Premature and stable critical heat flux for downward flow in a narrow rectangular channel

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1. Introduction

The static flow instability (FI) and critical heat flux (CHF) for subcooled flow boiling in a vertical narrow channels under low pressure condition are fairly crucial phenomena relative to thermal-hydraulic design and safety analysis for pool-type research reactors. It has been recommended that RRs and MTRs be designed to have sufficient margins for CHF and the onset of FI as well [1], since unstable flow could leads to premature CHF under very low wall heat flux in comparison to stable CHF. Even the fact and previous studies, however, the understanding of relationship among FI, premature CHF and stable CHF is not sufficient to date.

In this regards, subcooled flow boiling in a vertical rectangular channel was experimentally investigated to enhance the understanding of the CHF and the effect of the two-phase flow instability on it under low pressure conditions, especially for downward flow which was adopted for Jordan Research and Training Reactor (JRTR) and Kijang research reactor (KJRR) to achieve easier fuel and irradiation rig loading [2].

2. Experimental apparatus and procedures

An experiment on the flow boiling of water under atmospheric pressure was performed using the KAIST flow boiling loop, as shown in Fig. 1. The components and whole configurations were similar to the loop in the previous work [2] for flow instability except the boundary condition of test section part. Since the details of the components and test section were provided in the previous work, the modified part was mainly described here. First, instead of opening top of test section part to the ambient air, the top was closed and an open pool was newly installed at the exit of the channel. As a result, the channel exit pressure were maintained at atmospheric pressure. Second, the experiment in the present study conducted for various configurations of plenum to investigate plenum effect on critical heat flux for downward flow as shown in Fig.2; large plenum (9.4 liters), small plenum (0.8 liters) and without plenum cases. Small plenum case could be easily obtained by installing an interceptive panel in the middle of large plenum with bolting. Finally, throttling valve and a pressure transducer were installed to stabilize flow by adding inlet throttling and measure pressure drop across the throttling valve to quantify the additional inlet stiffness, respectively.

The experiment procedures were as follows: The loop was filled with deionized (DI) water by using supply pump. Completion of filling was checked by opening venting valves on the top of main components such as surge tank, pre-heater and test section part. Prior to the experiment, the liquid was circulated and allowed to boil owing to the preheater for half an hour to expel any non-condensable gas, which was removed via the opening of a needle valve and the venting valves. Furthermore, the power was supplied to the test section and nucleate boiling on the surface of heater was induced to remove any entrapped air in the heater itself. After the deaerating process, the flow loop components were adjusted to set the desired operating condition including inlet subcooling, mass flux, and throttling. Inlet temperature was controlled and maintained in feedback process through a proportional-integral-derivative (PID) system, which is connected to power and a thermal couple installed in the pre-heater. A centrifugal pump and upstream throttling valve were used to establish downward flow in a channel for desired mass flux and additional stiffness condition, which were measured an electromagnetic flow meter and pressure transduces across the valve. Then, a stepwise heating power escalation in the test section was initiated by slowly increasing the voltage of the test section. The increment of heat flux between two consecutive runs was ~20 kW/m^2 and all experiment parameters were monitored and recorded by data acquisition system. Each step took enough time to achieve steady state. The CHF condition is defined as a sudden increase in the temperature of the test section.

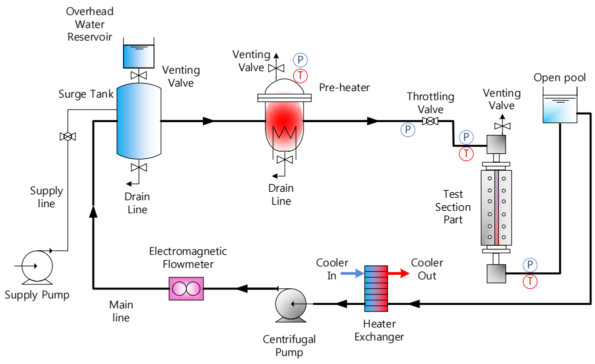

Fig. 1. Schematics of the KAIST flow boiling loop

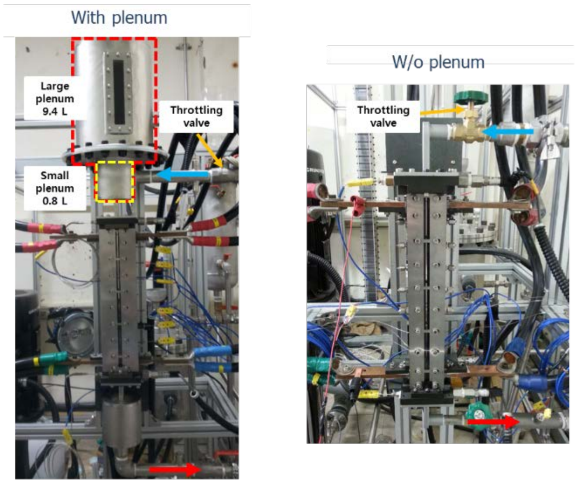

Fig. 2. Photographs of the test section part with and without plenum

3. Results and Discussions

3.1 Experimental results

Downward flow CHF data in a narrow rectangular channel with size of channel as shown in Table 1 were gathered for various fluid condition (Table 2). As reported in previous work, the onset of pressure drop fluctuation (OPDF) at which channel pressure drop begin to fluctuate with distinguishable amplitude could be identified. In addition, premature CHF were triggered at the maximum amplitude of fluctuation due to insufficient throttling as reported previously. Therefore, premature CHF and stable CHF were recognized each other by analyzing trends of pressure drop fluctuation with the same way from literature [3]. 24 CHF data were identified as stable one among 54 data.

Table 1: Channel dimension

Channel dimension	Width of clearance (heated)	40 mm (30 mm)
	Gap size	2.35 mm
	Channel length	350 mm

Table 2: Summary of OPDF and CHF data

	Inlet temp. (°C)	**Pressure (bar)**	**G (kg m^{-2}s)**	**X_e (-)**	**q“ (kW m^{-2})**	**Data num.**
OPDF	24~43	1.1~1.3	211~1290	-0.106~ -0.033	99~998	**50**
CHF	26~56	1.0~1.2	228~1286	-0.083~ 0.120	199~1598	**54**

3.2 Parametric trends

Mass flux and inlet subcooling effect on stable CHF were depicted in Fig. 3 and 4. As reported in previous works, CHF linearly increased as mass flux and inlet subcooling increased in a rough way. Therefore, the linear relationship between CHF and mass flux/inlet subcooling could be dealt with for development of empirical correlation predicting present experiment data as well.

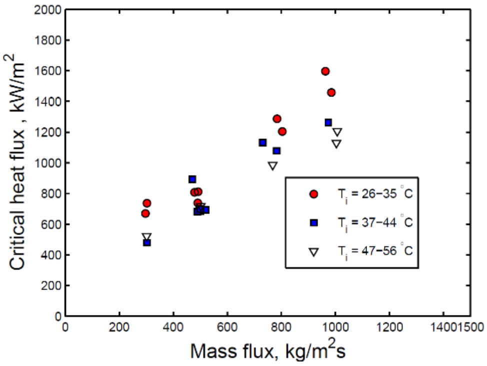

Fig. 3. Mass flux effect on stable CHF for various inlet subcooling conditions

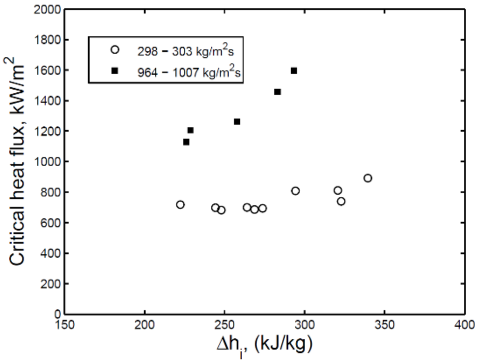

Fig. 4. Inlet subcooling effect on stable CHF for mass flux of 298-303 kg/m^{2}s and 964-1007 kg/m^{2}s

3.3 Correlation development

As reported previous work [3], the lowest premature CHF were strongly related to occurrence of OPDF and well predicted by the correlation of the onset of flow excursion instability (OFI) proposed by Lee et al. (2013) for OFI data for mass-flux-controlled conditions [2].

$$G_{OFI} = (G_{sat} + 27)/0.58 \tag{1}$$

where,

$$G_{sat} = \frac{P_H L_H q''}{A C_{pl}(T_{sat} - T_i)} \tag{2}$$

In the present work, the number of OPDF data were enlarged and compared with the correlation as well. As shown in Fig. 5, the correlation was well predicting the OPDF data, which gathered heat-flux-controlled system for various experiment conditions including inlet throttling. The mean absolute error (MAE) and root-mean-square error (RMSE) were calculated by 16.7% and 20.2%, respectively.

To develop the empirical correlation for present stable CHF data, we utilized the factor, $A/A_H G\Delta h_i$ since stable CHF showed linear relations with mass flux and inlet subcooling. And new empirical correlation of stable CHF for downward flow in a narrow rectangular channel was proposed.

$$q''_{CHF} = 0.93\frac{A}{A_H}G\Delta h_i + 213.2 \qquad (3)$$

The new empirical correlation showed best performance among correlations for all interest range of mass flux and inlet subcooling in the present data, which performance was estimated by a MAE of 8.3% and RSME of 10.0%.

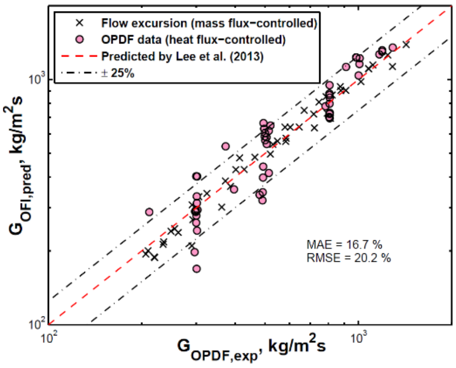

Fig. 5. Comparison OPDF data with OFI correlation proposed by Lee et al.

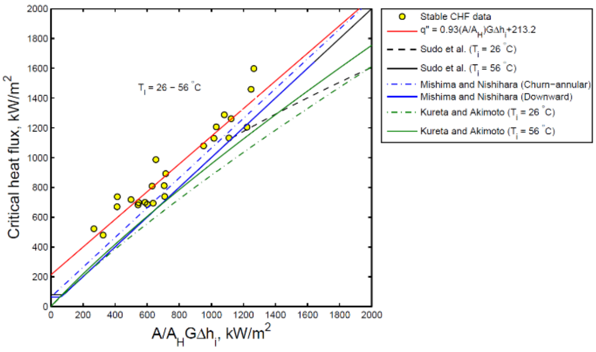

Fig. 6. Comparison stable CHF data with various correlations including new correlation

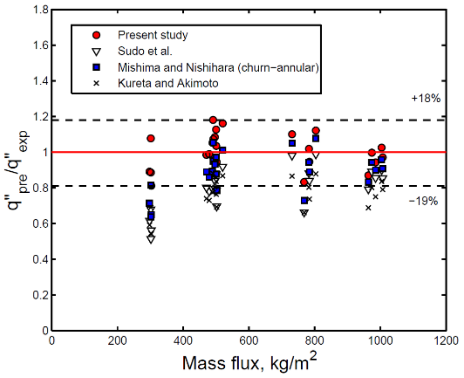

Fig. 7. Predicted CHF over experiment CHF Vs. mass flux for various correlation

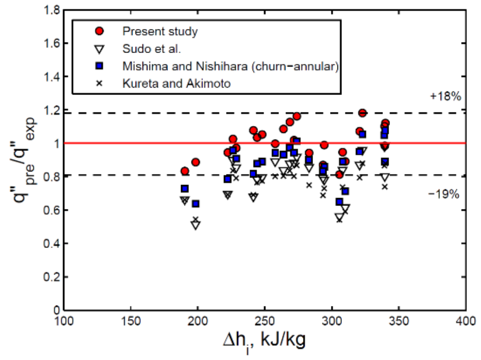

Fig. 8. Predicted CHF over experiment CHF Vs. inlet subcooling for various correlation

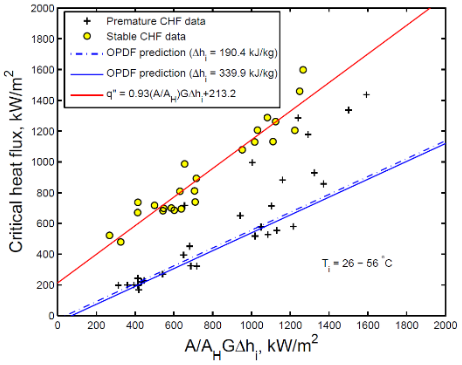

Fig. 9. Boundaries of CHF condition for downward flow in narrow rectangular channel eq. (1) and (3). Premature CHF could occur

Fig. 9 showed all CHF data including premature and stable one, which was recognized by analysis of pressure drop fluctuation. As shown in the figure, the upper and lower boundaries of CHF were well predicted by eq. (1) and (3). Premature CHF was triggered when system resistibility, which could be enhanced by inlet throttling, was insufficient to endure pressure drop fluctuation caused by vigorous boiling. As a result, premature CHF was lower than stable CHF.

3.4 Material and plenum effect

As described above, CHF data was gathered for various system configuration including with small/large or without plenum to check plenum effect on CHF. In addition, more CHF data were obtained with different heater material, invar instead of stainless 304. Consequently, any effect of material and plenum effect on OPDF and stable CHF was not found in this study.

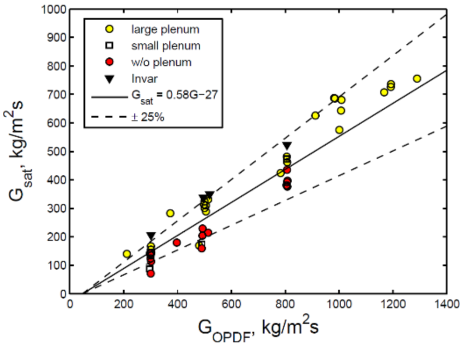

Fig. 10. Material and plenum effect on OPDF

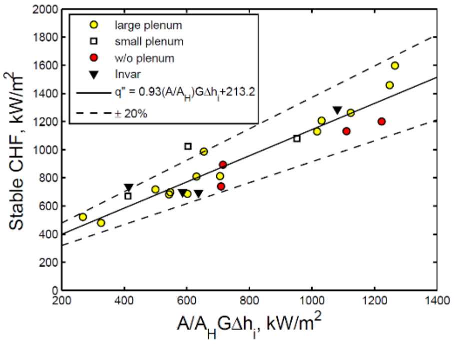

Fig. 11. Material and plenum effect on stable CHF

4. Concluding remarks

In this study, CHF for downward flow of water under low pressure in narrow rectangular channel was experimentally investigated. For conditions such as downward flow, narrow rectangular channel and low pressure, it has been deduced from literature that flow instability could largely influence on triggering CHF at lower heat flux, i.e. premature CHF. However, systematic investigation of premature and stable CHF for downward flow in narrow rectangular channel nonsexist. Total 54 CHF data, which includes premature and stable data was obtained for various fluid conditions and system configurations including inlet stiffness. The upper and lower boundaries of CHF were newly proposed based on the experiment.

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