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Pressure Effects on Critical Heat Flux under Low Pressure and Low Flow Conditions

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ABSTRACT

To find the effects of pressure on critical heat flux (CHF) for the conditions of low pressures (especially up to 10 *bar*) and low mass flux (~ 300 kg/m^2s), a series of experiments have been accomplished by using uniformly heated Inconel-625 tube. The experimental ranges are as follows: pressure (from 1.2 to 8 *bar*), mass velocities (from 100 to 250 kg/m^2s) and the inlet subcooling (Δh_i = 350 *kJ/kg*). According to the experimental data, it is found that the CHF is nearly independent of the pressure and increases with mass flux. From the results of the CHF correlation assessment for this experimental data, we could find somewhat different tendency of CHF behavior from every other CHF prediction correlation and table.

1. Introduction

Accurate prediction of critical heat flux is very important for the safety analysis of nuclear power plant (NPP). During the last four decades many researchers have conducted experimental studies on CHF using vertical round tubes throughout the world [1]. From the experimental data and theoretical considerations, many CHF prediction methods (i.e., correlations and CHF tables) were made for high-pressure and high-flow (HPHF) conditions. Opposite to the HPHF condition, for LPLF (low-pressure and low-flow) conditions, still the experimental data are rare especially in the range of 1~10 *bar* and 0~500 kg/m^2s. Most CHF prediction methods show apparently different behavior of CHF under this range. Though one of the major parameter of the CHF is pressure, its effect on CHF is not clear especially under 10 bar until now.

As pressure increases, specific heat of water, thermal conductivity, specific heat of vapor, and density of vapor increases, but all other physical properties decrease. It is obvious that the increase in thermal conductivity, density, and specific heat of vapor, and specific heat of water and the decrease in surface tension, viscosity of liquid and vapor will improve boiling heat transfer. But because each parameter affects CHF, it is very difficult to understand pressure effect clearly. Generally CHF is decreasing function of pressure except low pressure condition. [2]

AECL Research and IPPE has developed AECL-1995 Look-up table [4] to cover most of pressure range (100~20000 *kPa*) and mass flux range(0~8000 kg/m^2s). Their former table (1986 version) has been adopted in many best-estimate thermal-hydraulic codes such as RELAP5/MOD3, CATHARE, CATHENA, etc. According to this table, CHF increases with pressure to some pressure then decreases for inlet- and local-conditions in this low mass flow region (Fig. 1). However, Katto [5] and Shah [7] correlations which are both based on inlet-condition show a decreasing trend of CHF with pressure (Fig. 2-3). Weber [8] conducted experiments under low pressure (~12 *bar*) and low mass flux (~ 300 kg/m^2s) by controlling temperature using copper cylinder of 50mm length with relative length (*L/D*) of 4.47 and make a correlation for that region with their data and other's data (MacBeth, Lowdermilk, Biasi et al, and Katto) enlarging parametric limit of *L/D* to 100. This correlation was made on the basis of Katto's H-regime correlation and showed better prediction in LPLF region. According to their experimental data and correlation, the CHF increases with pressure (Fig. 4).

2. Experiments

2.1 Experimental configurations

KAIST experimental loop for LPLF condition is composed of mainly the pressurizing part (independent pressurizer to avoid any non-condensible gas getting into the system), the condensing part (heat exchanger, surge tank), the preheating part (two series of preheater to control inlet flow temperature accurately), the measuring part (measuring the test section wall temperature, the water temperature, the pressure and the mass flow rate to the inlet of the test section) and the testing part (uniformly heated vertical round tube test section). Its overall configuration was shown in Fig. 5. For pressurizing the system, test loop has a pressurizer connected to surge tank and nitrogen gas was injected to it through small diameter tube which prevents gas from contacting with working fluid (distilled and degassed water) directly.

Test section was made using Incornel-625 tube with the length of 1m, the inner diameter of 0.008m and the thickness of 1mm, and K-type thermocouples were spot-welded on it to check sudden temperature increase which is an indication of the CHF occurrence. Test section was heated electrically by a direct current (DC) power supplier (32 *V*, 2000 *A* Rectifier).

Flow rate was measured by turbine flow meter (0.1 ~ 1.0 *l/min*) and mass flux was calculated in real time using flow meter inlet temperature and pressure. Voltage signals from flow meter, thermocouples, pressure tap were obtained by HP 3852A Data Acquisition/Control units, and were recorded and processed by IBM PC/586.

2.2 Experimental procedures

Experiments have been performed for upward flow of water with different pressure and mass flux. Test conditions of them was shown in Table 1. Inlet subcooling was fixed nearly same condition with two preheater. One of them has a cooler for the condition of excess temperature increase in inlet of test section. Mass flux was calculated with flow rate and flow meter inlet water property on line, and controlled with throttling valve. After setting inlet subcooling, mass flux, and test section outlet pressure at desired value, heat flux was increased with enough duration time for stabilization of other experiment parameters. CHF point was defined as the condition where the maximum wall temperature of the test section increase suddenly over 250°C.

The experimental errors involved in the measurements are estimated at ± 1.6 ^oC for the Type-K thermocouples, ± 1.5 ^oC for the Type-T thermocouples, ± 1 *kPa* for the pressure tab, ± 3 % for the mass flux, and ± 5 % for the heat flux.

3. Results and Discussion

Typical behaviors of important test parameters with time during the experiments are shown in Fig. 6. Experimental parameters were fluctuated with time, but they are all within ± 3 % of the average values. About 40 data points were obtained

3.1 Experimental results

The overall CHF behavior on the mass flux is shown Fig. 7. The exit qualities lie in the value between 0.5 and 0.7 and increase with pressure for the same mass flux and inlet subcooling. In the next paragraph, we observed the CHF behavior according to the major parameter such as pressure and mass flux.

Mass flux effect: The CHF increases as G increases. For this fixed inlet condition, the increasing rate of CHF with G was small for P greater than 6 *bar*.

Pressure effects: The CHF slightly increased to some pressure and then decreased. However, the characteristics of this trend was different with each mass velocities. The results are discussed according to each mass velocities in the following paragraphs.

(a) For G = 100 kg/m^2s, no effect of pressure on CHF is observed. Because the effect of pressure on CHF is somewhat complicated, we can not say the effects.

(b) For G = 150 kg/m^2s, the CHF somewhat increases with pressure up to 7 *bar*, and then decreases.

(c) For G = 200 kg/m^2s, the CHF somewhat increases with pressure up to 7 *bar*, and then decreases also. From this mass velocity, the increasing is indistinguishable up to 5 ~ 6 bar.

(d) For G = 250 kg/m^2s, the CHF somewhat increases with pressure up to 6 *bar*, and then decreases.

3.2 Comparison with other CHF correlations and look-up table

Comparisons were done between experimental data and CHF correlations and look-up table. Correlations which were known to show good agreement with world wide CHF data for LPLF conditions: Katto[5], KAIST[9], Shah[7], Weber [8] correlation, and AECL-1995 Look-Up table[4]. Overall comparison results are configured in Fig. 8. with each mass flow condition.

AECL-1995 Look-Up table

Since the *AECL -1995 Look-Up table* is based on the exit quality, experimental data were assessed by using two comparison method: Heat Balance Method (HBM) and Direct Substitution Method (DSM).

(a) Using *HBM*: According to the comparison, AECL table has R value of 1.304 and RMS value of 0.33 showing nearly constant behavior of CHF under 150 kg/m^2s and increasing behavior of CHF over 200 kg/m^2s with pressure. AECL table overpredict CHF, especially as G approaches to 100 kg/m^2s.

(b) Using *DSM*: CHF calculated by DSM method are much higher than experimental and has increasing trends with pressure. This method shows R value of 2.34 and RMS value of 1.63 and these value are much higher as G decreases.

Overall, HBM predicts CHF better than DSM, and AECL table doesn't show good agreement with experimental data.

Other correlations

Katto and Shah correlations overpredict CHF and show somewhat deceasing trends of CHF with pressure and have R value of 1.51 and 1.21, RMS value of 0.52 and 0.24, respectively. Katto divided flow conditions into five regimes: L-, H-, N-, HP- and VL-regime. According to this regime determination scheme, our data were classified into L-regime which means low mass velocity region. In L-regime, it can be presumed that the dryout of an annular liquid-film flowing over the tube wall is mainly responsible for CHF. The CHF correlation for L-regime is as follows;

$$q_c = q_{c0}\left(1 + K\,\Delta H_i \,/\, H_{fg}\right) \tag{1}$$

$$\frac{q_{co}}{GH_{fg}} = 0.25\left(\frac{\sigma \rho_l}{G^2 L}\right)^{0.043} \frac{1}{L/d} \tag{2}$$

It is noted that in the Eq. (2), the density ratio($\rho_v \,/\, \rho_l$) is omitted, the effect of $(\sigma\rho_l \,/\, G^2 l)$ is very weak so that this equation form is not greatly affected by the pressure.

Weber correlation was based on Katto H-regime CHF correlation and its application range of relative length (*L/D*) is from 4.47 to 100. Although our test section has L/D value of 125, we compared test data with this correlation. This correlation had R value of 1.13 and RMS value of 0.17 for their range. However, the comparison result shows better agreement with our experimental data (R=1.10, RMS=0.14). According to their paper, as *L/D* increase , the CHF decreases. This can explain why this correlation generally overpredict our test data. The predicted CHF shows increasing trend. So its prediction error become larger and larger with pressure.

Until now, the pressure trend on CHF at LPLF were not known exactly and it become to important. Because our experimental data for this range are still under construction, we can not say the exact results. However our experiments are still processing as the efficiency of our experiments grows, the remaining works can be accomplished soon.

4. Conclusion

Experimental investigation has been conducted to find the effect of pressure on CHF under LPLF condition Based on the present data and comparison with existing correlation and look-up table, the following conclusions are obtained;

(1) At low pressure (~ 8 *bar*) and low mass flux (~ 250 kg/m^2s) condition, CHF somewhat increases to 6 bar and then decrease with pressure. But generally CHF seems to be independent of pressure.

(2) CHF increase with mass flux in the condition of same pressure and inlet condition, but the increment level decrease with mass flux.

(3) All CHF correlations and look-up table gives higher CHF value than experimental data.

(4) Prediction errors of the correlations and look-up table become larger with decreasing mass flux, so more experimental study under low mass flux is needed.

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Table 1. Test Conditions

Test Parameters	Test Points
P (bar)	1.2, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0
G (kg/m^2s)	100, 150, 200, 250
Δh_i *(kJ/kg)*	350
D (m)	0.008
L (m)	1.0

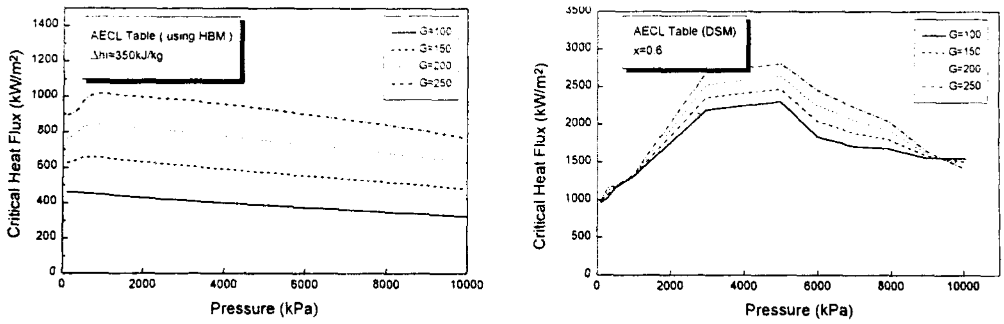

Figure 1. Overall pressure trend of CHF by AECL look-up table (HBM, DSM)

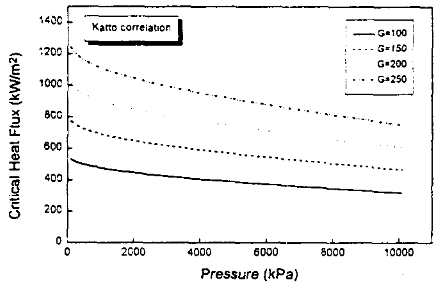

Figure 2. Overall pressure trend of CHF by Katto Correlation

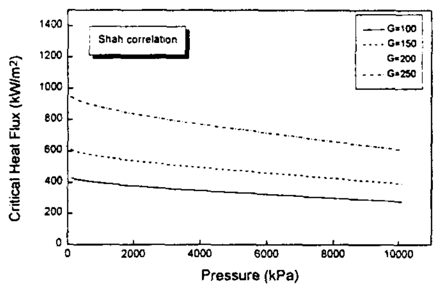

Figure 3. Overall pressure trend of CHF by Shah Correlation

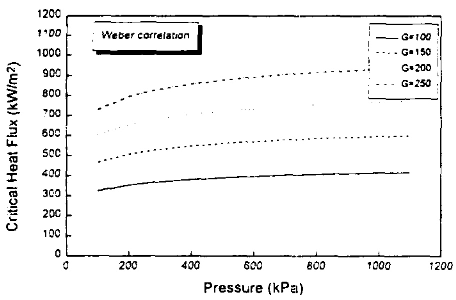

Figure 4. Overall pressure trend of CHF (Weber correlation)

Figure 5. Overall pressure trend of CHF by Shah Correlation

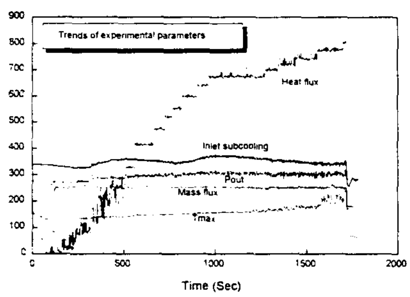

Figure 6. Trends of experimental parameters with time

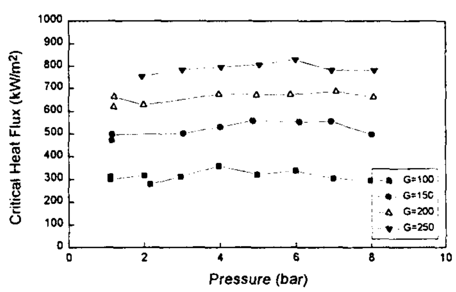

Figure 7. Overall trend of CHF with pressure

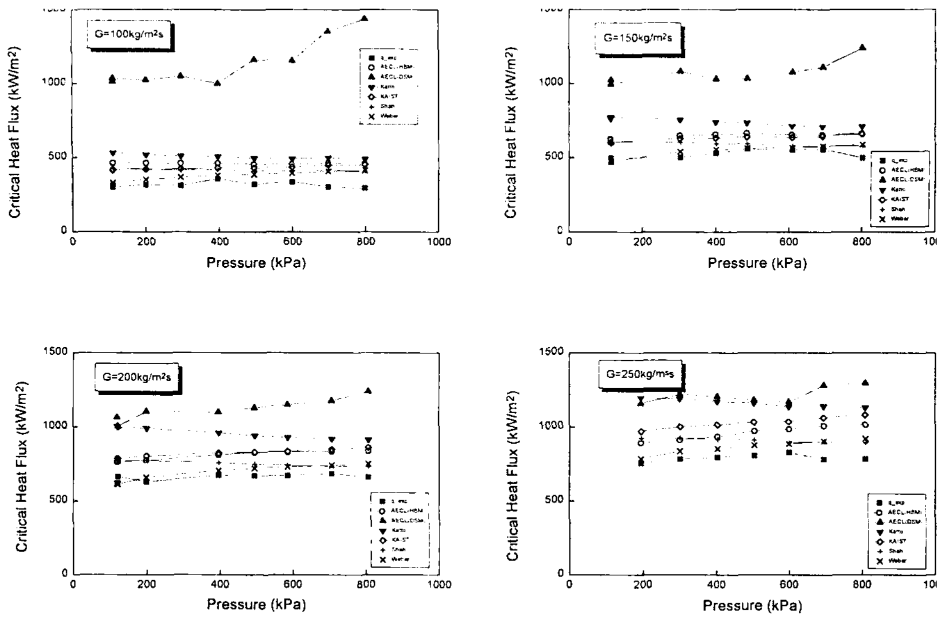

Figure 8. Comparison results with existing CHF prediction schemes