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An Empirical Correlation for Subcooled Two-Phase Critical Flow Rates in Short Tubes, Nozzles, and Orifices

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ABSTRACT

Critical two-phase flow rates of subcooled water through very short tube (L = 20 *mm*) with small diameters (D = 1.0 *mm*) has been measured for wide ranges of subcooling (0 ~ 186 °*C*) and pressure (0.5 ~ 2.0 *MPa*). Experimental results show that subcooled critical two-phase flow rates can be expressed in terms of two scaling parameters for geometries and initial conditions. They are discharge coefficient of cold water, $(C_d)_{ref}$, and dimensionless subcooling, ΔT^*_{sub}, respectively. A new empirical correlation expressed in terms of $(C_d)_{ref}$ and ΔT^*_{sub} is obtained for subcooled two-phase flow rates through very short length tube. Comparisons between the mass fluxes calculated by present correlation and a number of experimental data show that the agreement is very good.

1. Introduction

The critical flow rate is the maximum flow rate that can be attained by a compressible fluid as it passes from a high-pressure region to a low-pressure region. Although the flow rate of an incompressible fluid from the high-pressure region can be increased by reducing the receiving end pressure, a compressible fluid flow rate reaches a maximum for a certain (critical) receiving end pressure. This condition occurs for both single flow of gases as well as two-phase gas-liquid flows.

The critical flow phenomenon has been studied extensively in both single-phase and two-phase systems because of its important role in the loss of coolant accident (LOCA) analyses of light water reactors and the design of two-phase bypass systems in steam turbine plants and of venting valves in the chemical and power industries. Although the critical flow of single-phase compressible fluids may be considered as fairly well understood, a complete theory describing the critical flow of two-phase steam-water mixtures is not available yet. Furthermore, comparisons of various critical two-phase flow models with experimental data showed that none of the existing analytical models lead to a complete clustering around the equality line within ± 50 % [1].

Recently, an empirical correlation for the two-phase critical flow rates of the subcooled water has been proposed [2,3] and it quite accurately predicted available critical test data within 9 % standard deviation. However, this correlation tends to underpredict the critical flow rates in the very short length test sections or in the very small L/D geometries [2].

In this study, a new empirical correlation for two-phase critical flow rates of subcooled water in the very short length test section has been developed using test data obtained from the small scale critical flow test facility. This correlation uses the same scaling parameters (discharge coefficient and dimensionless subcooling) for critical flow phenomena [2]. This correlation together with that proposed by the previous work [2] can predict critical two-phase mass flux for wide ranges of stagnation and geometrical conditions.

2. Experimental Methods

A total of 36 critical two-phase flow tests were conducted by discharging high pressure water (0.5 ~ 2.0 *MPa*) from a blowdown vessel to the collection tank maintained at atmospheric pressure through the very short tube as summarized in Table 1. The major thermodynamic test parameters were the initial subcooling and the pressure of the water in the vessel.

The schematic of the blowdown apparatus is shown in Fig. 1. The blowdown facility consists of the following: (1) a test section, (2) a blowdown vessel equipped with an internal electric heater, (3) an accumulator, (4) a nitrogen tank, (5) a collection tank, (6) associated sensors and devices to measure temperatures, pressures, and water level, and (7) data acquisition systems.

Nitrogen was supplied to the blowdown vessel from the accumulator which was connected to the nitrogen tank. The pressure of the accumulator was kept at constant value by means of a pressure regulator. The mass flux through the test section was determined indirectly via continuous measurements of the water level in the blowdown vessel. The pressures and temperatures inside the blowdown vessel as well as at the inlet of the test section and the water level in the blowdown vessel were continuously recorded at the frequency of 20 Hz for each test run.

3. Test Results and Empirical Correlation

The estimated errors due mainly to signal noise are ± 400 Pa, ± 47 Pa, and 2.0 °C for inlet pressure, differential pressure for water level, and inlet water temperature, respectively. In addition, the overall uncertainty of mass flux estimation falls within 1.5 % of the interval about the mean value.

Fig. 2 shows mass flux data obtained from the present test section. The figure shows that the mass flux can be expressed in terms of the temperature for a given pressure condition, and the mass flux approaches asymptotically the mass flux for the cold water condition as the inlet temperature is decreased. These data trends have been also observed in the relatively longer test sections [2]. As the data trends are very similar to those in the relatively longer test sections, the same scaling parameters (the discharge coefficient of the cold water flow, $(C_d)_{ref}$, and the dimensionless subcooling, $\Delta T^*_{sub} = \Delta T \, / \, (T_{sat} - T_{ref})$, where subscript " ref " refers to the values at 20 °C) has been used to obtain a new empirical correlation for the critical flow rates through very short tube as follow (Fig. 3):

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

The mean relative error between the data and the calculated values, and the standard deviation of the data on the proposed equation are -1.3 % , and 3.8 %, respectively.

This correlation for the very short test section has the same form as that developed for relatively longer test sections (Eq. 2) [2]. However, the values of the sigmoidal fitting function parameters are different from those in Eq. 2:

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

In general, critical mass fluxes for very short test sections such as short tubes, nozzles, or orifices are greater than those of longer pipe for the same initial condition. This results may be attributed to the non-equilibrium effect caused by short residence time of metastable liquid. In view of Sozzi and Sutherland [4], length is important parameter for recovery from metastability. For this reason, the critical flow rates calculated by Eq. 1 are greater than those by Eq. 2 for the same initial and geometrical conditions

4. Comparison between Experimental Data and Correlations

To investigate the applicability and the limit of the new correlation (Eq. 1), a number of critical flow data were selected. These experiments comprise 1396 data points with pressures from 0.21 to 17.0 *MPa*, diameters from 0.25 to 509 *mm* and lengths from approximately zero to 2,335 *mm*. These data are from 15 different experimenters that include both for horizontal and vertical flows.

Comparison of measured critical mass fluxes of Powell's experiment and the predictions by Eq. 1 is presented in Fig 4. The figure shows that the proposed equation (Eq. 1) quite accurately predicted critical mass fluxes in venturi. In Fig. 5, the critical mass fluxes of Marviken Test-24 and the predictions by Eq. 1 and Eq. 2 have been compared. As seen in the figure, Eq. 1 better predicted the mass fluxes than Eq. 2.

A comparison of critical mass fluxes between the experimental data and the prediction is given in Fig. 6. As seen in the figure, Eq.s 1 and 2 quite accurately predicted critical flow rates. For the comparison, Eq. 1 was used for following cases; (1) $L/D < 10$ and $D < 15$ *mm*, (2) $L/D < 1$ and $D \geq 300$ *mm*. Considering the fact that these experimental data are from a wide range of test section sizes, geometries, flow orientations, and stagnation conditions, the agreement is excellent and therefore, it is confirmed that $(C_d)_{ref}$, and Δ

T^*_{sub} are scaling parameters for geometries and initial conditions, respectively.

It is concluded that Eq. 2 is generally applicable for the geometry of $L/D \geq 10$ with $L \geq 46$ *mm*, and that Eq. 1 is applicable for very short nozzles or orifices. For large diameter test sections (i.e., $D \geq 300$ *mm*), however, Eq. 1 is applicable for $L/D \leq 1$.

5. Conclusions

Critical two-phase flow rates of subcooled water through very short tube with small diameter have been experimentally investigated for wide ranges of subcooling and pressure. A new empirical correlation for subcooled two-phase critical flow rates has been developed in terms of two scaling parameters such as discharge coefficient and dimensionless subcooling. A comparison of critical mass fluxes calculated by the present correlation and the experimental data was made. The new correlation is applicable for very short tubes, nozzles, and orifices.

References

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4. G.L. Sozzi and W.A. Sutherland, "Critical Flow of Saturated and Subcooled Water at High Pressure," NEDO-13418, 1975

Table 1. The Blowdown Test Conditions

Pressure (*MPa*)	Subcooling (°C)	Diameter (*mm*)	Length (*mm*)	*L/D*	No. of Run
0.5	0.9 - 128.1	1.0	20	20	11
1.0	0.0 - 155.6				10
1.5	0.2 - 178.1				8
2.0	1.1 - 185.9				7

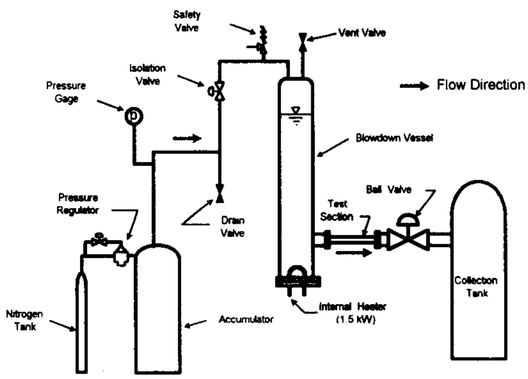
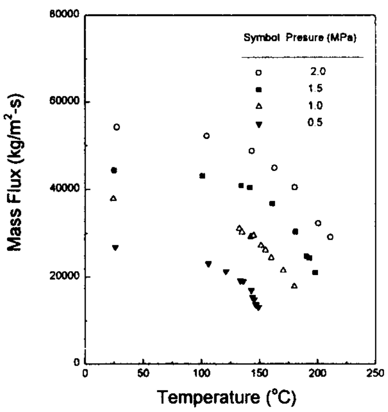


Fig. 1 Schematic Diagram of Blowdown Test Apparatus



Fig, 2 Mass Flux versus Stagnation Temperature

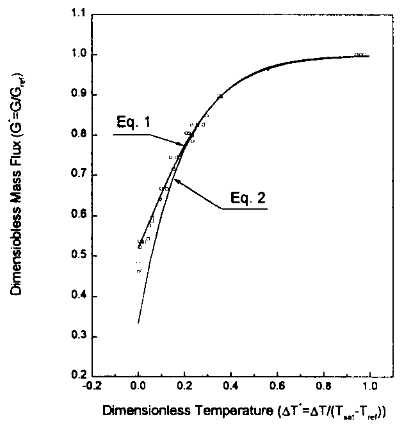


Fig. 3 Dimensionless Mass Flux versus Dimensionless Subcooling

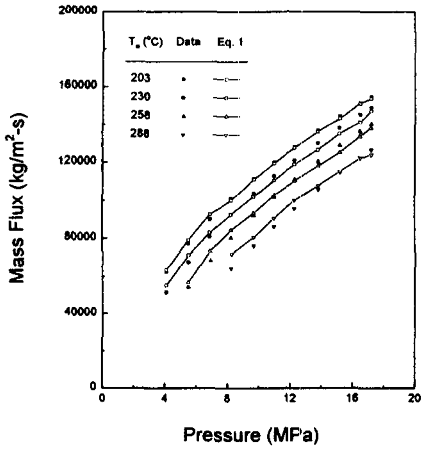


Fig. 4 Comparison between Model Predictions and Mass Flux Data in Powell's Converging-Diverging Nozzle

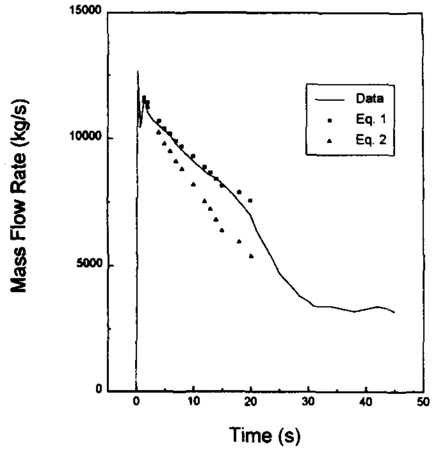


Fig. 5 Comparison between Model Predictions and Experimental Data of Marviken Test-24 (D = 500 mm, L = 166 mm: D / L = 0.33)

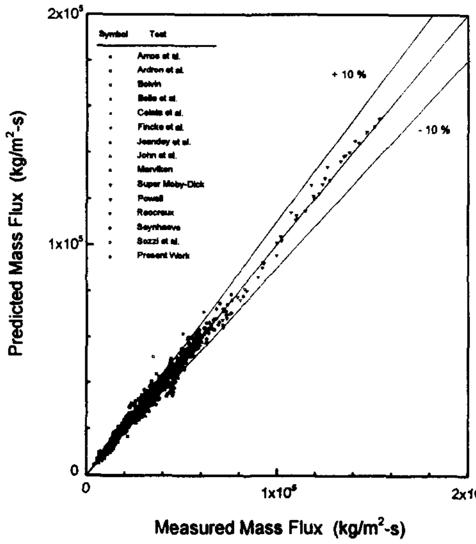


Fig. 6 Comparison of Critical Mass Flux Calculated by Present Correlations with Measured Data from Various Sources