The effect of subcooling on critical heat flux along a slightly inclined downward-facing heater plate

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1. Introduction

Compared to inconsistent reports on nucleate boiling characteristics, it has been consistently reported that liquid subcooling enhances critical heat flux (CHF). CHF can be presented as a linear function of liquid subcooling. Such a linear relationship between liquid subcooling and the CHF was observed in numerous experimental studies when various fluids were adopted, such as water, HFE7100, PF5060, FC72, FC86, R113, methanol, and isopropanol, and when several heater configurations were adopted, such as an upward-facing heater, vertical plate, and horizontal wire.

Positive linearity between the liquid subcooling and resulting CHF could also be confirmed in case of downward-facing heater. Note that El-Genk and Parker [1] studied the combined effect of heater orientation and liquid subcooling and showed that the subcooling effect was rapidly diminished when the heater orientation changed from 30° to 0° (downward-facing horizontal surface). However, it should be noted that aforementioned works used either very small or curved heaters. Thus, their work might obfuscate the complex physics associated with heater size.

Only Sulatskii et al. [2] thoroughly investigated the effect of subcooling on the CHF at various subcooling degrees on a large downward-facing flat heater with a slight inclination. Interestingly, a nonlinear characteristic between subcooling and the CHF was observed in their work. They discovered a regime in which subcooling negatively affected the CHF. This unusual instance of CHF dependence on subcooling was simulated in their CHF model by incorporating the negative influence of subcooling on local mass flow rate along the heater surface. Specifically, a term representing single-phase heat transfer to the subcooled liquid was added in calculation of the vapor mass flow rate. Their CHF model could successfully predict the anomalous dependence of subcooling on the CHF observed in their experiments. Note that the anomalous dependence can be interpreted as a weak contribution of the additional sensible energy needed to heat the subcooled liquid to a saturated state. Another interpretation may be thought of as a strong contribution of vapor layer motion on the CHF. It is apparent that a strong vapor layer motion contribution comes from the large geometry of the heater surface.

The purpose of this work is to present experimental data for the CHF on a flat, downward-facing surface at various subcooling conditions to investigate the influence of subcooling on boiling heat transfer. An effort was made to examine the two-phase instability including the condensation induced water hammer (CIWH) observed in the present study, and also to investigate their influence on the CHF. Detailed research content can be found in the paper of Jeong and Kim [3].

2. Experimental apparatus

In order to achieve a stable formation of large vapor slug and its sliding motion, length and width of heater were determined as 216 mm and 108 mm, respectively. Figs. 1 and 2 present the sectional view of the test section and the forced convective water boiling loop, respectively.

The test section contains a copper heating block which is a heat source. Tangential plane of the heater surface in contact with water is inclined 10 degree from the horizontal, and the heater surface faces downward.

Local heat flux and temperature gradient were calculated using a three-point backward space Taylor series approximation. Many thermocouples were installed in the heater block by drilling micro-holes. The absolute uncertainty of the surface temperature was calculated as ±0.6K.

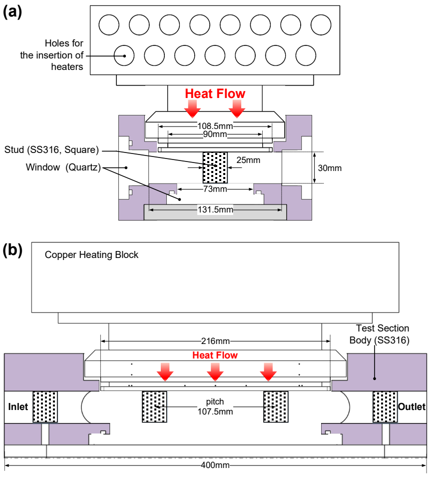

Fig. 1. Sectional views of the test section; stud structures were eliminated in this study.

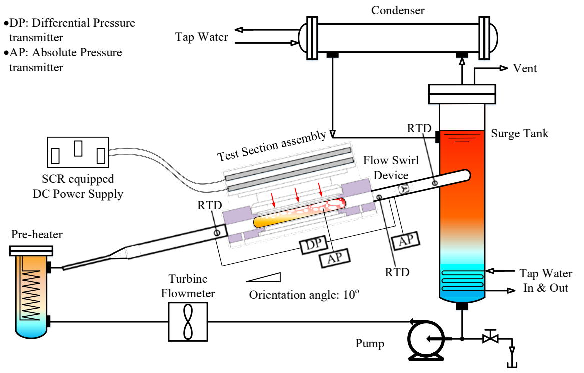

Fig. 2. Simplified schematic of the boiling loop.

3. Results

3.1 Influence of subcooling on CHF

The present subcooled boiling data under the pool boiling condition (G=40 kg/m^2-s) are compared to the CHF models of Brusstar and Merte, Sulatskii et al., and He et al. in Fig. 3. Subcoolings of 5, 10, 15, and 20 K were applied to investigate the effect of subcooling on the CHF under the pool boiling condition. The subcooling effect appeared in two types of trends. One is a rather linear relationship between the subcooling degree and the CHF, which was also observed in the CHF models of Brusstar and Merte and He et al. The other is a weak dependence of subcooling on the CHF, which appeared in the present study and the CHF model of Sulatskii et al. The non-linear dependence of CHF on subcooling was observed in work conducted by Sulatskii et al., which shows the existence of a minimum CHF under a subcooling of approximately 20 K. For up to 15 K subcooling, the present subcooled CHF data are comparable with the trend observed in the CHF model developed by Sulatskii et al., and is also consistent with the adverse effect of subcooling on velocity of two-phase boundary layer flow.

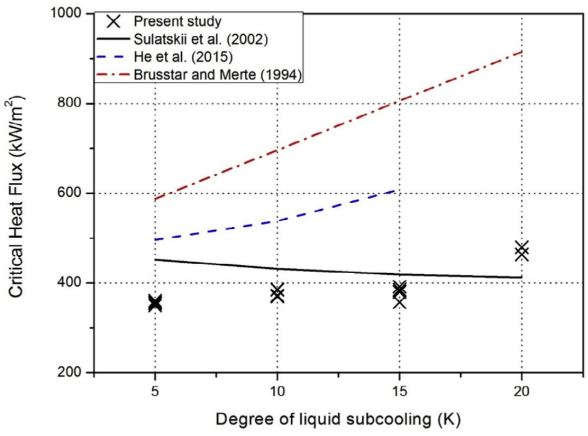

Fig. 3. Dependence of the CHF on degree of subcooling.

The large discrepancy in the trends can be explained by examining the heater configuration used in the CHF experiments. Brusstar and Merte used a small heater, and thus the departing bubbles could quickly escaped from the heater surface to the surrounding bulk liquid region in an isolated form. This was possible because of weak bubble coalescence phenomenon along the heater surface, even at a high heat flux condition.

A notable feature was observed in Fig. 3; an abrupt increase in the CHF value occurred when the liquid subcooling changed from 15 to 20 K. This can be explained based on the characteristics of bubble behavior. When the liquid subcooling increases from 15 to 20K, the sliding bubble motions prevalent in the two-phase boundary layer were observed to decrease substantially, and thus the bubble coalescence process was weakened. The resulting phase distribution near the surface with less vapor fraction is obviously favorable for the liquid supply process because of the enlarged cooling path through which liquid is supplied to the heater surface from the bulk region. In this way, the considerable increase in CHF value can be explained by examining the transition of the flow pattern.

However, it should be noted that the repetitive flow reversal phenomenon with pressure oscillation appeared in the subcooled boiling experiments, as mentioned in the introduction. Such a transient phenomenon in two-phase flow should be considered when analyzing the observed abrupt increase in the CHF value with increase in subcooling from 15 to 20 K.

3.2 Transient two-phase flow and its influence on the CHF

A violent boiling process was observed in the present experiment beyond a specific subcooling and heat flux. The violent boiling phenomenon is characterized by the repetition of rapid growth of a large bubble, and its condensation at the unheated downstream channel. The rapid condensation of a large bubble causes flow reversal and pressure oscillation with sporadic pressure shocks. This violent boiling phenomenon appears similar to geysering, as explained by Ruspini et al. In the present study, the observed sporadic pressure shocks can be regarded as the condensation induced water hammer, even though its amplitude was confirmed to be insufficient to break the pipeline. This is because the experimental facility in the present study experiences substantial mechanical loadings, such as vibration of the entire boiling loop when sporadic pressure shocks appear. Thus, the experiment should be stopped for the integrity of the facility.

The simultaneous occurrence of the flow reversal and pressure shock is regarded as a notable transient behavior that is responsible for the abrupt change in the CHF with the increased subcooling. Note that the flow reversal is concentrated near the heater surface. Thus, the bubbles hovering right above the heater surface can be effectively mixed with the reversed subcooled liquid and condensed therein. Furthermore, the sporadic pressure shocks with rather large amplitudes were observed to contribute to condensing the bubbles and suppressing bubble growth by significantly increasing the saturation temperature. In this way, the bubbles covering most of the heater surface can be eliminated instantaneously, which in turn facilitates the liquid supply to the heater surface. As a result, the heater surface can be effectively cooled down and a higher CHF can be achieved.

4. Conclusions

Up to subcooling 15 K, a weak dependence of CHF on the subcooling was observed. This result is consistent with the experimental results from Sulatskii et al. The subcooling provides an adverse effect on velocity of the two-phase boundary layer flow and correspondingly degrades an entrainment process behind the sliding bubble, through which the bulk liquid is pumped into the heater surface.

The repetitive flow reversal phenomenon with pressure shock appeared owing to rapid condensation at the unheated section right after the test section. Such phenomenon is considered to be responsible for the observed abrupt increase in the CHF with an increase in subcooling from 15 to 20 K. This is because the flow reversal and pressure shock effectively eliminated the large amount of vapor hovering right above the heater surface.

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