A Proposed Correlation for Critical Flow Rate of Steam/Water Flow

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1. Introduction

In the safety analysis of loss-of-coolant-accident (LOCA) and steam generator tube rupture (SGTR) scenarios of light water reactors, a modeling of a break is very important to predict the accident's result. For example, the design of a break simulator to simulate a LOCA in light water reactors requires accurate knowledge of the leakage flow through the break, whose shape can be assumed as an orifice or a nozzle according to the characteristics of the break shape. In the case of a small-break LOCA (SBLOCA) scenario, the critical flow mostly occurs by sub-cooled and saturated liquid water including a two-phase water flow at relatively high-pressure conditions.

Among previous critical flow maps, Moody's maps [1] are well known for their critical flow rate and pressure of a single component and two-phase mixture with respect to the upstream enthalpy and pressure. In Moody's model, a slip ratio defined by maximizing the critical flow rate with respect to the slip ratio was introduced, and thus its predictions tended to be too conservative. Later, Moody [2] suggested other maps based on a homogeneous equilibrium model (HEM), and they were useful to predict a choked condition for a given upstream condition. However, their predictions of the critical flow rate seemed to show quite an underestimation compared to various test data.

The author [3] suggested more practicable critical flow maps for a critical mass flux and pressure of a steam-water flow with respect to the upstream stagnation conditions using an extended Henry-Fauske model [4]. From a comparison with the selected test data, suggested maps showed conservative predictions within reasonable ranges. In this report, a new correlation for the critical flow rate was developed to simulate the suggested critical flow maps [3] within a reasonable range of error.

2. Methods and Results

Most correlations for the critical flow rate were suggested using an incompressible flow equation for the orifice [5] as follows:

$$g_c = K\sqrt{2(P_0 - P_b)\rho_{f0}} \qquad (1)$$

Here, g_c is the critical mass flux; K, a discharge coefficient, e.g., typically 0.61; P_0, the stagnation pressure; P_b, the back pressure; and ρ_{f0}, the fluid density based on the stagnation condition. Despite its usefulness, Eq. (1)'s predictions had some limitations for all ranges of water flow. The orifice type correlation, like Eq. (1), for example, was found to predict a rather under-estimation for large sub-cooling and an over-estimation for small sub-cooling and two-phase mixture conditions with respect to the ideal data. The main reason for these discrepancies seems to be due to the use of the total hydraulic pressure difference, e.g., P_0-P_b, as a driving force for the critical flow.

To overcome the limitations of the orifice type correlation, a practicable correlation predicting the critical flow rate for any kind of water condition using a Bernoulli type relation was suggested as follows:

$$g_c = \sqrt{2[P_0 - C_f P_{sat}(T_0)]\rho_{f0}} \qquad (2)$$

Here, P_0 is the stagnation pressure; P_{sat}, saturation pressure; T_0, the stagnation temperature; ρ_{f0}, the fluid density based on the stagnation condition; and C_f, a choking correction factor dependent upon the stagnation pressure and sub-cooled temperature (C_f was introduced first in a previous study [6]). In the case of a two-phase flow, the fluid density was obtained using an assumption of a homogeneous mixture. Note that Eq. (2) calculates the maximum flow rate using a thermal pressure difference between the stagnation pressure and the saturation pressure at the stagnation temperature as a driving force for the critical flow, and simulates the critical flow rate for an idealized data, and thus there is no discharge coefficient in the equation.

From the review of idealized data for sub-cooled and saturated water with a pressure range of 0.5-20 MPa, a dimensionless parameter called a dimensionless sub-cooled temperature, i.e., $\triangle T^*_{sub}$ defined as Eq. (3), was found to correlate the idealized data effectively.

$$\Delta T^*_{sub} = \frac{T_{sat}(P_0) - T_0}{T_{sat}(P_0) - T_{ref}} \qquad (3)$$

Here, $T_{sat}(P_0)$ is a saturation temperature corresponding to the stagnation pressure, P_0; T_0,the stagnation temperature; and T_{ref}, a reference temperature defined as 20 ^oC . For sub-cooled and saturated water, it was found that C_f was dependent on the stagnation pressure for $0.0 \le \triangle T^*_{sub} < 0.15$, and independent on the stagnation pressure for $0.15 \le \triangle T^*_{sub} \le 1.0$. In addition, for a two-phase mixture, C_f was mainly dependent on the stagnation pressure.

Table 1 shows a summary of the C_f values for a wide range of upstream pressures, e.g., 0.5-20.0 MPa, to correlate the extended Henry-Fauske model [4].

Table 1. Values of the choking correction factor for water flow

Upstream State	Condition	P_0 [MPa]	C_f	Remark
Sub-Cooled and Saturated Water	$0.0 \le \triangle T^*_{sub} < 0.15$	0.5	0.87	10% Error
		1.0	0.85	
		2.0,3.0	0.83	
		4.0-6.0	0.82	
		7.0-20.0	0.81	
	$0.15 \le \triangle T^*_{sub} \le 1.0$	0.5-20.0	1.0	5% Error
Two-Phase Mixture	$0.0 < x \le 1.0$	0.5	0.81	10% Error
		1.0	0.80	
		2.0-11.0	0.79	
		12.0,13.0	0.78	
		14.0-17.0	0.77	
		18.0	0.76	
		19.0,20.0	0.75	

To check the feasibility of Eq. (2), idealized critical mass fluxes [3] were compared with those of Eq. (2) for four different upstream pressure conditions, e.g., 1.0, 5.0, 10.0, and 15.0 MPa, as shown in Fig. 1. As can be seen in the figure, the suggested correlation predicted the idealized critical values for sub-cooled and saturated water including a two-phase mixture with a reasonable error range, i.e., within 10%. In the figure, ± 10% error ranges, for example, were also depicted for the case of P_0 = 10.0 MPa.

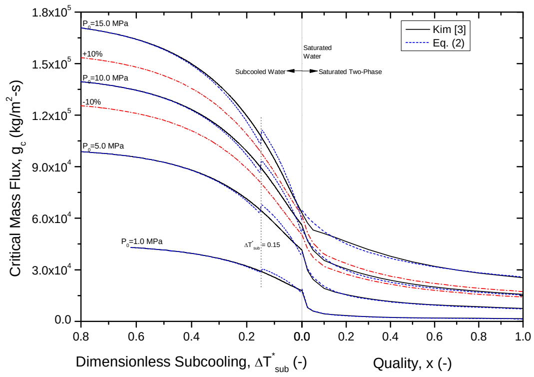

Fig. 1 Comparison between idealized critical mass fluxes and Eq. (2)'s prediction

3. Summary and Conclusions

A new correlation predicting the idealized critical mass flow rates of water for sub-cooled and saturated liquid water including a two-phase water flow was developed for wide ranges of upstream stagnation pressures, e.g., 0.5-20.0 MPa. A choking correction factor dependent upon the upstream stagnation pressure and sub-cooled temperature was introduced into a new correlation, and its values were suggested satisfying the idealized nozzle data within 10% error ranges. The suggested correlation would be instructive and helpful for related studies and/or engineering works.

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