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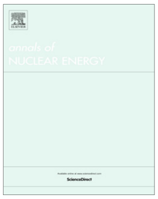

Review

# Overview of geometrical effects on the critical flow rate of sub-cooled and saturated water

Yeon-Sik Kim *

*Thermal Hydraulics Safety Research Division, Korea Atomic Energy Research Institute, 111, Daedeok-Daero 989 Beon-Gil, Yuseong-Gu, Daejeon 305-353, Republic of Korea*

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ABSTRACT

A new correlation predicting the idealized critical mass flow rates of sub-cooled and saturated water was suggested, which can be applicable for wide ranges of stagnation pressures, e.g., 0.5–20.0 MPa. The suggested correlation will be instructive and helpful for related studies and/or engineering works. In addition, an overview of the geometrical effects on the critical flow rate of sub-cooled and saturated water was investigated, especially on the length and diameter aspects. As transition criteria from non-equilibrium to equilibrium choking, a length to diameter ($L/D$) ratio of 25 was suggested for the nozzle or pipe flows. In the case of an orifice, an increase of the $L/D$ ratio induces a decrease of the form loss coefficient and thus results in an increase of the critical flow rate. Moreover, the trend of the critical flow rate at the orifices was found to be dependent upon the form loss coefficient, but the nozzle and pipe are dependent upon the length. In a nozzle or pipe, the entrance shape also affects the critical mass flow rate, e.g., smaller form loss coefficient and larger critical mass flow rate. Diameter effects occurred regardless of the diameters, lengths and upstream pressures under the same $L/D$ ratio. A further discussion was conducted for the over-measurement of critical mass flow rate under lower sub-cooling temperatures, which was found in smaller throat diameters of the orifices, and the slip ratio between two-phases at the choking location was proposed as one of reasons for the over-measurement.

**Contents**

## 1. Introduction

In the safety analysis of loss-of-coolant-accident (LOCA) scenarios of light water reactors, an appropriate modeling of a break is important to simulate the accident result. The mass flow rate through a break in the cooling fluid piping is of special concern. The mass flow rate through the break will determine a sequence of events, e.g. the time at which the reactor core becomes uncovered, and provide a basis for how much emergency cooling water should be injected into the core to assure sufficient core cooling. In light water reactors, a maximum flow rate through a break

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* Tel.: +82 42 868 2868; fax: +82 42 861 6438.
*E-mail address:* yskim3@kaeri.re.kr

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**Nomenclature**

| | |
|---|---|
| LOCA | loss of coolant accident |

*Symbols*

| | |
|---|---|
| $A_0$ | cross-sectional area ($m^2$) at throat of test section |
| $A_1$ | cross-sectional area ($m^2$) at inlet of test section |
| $A_2$ | cross-sectional area ($m^2$) at outlet of test section |
| $C_d$ | discharge coefficient |
| $C_f$ | choking correction coefficient for Eq. (2) |
| $D$ | inner or throat diameter, [m or mm] |
| $f$ | friction or fanning factor |
| $g_c$ | critical mass flux, [$kg/m^2$-s] |
| $L$ | length, [m or mm] |
| $L/D$ | length to diameter ratio |
| $P$ | pressure, [Pa or MPa] |
| $\Delta P$ | pressure drop or loss, [Pa] |
| $R$ | radius of curvature, [m or mm] |
| $Re$ | Reynolds number, $Re = \rho u D/\mu$ |
| $T$ | temperature, [°C] |
| $\Delta T_{sub}$ | sub-cooled temperature, defined as $T_{sat}(P_0) - T_0$, [°C] |
| $\Delta T^*_{sub}$ | dimensionless sub-cooled temperature, defined as $(T_{sat}(P_0) - T_0)/(T_{sat}(P_0) - T_{ref})$ |
| $u$ | velocity, [m/s] |

*Greeks*

| | |
|---|---|
| $\rho_f$ | density of water, [$kg/m^3$] |
| $\rho_{f0}$ | density of water at stagnation temperature, [$kg/m^3$] |
| $\varphi$ | parameter, as defined $\varphi(l) = 0.25 + 0.535 * l^8/(0.05 + l^8)$ |
| $\iota$ | parameter, as defined $\iota = L/D$ |
| $\mu$ | viscosity (kg/m-s) |
| $\rho$ | density ($kg/m^3$) |
| $\tau$ | a parameter, as defined $\tau(\varphi, l) = (2.4 - l) * 10^{-\varphi}$ |
| $\zeta$ | pressure loss coefficient |
| $\xi$ | a parameter, as defined $\xi = 0.03 + 0.47 * 10(-7.7 * R/D)$ |

*Subscripts*

| | |
|---|---|
| *0* | stagnation or upstream condition |
| *b* | back pressure or discharge condition |
| *c* | critical or choke condition |
| *f* | liquid phase |
| *ref* | reference temperature, 20 °C |
| *sat* | saturation condition |

happens according to the given upstream conditions for the break and an accurate estimation of the maximum flow rate, the so-called critical flow rate, is essential for reactor safety.

Various works have been performed on the critical flow phenomena experimentally and theoretically. As a summary, their results were classified into two types of non-equilibrium flow models as Richter (1983) commented, e.g., hydrodynamic non-equilibrium and thermal non-equilibrium models. In addition, geometrical effects were also found to be the main cause of deviation between predictions and experiments.

Fauske (1965) performed a test for the critical flow rate of saturated water through tubes using a high-pressure test facility and found that the data showed three different regimes, depending upon the length to diameter ($L/D$) ratio, e.g., $0 < L/D < 3$, $3 < L/D < 12$, and $12 < L/D < 40$. In the first regime, i.e., $0 < L/D < 3$, the fluid breaks immediately from the tube wall and remains as a metastable liquid core jet with vaporization from the jet surface taking place. In the second regime, a breakup of a metastable liquid jet is taking place. In the last regime, the momentum pressure drop is the controlling factor owing to the measured constant pressure ratio, e.g., $P_c/P_0 \approx 0.55$, and the small difference in flow rate can be contributed to a greater friction loss for the longer tubes. It is noteworthy that an asymptotic critical pressure ratio of 0.55 was found for wide ranges of initial pressure, e.g., 0.79–12.5 MPa, as shown in Fauske (1965).

Moody (1975) investigated a critical flow rate of liquid–vapor mixtures from vessels and suggested the effect of friction parameters, e.g., $f \cdot L/D$. In the case of $f \cdot L/D < 3.0$, the pipe exit choked flow state does not influence homogeneous choking at the entrance. For large friction region, e.g., $f \cdot L/D > 3.0$, the pipe entrance flow will be un-choked, and the blowdown rates will be less than that predicted by homogeneous choking in terms of vessel stagnant properties. He also concluded that downstream from the pipe entrance, the two-phase blowdown probably tends toward a slip flow pattern.

Sozzi and Sutherland (1975) performed critical flow tests especially on the effects of inlet stagnation conditions, flow length, inlet flow geometry, downstream flow geometry, and diameter. They found that a strong length dependence on the critical flow through short flow lengths ($L < 127$ mm) had been characterized as non-equilibrium effects. In short flow lengths, fluid passing will not have sufficient time to completely nucleate before leaving the pipe or tube. For longer flow lengths, e.g., $L > 127$ mm, the critical flow rates were predicted by the homogeneous equilibrium model. In longer flow lengths, fluid passing will have sufficient time to reach equilibrium conditions. In addition, they also remarked the effect of diameter, e.g., the critical mass flux decreases with an increasing throat diameter.

Fauske (1985) suggested a practical guideline to predict a critical flow rate for sub-cooled and saturation stagnation conditions. He found that the flow length is the dependent variable for the classification between non-equilibrium and equilibrium conditions, e.g., if $L < 100$ mm, non-equilibrium regime; $L > 100$ mm, equilibrium regime. This guideline seemed to be very close to the findings of Sozzi and Sutherland (1975).

From previously theoretical and experimental works, a conclusion can be made that the critical flow rate is deeply dependent on non-equilibrium and equilibrium conditions at the choking location and even the throat diameter. In this paper, geometrical effects on the critical flow rate for sub-cooled and saturated water were summarized and investigated, especially on the effect of thick orifices.

## 2. Prediction of critical flowrate for sub-cooled and saturated water

The critical flow rate for sub-cooled and saturated water is important, especially for a small break LOCA assessment in light and heavy water reactors. In general, the sequence of events of an SBLOCA consists mainly of five phases: blowdown, pressure plateau, loop seal clearing, boil-off, and recovery (Kim and Cho, 2014). For the first three phases, the leakage through a break is under sub-cooled and saturated condition, and an accurate prediction of the break flow is essential for an assessment of the overall behavior. This is why the accurate prediction of critical flowrate for sub-cooled and saturated water is important for small break LOCA behaviors.