AN EXPERIMENTAL STUDY OF CRITICAL HEAT FLUX IN A TUBE FOR NEAR-CRITICAL PRESSURES

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Abstract

The experiment of critical heat flux was conducted in a tube of inner diameter of 7.95 mm and heating length of 0.8 m with water flowing upward, covering the ranges of pressure of 8.6 – 20.9 MPa, mass flux of 447 – 1179 kg/m^{2}s, outlet subcooling of 1 – 96 K and critical heat flux of 0.69 – 3.68 MW/m^2. The CHF characteristics and parametric trends are studied, and the experimental results are compared with the predictions of 96 CHF Look-up Table.

1. Introduction

The critical heat flux (CHF) is referred to a boiling crisis, in which the wall can no longer support continuous liquid contact, characterized by a sharp rise in the surface temperature. It is very important to the reactor safety because the occurrence of boiling crisis could lead to a failure of fuel element. For the supercritical water-cooled reactor (SCWR), in startup and shutdown periods or accident conditions, the system will experience subcritical pressure, and the accurate estimation of critical heat flux is a concern.

During past five decades the critical heat flux has been investigated extensively over the world theoretically and experimentally, and a great number of correlations and physical models have been proposed. In recent years the look-up table method is widely accepted due to its higher accuracy and convenience for application and updating, and is adopted in the reactor safety analysis code RELAP5 [1]. A comprehensive review on these studies has been given in the IAEA document [2]. In general, because of the complexity of the phenomena and the lack of adequate knowledge of the mechanism, all these prediction methods are heavily relied on the experimental data base.

In recent years more attention has been paid on the experiments of CHF for near-critical pressures due to its importance to the safety of SCWR. They include the experiments of R-136a by Vijayarangan et al. [3], Hong et al. [4], Chun et al. [5] and the experiment of water by Yin et al. [6]. In general, the data are not adequate to validate the prediction methods, and at present the CHF can not be predicted with confidence for the near-critical region.

In the present study an experiment on critical heat flux in subcooled boiling of water was performed in a tube for near-critical condition, aiming at getting more insight into the characteristics and collecting more needed data for verification of the existing prediction method.

2. Experimental facility and procedure

The test section is a stainless steel tube of inner diameter of 7.95 mm and outer diameter of 10mm with water flowing upward inside. It has a heating length of 0.8 m with a leading un-heating length of 0.5 m for full development of hydraulic condition. Previous to the occurrence of CHF the wall is at subcooled boiling with relatively uniform temperature along the length, providing essentially uniform heat flux.

The experiment was performed at a supercritical water loop in China Institute of Atomic Energy. As shown in Fig. 1, the de-ioned water was supplied by a three-head piston pump with a maximum pressure of 45 MPa and a flow rate of 2.4 m^3/h. It passed a dumping tank, a preheater, and flowed upward through the test section, sequentially. Then it was cooled by heat exchangers, and finally flowed back to the pump. The flow rate of the test section was controlled by the valves in the bypass and main path, and the inlet temperature was controlled by the power to preheater. The test section was heated by a DC supply with capacity of 7,000 A×65 V, and the preheater was heated by a AC supply. With this system the experiment can be performed at stable conditions.

The major measurements of the parameters include: the outlet pressure by a pressure transducer (DCY-1151), the flow rate by a turbine flow-meter (LWGY-6), the inlet and outlet water temperatures of the test section by NiCr-NiSi thermocouples and the voltage and current across the test section. In addition, six thermocouples were installed on the outer surface of test section to measure the wall temperatures at different locations. All the readings were recorded by a data acquisition system. The occurrence of the boiling crisis was detected by photocells near the top of test section.

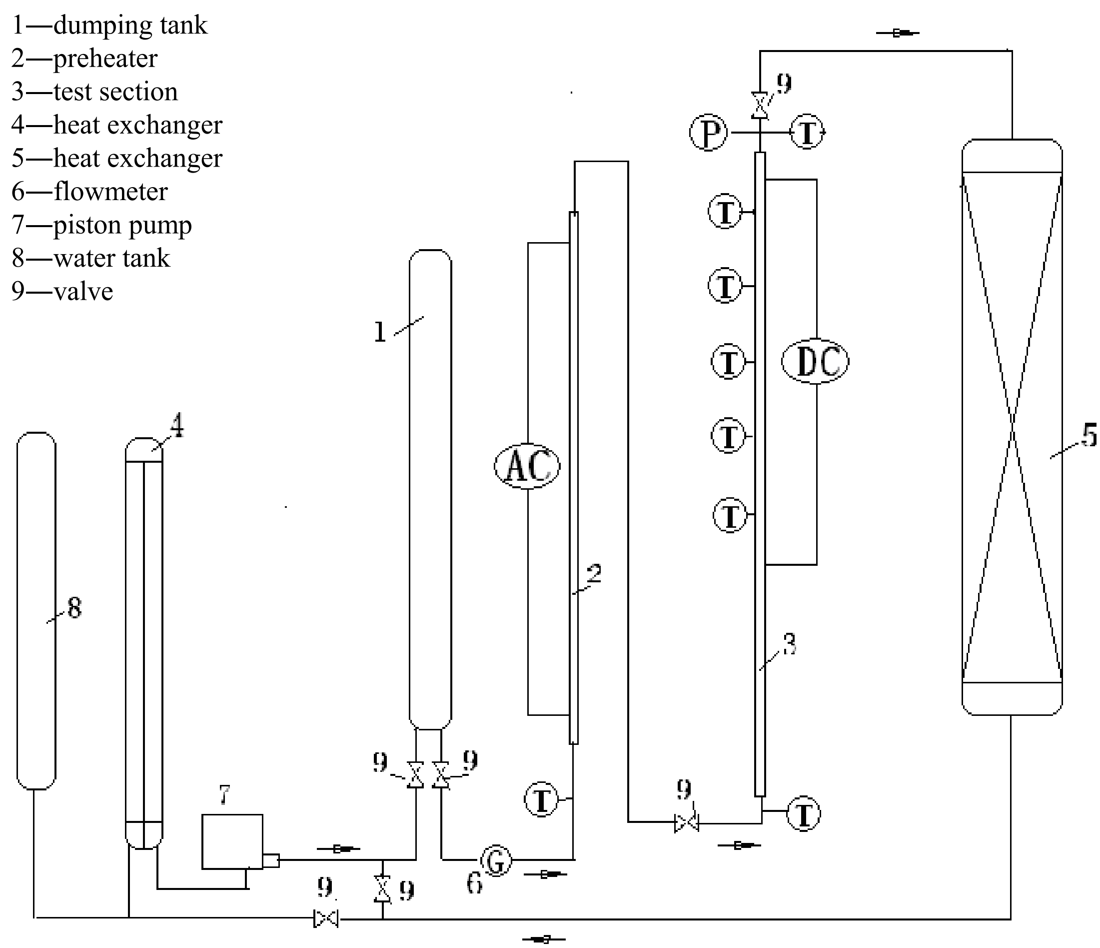


Figure1 Schematic diagram of test loop

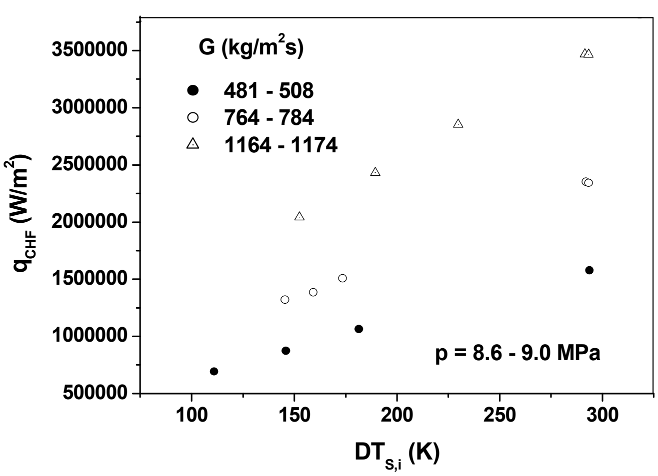
During test, at first the desired pressure, flow rate and inlet temperature were established. Then, the power to the test section was switched on. The boiling crisis was approached by increasing the power to the test section step by step, keeping the pressure, flow rate and inlet temperature at constant. When the condition was close to the onset of CHF the increase of power for each step was less than 0.5% until the occurrence of boiling crisis was detected by photocell, which switched off the power to the test section. The heat balances of all runs were within 3% with majority within 1.5%.

3. Experimental results

The experimental data were obtained over the range of pressure of p = 8.6 – 20.9 MPa, mass flux of G = 447 – 1179 kg/m^{2}s, inlet subcooling of $DT_{S,i}$ = 111 – 347 K, outlet subcooling of $DT_{S,o}$ = 1 – 96 K and the critical heat flux of q_{CHF} = 0.69 – 3.68 MW/m^2. The results are shown in Fig.2 and 3 by displaying q_{CHF} versus $DT_{S,i}$ or $DT_{S,o}$.

It was observed in the experiment that, at a fixed heat flux before the CHF the wall temperature was quite stable. For pressure of below 18 MPa, the onset of CHF was characterized by an abrupt jump of the wall temperature near the exit of test section, as was caught by photocells. Just previous to it some flow instability was observed. For higher pressure, when the heat flux reached a certain high level the wall temperature was not stable, but behaved a slow increase (or excursion), characterizing the heat transfer deterioration or crisis.

As seen from Fig.2, for fixed pressure and mass flux the increase in the inlet subcooling results in an increase in the critical heat flux. For lower pressure, the CHF occurs at relatively small local subcooling and exhibits a steep increase trend with the increase of local subcooling. For p = 8.6 – 9.0 MPa with G < 508 kg/m^{2}s, for instance, the increase in $DT_{S,i}$ from 111 to 294 K results in the increase of q_{CHF} by about 130% with the $DT_{S,o}$ varied from 1 to 13 K. The slope of $q_{CHF} \sim DT_{S,o}$ is decreased for higher mass flux or higher pressure, and for p > 18 MPa the trend becomes mild.



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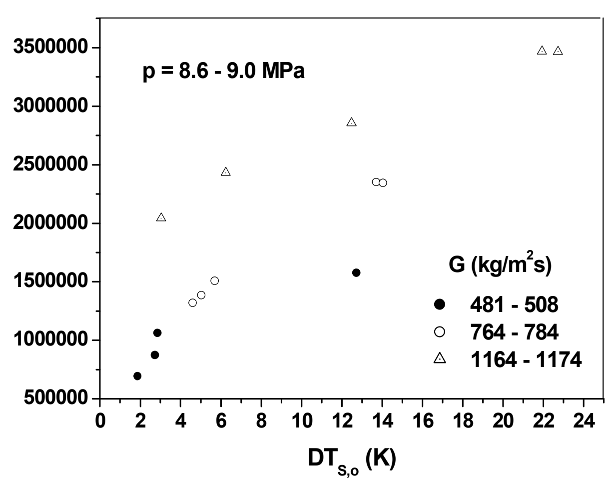

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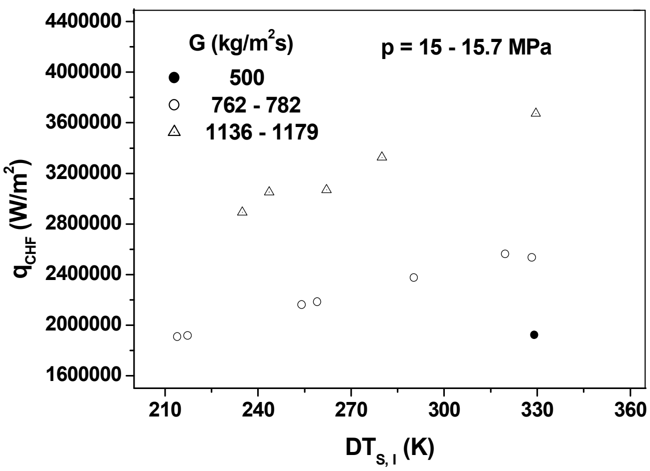

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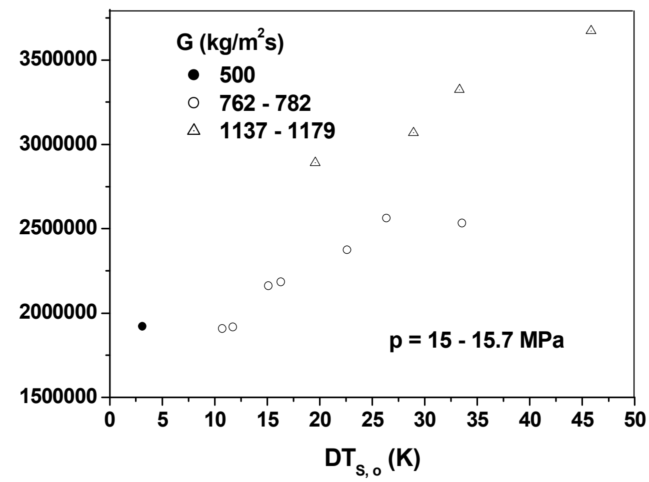

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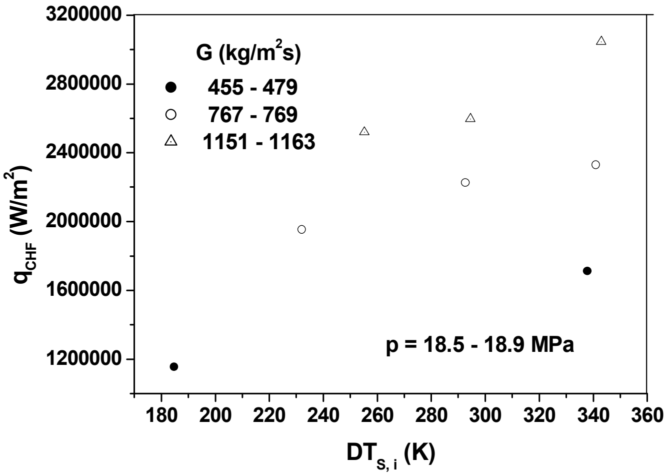

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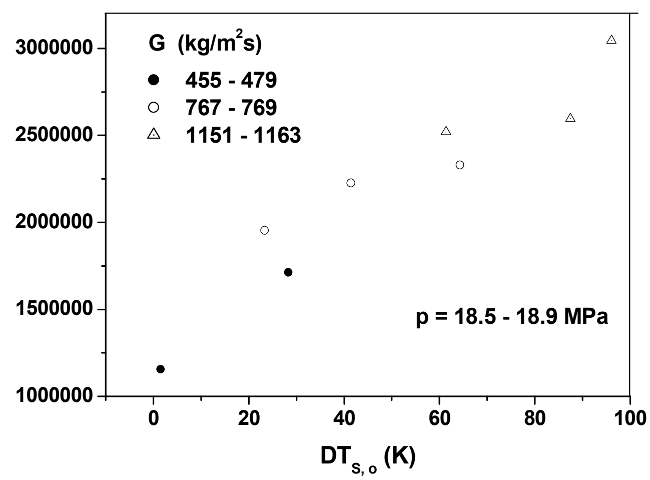

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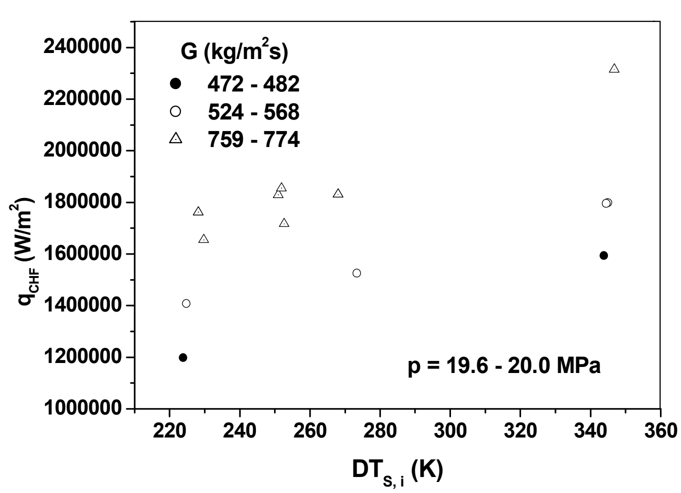

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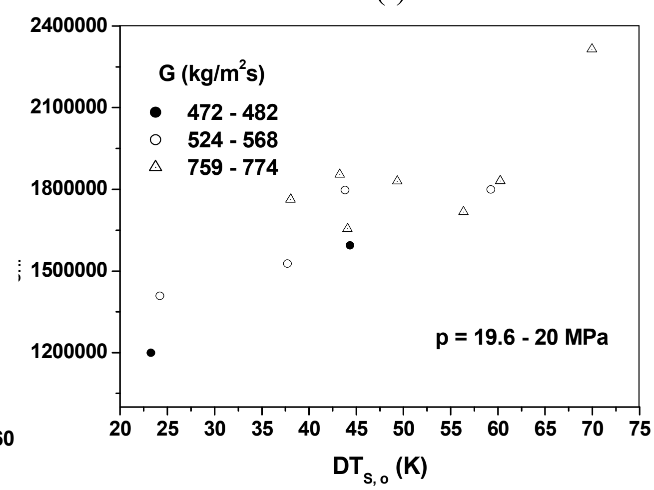


(h)

Figure 2 Variations of the CHF with $DT_{S,i}$ and $DT_{S,o}$ for different mass fluxes and pressures

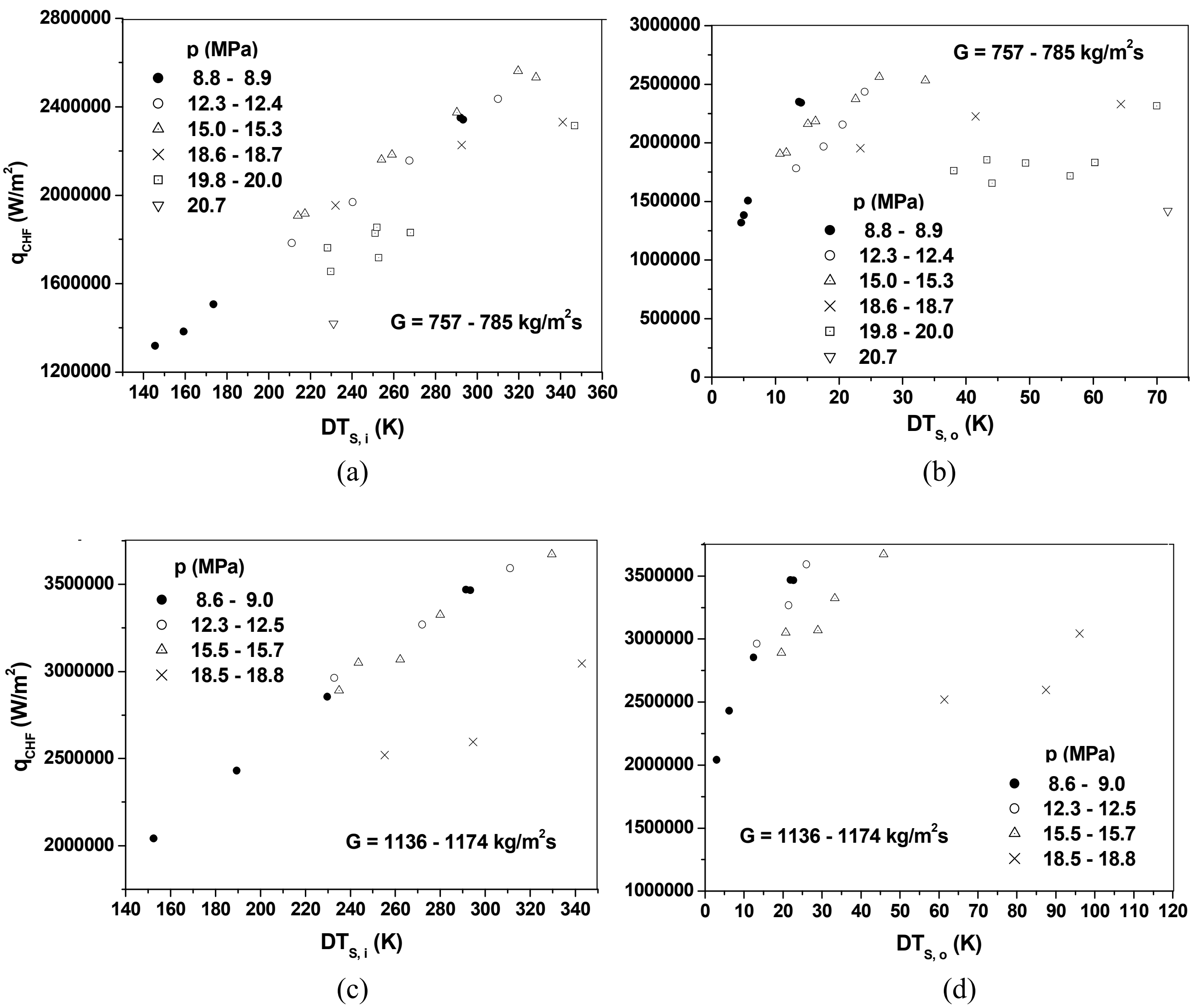


Figure 3 Effect of pressure on the critical heat flux

It is observed from the figures of $q_{CHF} \sim DT_{S,\,i}$ that for fixed inlet subcooling the CHF increases as the mass flux increasing. While from the figures of $q_{CHF} \sim DT_{S,\,o}$, at higher pressure the effect of mass flux appears not so distinct for fixed $DT_{S,o}$.

The effect of pressure on the CHF is shown in Fig.3. In the region of $p < 16$ MPa the difference in the CHF between different pressures appears not appreciable for same $DT_{S,\,i}$ and G. While for higher pressure the CHF tends to decrease, and at near–critical pressure with similar $DT_{S,\,i}$ and G, substantially lower CHF is obtained with larger local subcooling. This result is consistent with that observed in the similar experiments [4 – 6].

4. Discussions

In a subcooled flow boiling the surface is covered by a bubbly layer, and the heat is transferred from the wall to the bubbly layer, subsequently to the liquid core. An excessive increase in the bubbles serves as a thermal shield, leading to deteriorated heat transfer or boiling crisis. Two major mechanisms of the boiling crisis are generally identified: (i) limiting heat transfer capability from the interface of bubbly layer to the subcooled liquid core, and (ii) critical enthalpy in the bubbly layer near the wall [7]. The first one occurs at higher subcooling and higher mass flux, in which the thickness of bubbly layer is very small and the heat for increase of the enthalpy of bubbly layer is negligible small. For this condition the wall heat flux is high and nearly all the wall heat flux is transferred through the bubbly layer to the liquid core. The limit of heat transfer to the liquid core can result in a drastic increase in the bubble generation, leading to a crisis of heat transfer. Therefore this type of CHF is local heat flux dominant. The second one occurs at low mass flux and low subcooling, in which the heat exchange from the bubbly layer to the liquid core is less efficient and the local enthalpy or quality of bubbly layer near the wall is the integrated result of the heat exchange upstream. Therefore, the CHF is dominated by the total power.

In the present experiment, the CHF of lower pressure with lower mass flux is likely total power dominant. For the inlet subcooling varying over a wide range the CHF occurs at small local subcooling, and the power for the test section to reach the saturation condition is a measure, as accounted by

$$q_{CHF} = Cq_s \qquad (1)$$

with

$$q_s = \frac{(H_s - H_i)GD}{4l}$$

where H_i and H_s are the inlet enthalpy and saturation enthalpy, respectively, G is the mass flux, D the diameter and l the heating length. The results of lower pressure with lower mass flux are represented by Eq.(1) with C = 0.9 – 1.0.

This equation suggests the primary importance of the mass flux, inlet temperature and heating length to the CHF. The heat flux increases as the inlet subcooling increasing, associated with an increase in the gradient of enthalpy over a cross section. For the same enthalpy near the wall a higher heat flux corresponds to a lower average temperature. This type of CHF occurs at near saturation condition, and larger increase in the CHF with $DT_{S,i}$ corresponds to a relatively small increase in the $DT_{S,o}$, as observed in the experiment.

Eq.(1) clearly shows the increase of CHF with mass flux for fixed inlet subcooling. For fixed local subcooling, however, higher mass flux would correspond to higher inlet enthalpy, so that under certain conditions the trend of the CHF with local subcooling appears not distinct.

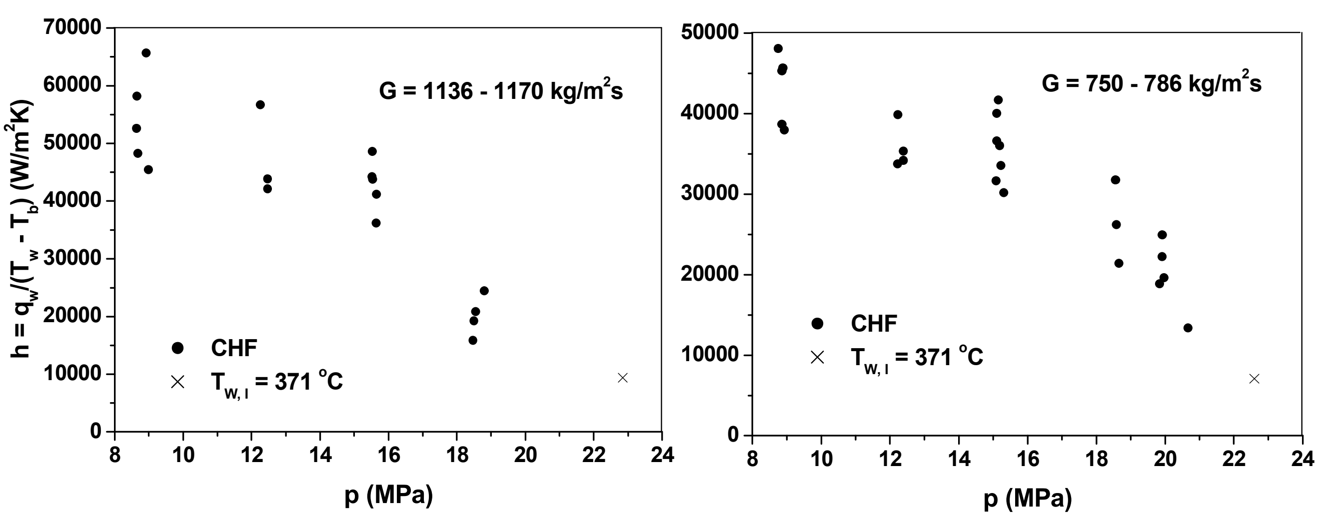
For higher subcooling with higher mass flux the heat flux is higher due to higher heat transfer efficiency to the liquid core, and the domination of local heat flux for the CHF is increased. Under this condition, higher CHF is obtained at higher local subcooling, and the trend of $q_{CHF} \sim DT_{S,o}$ is not so steep as in low flow.

Compared to lower pressure, for p > 18 MPa with similar inlet temperature and mass flux much lower

CHF is obtained at higher local subcooling. It would be the result of the difference in the bubble behavior, and can be understood from the results of heat transfer coefficients. Fig.5 illustrates the variations of h (= $q_{CHF}/(T_w-T_b)$) with p. In this figure the h is obtained from the measured wall temperature just previous to the onset of CHF at the location of 8 cm from the top end of the heating length, and the heat transfer coefficient at supercritical pressure with the wall temperature (T_{Wi}) just below the critical point is compared. Note that for similar p and G the h varies with $DT_{S,o}$ and higher h corresponds to lower $DT_{S,o}$. As seen from the figures, the heat transfer coefficients exhibit a general decrease trend with the increase of pressure, and in the near-critical region the h decreases more sharply and converges to that of supercritical pressure. Fig.6 illustrates the variation of the heat transfer coefficient with mass flux. As seen, for p < 16 MPa the h increases with mass flux, while for p > 18 MPa it exhibits an opposite trend.

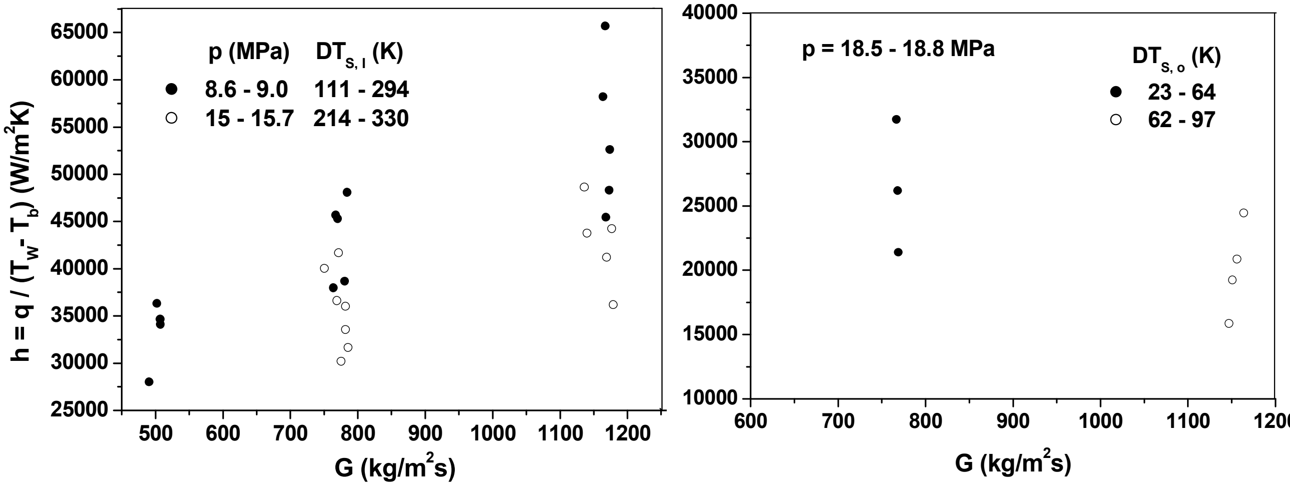
In subcooled boiling several mechanisms are identified for the substantial enhancement of heat transfer coefficient: (i) heat transfer by the latent heat of bubbles, (ii) micro-layer evaporation, (iii) micro-convection by bubble agitation, and (iv) single-phase convection between patch of bubbles [7]. At near-critical pressure the latent heat and surface tension are decreased substantially, so the bubble size is much smaller and the enhancement effects by all these mechanisms would be diminished, associated with lower heat transfer coefficient and lower CHF.

In the experiment it was noted that for fixed pressure, mass flux and inlet temperature, after certain runs of tests lower critical heat flux could be obtained with lower local temperature, especially for p > 16 MPa. This could be attributed to the variation of the surface condition caused by deposit. It is generally accepted that the improved heat transfer can be obtained on a boiling surface with porous deposit as a result of increase in the number of nucleate sites [7]. In the present experiment, however, an adverse effect was observed in the near-critical region. This can probably be explained by the fact that at high pressure the bubble is very small, especially at higher flow and higher subcooling, so that the surface imperfection or deposit could have a restriction effect on the movement of the bubbles on the surface, resulting in a reduction of heat transfer coefficient and the CHF. This result indicates that for near-critical pressure the effect of surface condition on the CHF could be appreciable. For this consideration, in the present experiment the test section was wiped with acetone after every 3 – 5 runs. By this procedure, the results showed better repeatability.



(a) (b)

Figure 4 Heat transfer coefficient just previous to the onset of CHF for different pressures
($DT_{S,i}$ = 111 – 347 K)

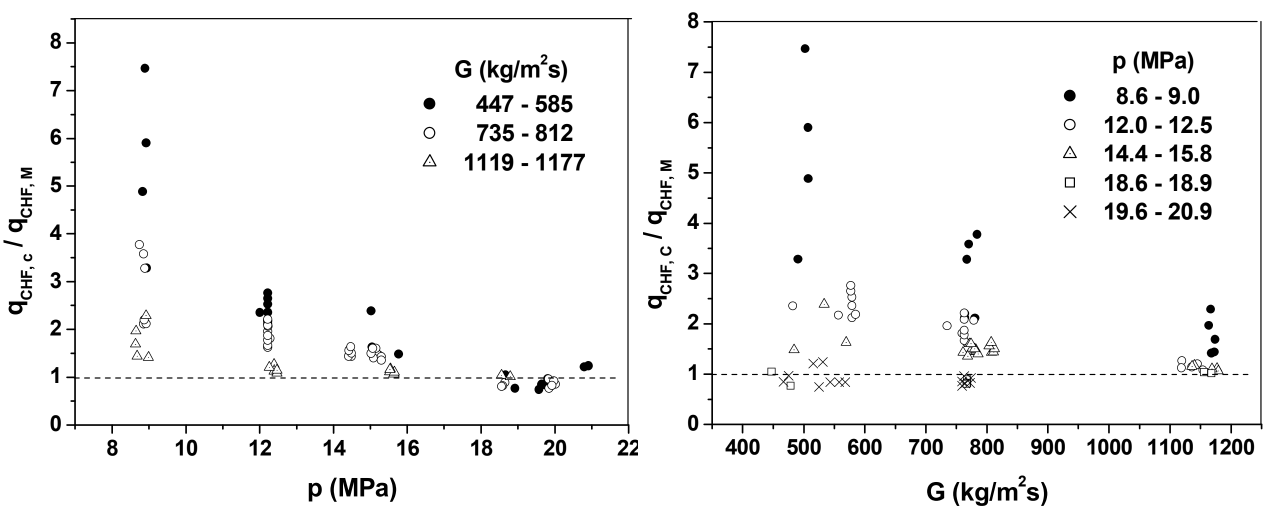


(a) (b)

Figure 5 Heat transfer coefficients just previous to the onset of CHF for different mass fluxes

5. Comparison

In the reactor safety analysis code RELAP5 a look-up table is adopted to predict the critical heat flux [1]. It was based on the data in tube of D = 8mm, and represents the critical heat flux with a tabulation at discrete local parameters of pressure (0.1 – 20 MPa), mass flux (0 – 8000 kg/m^{2}s) and quality (-0.6 – 1.0). In Fig.6 the present experimental results are compared with the predictions of the 96-CHF look-up table [8] by the ratio of $q_{CHF,C}$ / $q_{CHF,M}$ versus p and G ($q_{CHF,C}$ and $q_{CHF,M}$ are the calculated values and measured values, respectively). As seen, for G > 1000 kg/m^{2}s and p > 18 MPa, the experimental data are close to the predictions. While for lower pressure with lower mass flux the deviation is increased. At this condition the steep trend of CHF with local subcooling (or quality) is not predicted properly by the table, and at low mass flux with low subcooling the experimental data are overpredicted substantially.



(a) (b)

Figure 6 Comparison of the present experimental results with predictions of 96-CHF Look-up Table □x_o = -0.01 - -0.85□

6 Conclusions

An experiment of critical heat flux in subcooled boiling of water has been performed in a tube of inner diameter of 7.95 mm and heating length of 0.8 m with water flowing upward, covering the ranges of pressure of 8.6 – 20.9 MPa, mass flux of 447 – 1179 kg/m^{2}s and local subcooling of 1 – 96 K. Under these conditions the following conclusions are drawn:

- The critical heat flux increases as inlet subcooling and/or mass flux increasing. At lower pressure and lower mass flux the CHF occurs at small local subcooling with steep increase trend of $q_{CHF} \sim DT_{S,o}$, characterizing the mechanism of total power dominant. At increased mass flux and/or pressure the slope is decreased.

- In the region of $p < 16$ MPa the effect of pressure on the critical heat flux is not appreciable. While as the pressure increases toward to the critical point, the critical heat flux tends to decrease substantially.

- In the near-critical pressure region the heat transfer coefficient is decreased considerably, especially for increased mass flux and subcooling.

The present experiment has shown an appreciable effect of the surface condition on the critical heat flux. It will be studied further in the experiment with different material over extended range of conditions.

7. Acknowledgement

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8. References

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