameter ($D \geq 300$ *mm*). This situation is surprising since the lengths of these test sections (166 and 290 *mm*) are longer than those of test sections used to develop Eq. 1, and it successfully predicted critical mass fluxes in slits ($D_h \leq 1.28$ *mm*, $L = 46$ *mm*) [7], and short tube ($D = 4.6$ *mm*, $L = 46$ *mm*) [8]. It is desired that more studies on characteristic length for thermal nonequilibrium in larger diameter test sections be needed.

Based on the comparisons between the Marviken data and the model predictions, it is concluded that the correlation type critical mass flux model developed using the scaling parameters is capable of predicting the entire range of Marviken data for subcooled conditions.

## 4. Conclusions

Critical flow rates of the Marviken Test were calculated using the correlations based on the critical flow scaling parameters and the compared with the measured data. The results show that the correlations can successfully predict the critical mass fluxes in very large diameter pipes. Eq. 2 developed for very short geometries ($L = 20$ *mm*) with small diameter ($D = 1.0$ *mm*) can be used for relatively long test section (up to 290 *mm*) if the $L/D$ is less than 1.0. For other cases, Eq. 1 developed for relatively longer lengths ($L \geq 40$ *mm*) is adequate.

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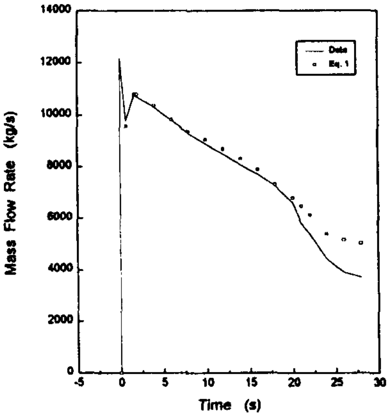

Fig. 1 Comparison Between Predictions and Data of Run-15 ($D = 509$ *mm*, $L = 1{,}809$ *mm*)

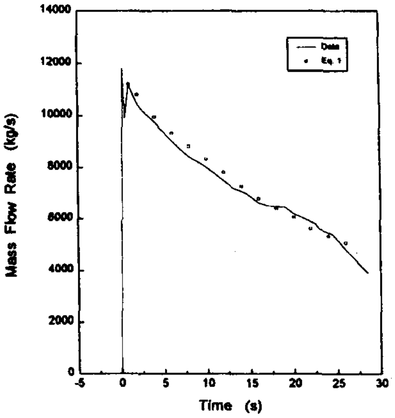

Fig. 2 Comparison Between Predictions and Data of Run-21 ($D = 500$ *mm*, $L = 730$ *mm*)

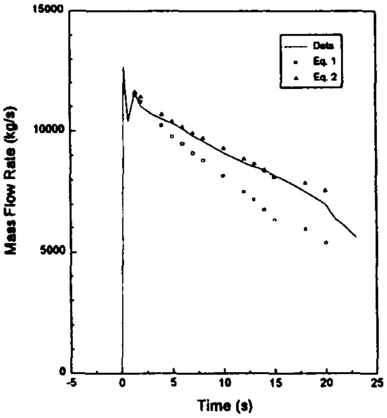

Fig. 3 Comparison Between Predictions and Data of Run-24 ($D = 500$ *mm*, $L = 166$ *mm*)

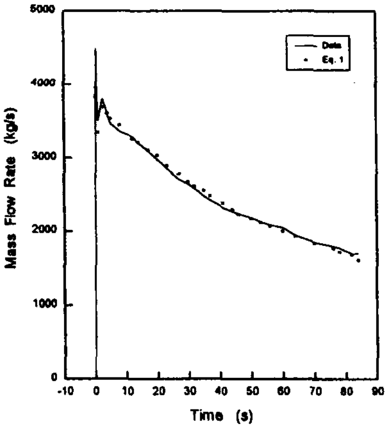

Fig. 4 Comparison Between Predictions and Data of Run-17 ($D = 300$ *mm*, $L = 1{,}116$ *mm*)

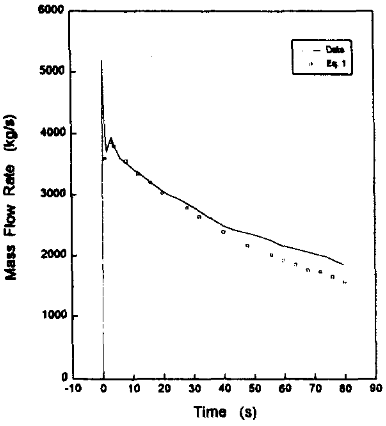

Fig. 5 Comparison Between Predictions and Data of Run-26 ($D = 300$ *mm*, $L = 511$ *mm*)

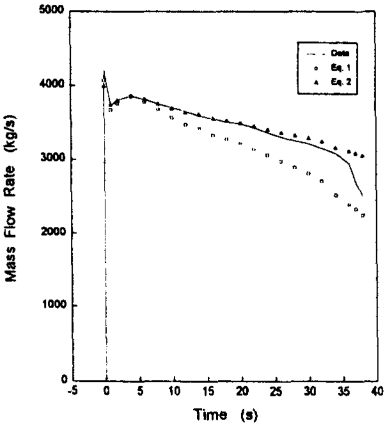

Fig. 6 Comparison Between Predictions and Data of Run-07 ($D = 300$ *mm*, $L = 290$ *mm*)

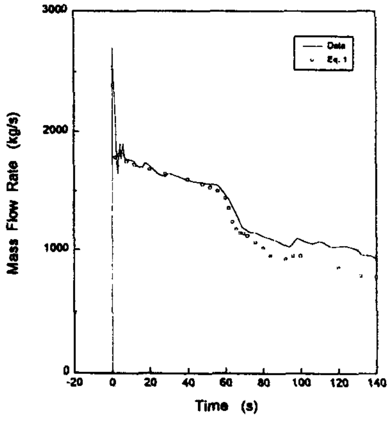

Fig. 7 Comparison Between Predictions and Data of Run-13 ($D = 200$ *mm*, $L = 590$ *mm*)

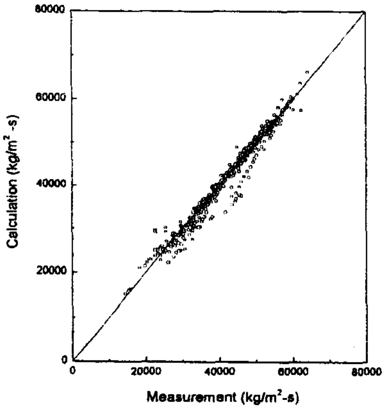

Fig. 8 Comparison Between Model Predictions and Test Data of Marviken Program