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A Study of Critical Flowrate in the Integral Effect Test Facilities

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1. Introduction

In the safety analysis of loss-of-coolant-accident (LOCA) scenarios of light water reactors, a modeling of a break is very important to predict the result of an accident. For example, the design of a break simulator for a simulation of a small break loss-of-coolant-accident (SBLOCA) in a light water reactor requires an accurate knowledge of the break flow of sub-cooled water through the break, whose shape can be assumed as an orifice or a nozzle according to its aspect of the break. In the case of a SBLOCA scenario, a critical flow mostly occurs by sub-cooled and saturated water at relatively high-pressure conditions. In earlier studies, most of the information available in the literature was either for a saturated two-phase flow or a sub-cooled water flow at medium pressure conditions, e.g., up to about 7.0 MPa.

The choking is regarded as a condition of maximum possible discharge through a given orifice and/or nozzle exit area. A critical flow rate can be achieved at a choking under the given thermo-hydraulic conditions. The critical flow phenomena were studied extensively in both single-phase and two-phase systems because of its importance in the LOCA analyses of light water reactors and in the design of other engineering areas. Park [1] suggested a modified correlation for predicting the critical flow for sub-cooled water through a nozzle. Recently, Park et al. [2] performed an experimental study on a two-phase critical flow with a non-condensable gas at high pressure conditions. Various experiments of critical flow using sub-cooled water were performed for a modeling of break simulators in thermo-hydraulic integral effect test facilities for light water reactors, e.g., an advanced power reactor 1400MWe (APR1400) and a system-integrated modular advanced reactor (SMART). For the design of break simulators of SBLOCA scenarios, the aspect ratio (L/D) is considered to be a key parameter to determine the shape of a break simulator. Typical shapes of break simulators based on the aspect ratio are an orifice and/or a nozzle (or pipe), e.g., an orifice is for the case in which the aspect ratio is less than 2.5, and a nozzle (or pipe) is for when the aspect ratio is greater than 2.5.

In this paper, an investigation of critical flow phenomena was performed especially on break simulators for LOCA scenarios in the integral effect test facilities of KAERI, such as ATLAS and FESTA.

2. Overview of the Critical Flowrate Models for Sub-cooled and Saturated Water

As well known, there were various studies on the critical flow models for sub-cooled and/or saturated water. In particular, Fauske, Moody, and Henry suggested basic theoretical models based on their own assumptions, and Zaloudek provided an insight of physical phenomena for a critical flow in an orifice type flow path. Sozzi and Sutherland performed a critical flow test of saturated and sub-cooled water at high pressure for orifice and nozzles. In addition, a full-scale critical flow test, i.e., Marviken, was also performed under a multi-national project.

Previous studies related to the critical flowrate for sub-cooled and saturated water were investigated, including tests performed at KAERI related to the break simulators in integral effect test facilities.

3. Discussions of Critical Flowrate Compared to Selected Test Data

3.1 Diameter effect

From a review of the effect of diameter on the critical flowrate with respect to all dimensional scales, it was found that there should be a dominant parameter affecting the critical flowrate, which would be the slip ratio between phases, as assumed by the authors. Henry [3] discussed the effect of the slip ratio on his theoretical model and concluded that the slip ratio was within a limited range of 1-1.3, which should be identified experimentally. The authors found that Henry’s finding may not be applicable to our suggested assumption, e.g., the physical reason for the diameter effect on the critical flowrate is mainly due to the slip ratio. In this paper, the authors would like to suggest this assumption deliberately and reserve it as a further work of this study.

3.2 Comparison of critical flow models and selected test data

A summary of the calculation results is shown in Table 1. For Zaloudek’s calculation, the correlation of critical mass velocity for the second-step-critical flow was used. As shown in the table, a large amount of over-prediction was found. Moody’s calculation was available only for saturated conditions. For a sub-cooled condition, Moody’s other method could be used.

Table 1. Summary of calculation results (unit: kg/m^2-s)

No.	Test Data	Zaloudek	Moody [a]	Hybrid[a]	Park[b]	$MARS_{H-F}$ [c]	$MARS_{T-R}$ [c]	TRACE[c]	Remark
1	59,029.5	77,277.3	NA	NA	59,377.0	61,993.2	58,856.8	56,739.5	Orifice; Sub-cooled
2	53,795.5	56,754.2	NA	NA	55,992.6	55,547.6	55,618.7	72,497.2	Orifice; Sub-cooled
3	52,267.3	36,509.2	37,151.9	35,535.2	53,670.9	45,924.7	36,438.4	71,069.1	Orifice; Saturated
4	9,847.0	23,393.8	NA	NA	9,927.3	8,416.8	5,533.2	7,172.7	Pipe; Sub-cooled
5	12,042.0	26,942.3	NA	NA	12,430.7	11,599.0	7,874.7	9,367.1	Pipe; Sub-cooled
6	30,583.0	42,926.6	NA	NA	26,526.1	25,711.5	24,356.8	22,134.1	Pipe; Sub-cooled
7	9,782.0	24,242.8	NA	NA	11,460.3	9,001.6	7,154.7	7,467.7	Pipe; Sub-cooled
8	11,050.0	28,451.6	NA	NA	14,675.2	12,586.2	10,102.6	9,986.1	Pipe; Sub-cooled
9	23,921.0	42,821.5	NA	NA	28,237.6	26,480.1	25,586.0	23,130.5	Pipe; Sub-cooled
10	41,691.5	50,227.6	NA	NA	43,801.0	44,562.0	42,701.6	32,441.4	Pipe; Sub-cooled
11	21,588.5	36,548.0	29,311.6	27,552.7	27,624.2	26,532.9	19,470.7	20,145.6	Pipe; Saturated
12	29,779.7	35,767.1	30,074.6	28,343.5	28,389.9	26,250.0	20,294.0	20,838.8	Pipe; Saturated
13	45,522.5	54,507.5	NA	NA	48,480.7	47,962.5	47,256.3	37,501.1	Pipe; Sub-cooled
14	17,072.8	36,548.0	29,311.6	27,552.7	27,624.2	23,150.5	16,848.2	20,417.8	Pipe; Saturated
15	19,141.8	35,767.1	30,074.6	28,343.5	28,389.9	22,708.2	19,260.2	21,056.9	Pipe; Saturated

Note a: NA means that authors could not obtain calculation results using an in-house steam table.
b: Underlined data were obtained for saturated condition.
c: Underlined data mean flowrates with no occurrence of choking at the test section itself.

Results of a quantitative comparison, e.g., R^2-values, were compared, as shown in Table 2.

Table 2. Summary of R^2-values for each model with respect to test data

Zaloudek	Moody	Hybrid	Park	$MARS_{H-F}$	$MARS_{T-R}$	TRACE
0.730	0.915	0.915	0.951	0.957	0.924	0.857

It is noteworthy that in the test of the critical flowrate, the test facility should be designed cautiously to avoid choking outside of the test section itself, especially downstream. In most of the calculation data underlined in Table 5 for MARS and TRACE calculations, choking locations were found downstream of the test section. This means that the measured data can be the critical flowrates for the test facility, not for the test section. For a qualitative comparison, all data are displayed in a figure, as shown in Fig. 1.

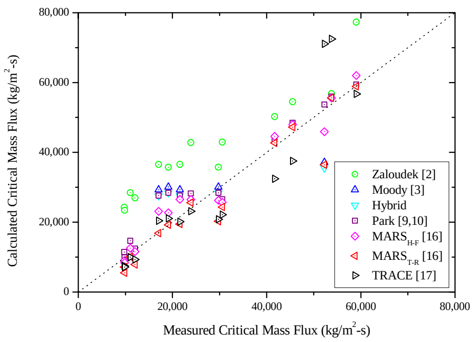

Fig. 1 Comparison between model's calculations and test data

3.3 Discussions on break simulators for SBLOCA in the integral effect test facilities

The break simulators for the SBLOCA scenarios in the integral effect test facilities of KAERI, e.g., ATLAS and FESTA, were designed by Park's model [1]. The shapes of the break simulators were bell-mouthed or sharp-edged pipe (or nozzle) types with respect to the required total loss coefficient. In the SBLOCA scenarios of ATLAS, the sequence of events typically consisted of a blowdown, pressure plateau, loop seal clearing, boil-off, and core recovery. From the blowdown to loop seal clearing phases, the break flow was sub-cooled and/or saturated water. After the loop seal clearing phase, the break flow changed to a steam-water two-phase flow. However, in the SBLOCA scenarios of FESTA, the break flow was sub-cooled and/or saturated water for all sequence of events of the SBLOCA scenarios. Under this circumstance, the designed break simulators may introduce some distortion of the break flowrate for the later phases of the SBLOCA scenarios at ATLAS. As discussed before, Park's correlation was developed for sub-cooled and/or saturated water conditions. In the later phases of the SBLOCA scenarios in ATLAS, the break flow changed to two-phase steam-water conditions.

In a separate evaluation of Park's model for a saturated two-phase critical flow, the R^2-value was evaluated as 9.47E-4 for the selected test data, which means that Park's model is little correlated with the two-phase steam-water critical flow test data. Thus, a break simulator by Park's model should be used cautiously for a two-phase critical flow.

4. Conclusions

In this study, various studies on the critical flow models for sub-cooled and/or saturated water were reviewed. For a comparison among the models for the selected test data, discussions of the comparisons on the effect of the diameters, predictions of critical flow models, and break simulators for SBLOCA in the integral effect test facilities were presented.

References

[1] C-K. Park, J-W. Park, M-K. Chung, and , M-H. Chun, "An Empirical Correlation for Critical Flow Rates of Subcooled Water through Short Pipes with Small Diameters," *Nuc. Eng. and Tech.*, Vol. **29**, No. 1, pp. 35-44 (1997).

[2] H-S. Park, N-H. Choi, S-K. Chang, C-H. Chung, S-J. Yi, C-K. Park, and M-K. Chung, "Experimental Study on a Two-phase Critical Flow with A Non-Condensable Gas at High Pressure Conditions," *Int. J. Multiphase Flow*, **33**, pp. 1222-1236 (2007).

[3] R.E. Henry, "A Study of One- and Two-Component, Two-Phase Critical Flows at Low Qualities," ANL-7430 (1968).