Proceedings of the Korean Nuclear Society Spring Meeting
Kwangju, Korea, May 1997

Critical Heat Flux for Low Flow in Vertical Annulus under Various Pressure Conditions

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Abstract

It is important to understand correctly a CHF under low flow condition for the *purpose of enhancing* the reactor safety and performance in the LWRs. The CHF experiments have been carried out for an internally heated vertical annulus in RCS loop facility. The experimental conditions cover ranges of pressure from 1.82 to 12.08 MPa, mass flux from 300 to 550 $kg/m^2 \cdot s$ and inlet subcooling of 210 kJ/kg. The CHF data decrease with increasing pressure at high value of mass flux. For mass flux of about 300 $kg/m^2 \cdot s$, the CHF are little influenced by pressure. The CHF data are correlated well by using the dimensionless heat flux and dimensionless mass flux for a fixed inlet subcoolimg, except the data group of 12.08 MPa. It seems that the Doerffer correlation and Katto correlation overestimate the CHF for low pressure and lower value of mass flux within this experimental ranges. The Bowring correlation gives a better prediction than the other two correlations.

1. Introduction

Most of Critical Heat Flux(CHF) studies have been concentrated on high pressure and high flow rate conditions corresponding to normal operation ranges of light water reactors(LWRs). Therefore, though several prediction methods for CHF which are reliably applicable to normal operating conditions of LWRs have been developed, these prediction methods have a relativly narrow range of validity. Importance of the CHF behavior under a low flow rate condition has been pointed out earlier in relation to the analysis of accident situations for LWRs. Furthermore, in a future LWR which should be adopted various passive safety features, the reactor core coolability by natural circulation plays a key role in thermal hydraulic behavior during the operational transients and the accident situations. In order to achieve optimal design and to ensure a high degree of safety of future LWRs, therefore, the CHF characteristics under low flow conditions in natural circulation phase must be clearly understood.

It is known that the CHF phenomenon at low flow condition is complicated and the CHF data are scattered due to unstable flow because the effect of buoyancy and a inherent thermal hydraulic characteristic of experimental facility become remarkable. Several studies on CHF at low flow rate and low pressure conditions have been performed with more attention in recent years. Only a few studies on the CHF in an internally heated vertical annulus at low flow and low pressure were reported [1, 2 and 3]. However, the effect of pressure on CHF at low flow conditions has not sufficiently been clarified.

In this paper, therefore, CHF is investigated experimentally in internally heated annulus at low flow with various pressure conditions. The CHF data obtained in the present experiments are compared with several exsisting correlations. The effect of pressure on CHF under low flow condition is characterized from the experimental results.

2. Experimental Facility

The CHF experiments reported in this paper have been carried out in reactor coolant system thermal hydraulic loop facility(RCS loop facility) at the Korea Atomic Energy Research Institute(KAERI). Figure 1 shows the flow diagram of the RCS loop facility. It basically consists of a main circulating pump, preheater, CHF teat section, steam/water separator, pressurizer and cooler. The flow rate of test section inlet is varied by adjusting the motor speed of circulating pump and the flow control valve. Three kinds of orifice flow meters with different measuring ranges are installed to measure the flow rate of water entering to test section. A flow fluctuation, which is usually observed in low flow conditions, is prevented by throttling valve located upstream of the test section inlet.

Figure 2 shows the details of the test section used in this experimental studies. The test section which is an inner heated annulus flow channel consists of a outer pipe of 19.4 mm inside diameter and an inner heater rod of 9.54mm outer diameter having heating length of 1842 mm at room temperature. The inner heater rod is heated indirectly by electricity with uniform axial power distribution. The sheath and heating element of heater rod are made of Inconel 600 and Nichrom, respectively. For measuring heater rod surface temperature and detecting the CHF occurrence, six Chromel-Alumel thermocouples with a sheath outer diameter of 0.5mm are embedded on the outer surface of the heater rod at the locations of 10, 30, 110, 310, 510 and 910 mm from the top end of heated section. The main parameters mesured in the experiments are the water temperatures and pressures at inlet and outlet plenums and at the bottom and top of heated section, the differential pressure in test section, the flow rate of test section inlet, surface temperature of heater rod and the power applied to test section. For the present experiments, the CHF condition is determined as occurred when the surface temperature of heater rod exceeds 400 ℃. When the CHF occurs, the heater power is automatically decreased to 80 % or tripped by a CHF detector.

All the data from the sensors and transmitters were treated and analyzed by a data aquisition and control system consisting an A/D and D/A converter, and workstation computer. As a result of estimation by considering the calibrations of sensors and the accuracy of equipments, the uncertainties in measurements were less than ±0.3 %, ±1.5 %, ±0.6 % and ±1.0 % for the pressure, flow rate, temperature, and heat flux, respectively.

3. Experimental Results

The experimental conditions under which the present data have been obtained cover ranges of pressure from 1.82 to 12.08 MPa, mass flux from 300 to 550 $kg/m^2 \cdot s$ and inlet subcooling of 210 kJ/kg. The equilibrium exit qualities are from 0.25 to 0.40.

The present CHF data are plotted in Fig. 3 as a function of mass flux. The pressure is the test section inlet pressure in this work. Figure 3 indicates that the CHF data rise linearly with increasing mass flux in this experimental ranges. The solid lines are the linear fitting lines obtained by means of a least squares regression for the CHF data groups corresponding to each pressure condition. The standard errors of estimate and correlation coefficients of these lines are estimated within 1.5% and 0.994, respectively. To examine the effect of pressure on the CHF, the CHF values calculated by the liner fitting equations are shown in Fig. 4 as a function of pressure. The CHF decreases with increasing pressure at high value of mass flux, but decreases much less rapidly for low mass flux. For mass flux of 300 and 350 $kg/m^2 \cdot s$, the CHF are scarcely influenced by pressure, except the CHF values at 12 MPa.

Figure 5 shows the relation of mass flux and exit qualities on CHF conditions. In high pressure, the exit quality changes sharply with mass flux. On the other hand, the exit quality changes with relatively lower slope in low pressure conditions.

The Doerffer correlation [4], Bowring correlation [5] and Katto correlation [6] have been selected for the comparison with the present data. The Doerffer correlation was developed for internally heated annuli, based on an 8mm tube AECL-OU CHF look-up table as the reference. Figure 6 shows the comparison of the Doerffer correlation prediction with the present CHF data. The correlation overestimates the CHF in low pressure ranges and the overestimation of the correlation decreases with increasing the pressure. In high presssure conditions, the correlation predicts the CHF resonably well. The overestimation in low pressure is due to the insufficient data and large uncertainties of AECL-OU look-up table in low flow ranges, and the incorrect pressure correction factor of the Doerffer correlation. Bowring developed the correlation for ranges of pressure from 0.6 to 15.5 MPa and mass flux from 50 to 4000 $kg/m^2 \cdot s$ in rod bundle geometries. In comparison of Bowring correlation with the present CHF data, the heated and hydraulic equivalent diameters for the annulus were used. Comparison of the correlation with the present data is shown in Fig. 7. The Bowring correlation shows the general agreement with the present CHF data regardless of the pressure and inlet subcooling. Katto correlation consists of four equations corresponding to the different regions of CHF characteristics. All of the present CHF data fell into the H-regime defined by Katto whch is applicable to relatively low flow conditions. Figure 8 shows comparison of Katto correlation with the present data. The Katto correlation overpredicts the CHF data throughout the range of the present conditions. From Figs. 6, 7 and 8, the Bowring correlation gives a better prediction than the other two correlations.

4. Conclusion

The CHF experiments have been carried out in an internally heated vertical annulus. The experimental conditions covered ranges of pressure from 1.82 to 12.08 MPa, mass flux from 300 to 550 $kg/m^2 \cdot s$ and inlet subcooling of 210 kJ/kg. The obtained CHF data have been compared with several CHF correlations which are widely used. The following conclusions from this study can be drawn :

(1) For a fixed inlet subcooling, the CHF data rise linearly with increasing mass flux and decrease with increasing pressure at high value of mass flux. For mass flux of about 300 $kg/m^2 \cdot s$, the CHF is scarcely influenced by pressure.

(2) There are considerable difference in the parametric trends of exit qualities on CHF conditions with mass flux between low pressure and high pressure conditions.

(3) Within our experimental ranges, the Doerffer correlation and Katto correlation overestimated the CHF for low pressure and lower values of mass flux. The Bowring correlation gives a better prediction than the other two correlations.

Nomenclature

CHF	Critical heat flux(MW/m^2)
CHF_M	Measured critical heat flux(MW/m^2)
CHF_P	Predicted critical heat flux(MW/m^2)
G	Mass flux($kg/m^2 \cdot s$)
P	Pressure(MPa)
q	Heat flux(MW/m^2)
X_{EX}	Equilibrium exit quality (-)
$\triangle h_{in}$	Inlet subcooling(kJ/kg)

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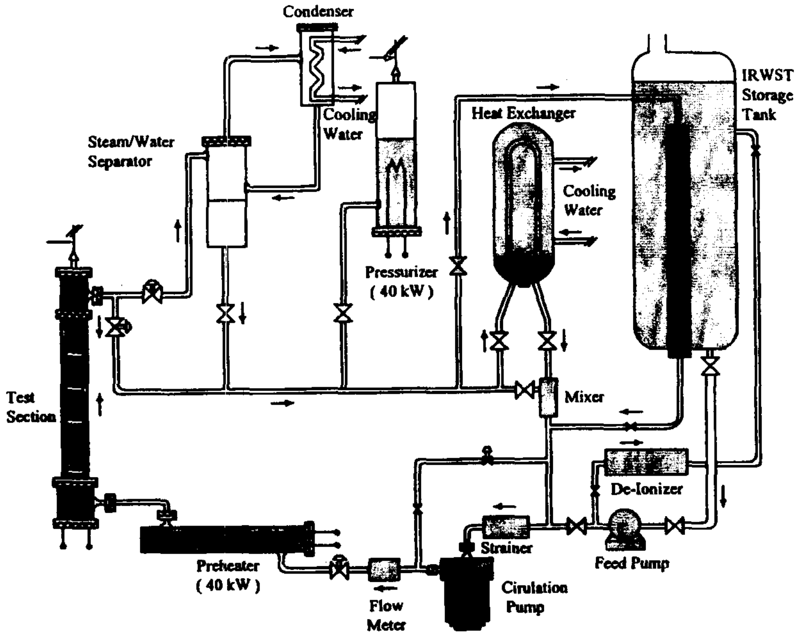

Fig. 1. Simplified Flow Diagram of RCS Loop Facility

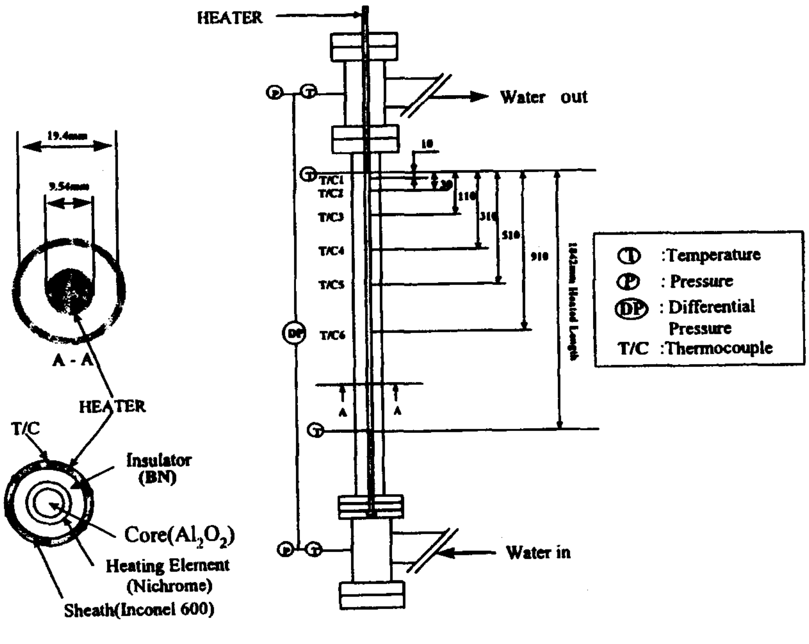

Fig. 2. Test Section Geometry and T/C Locations

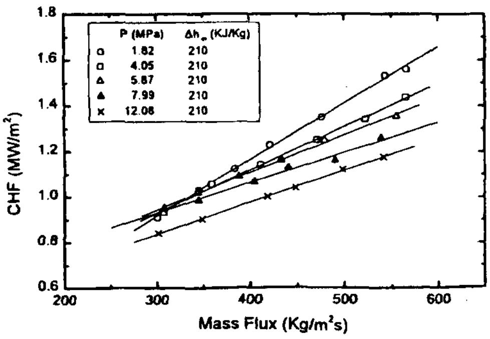

Fig. 3. Parametric Trends of CHF with Mass Flux

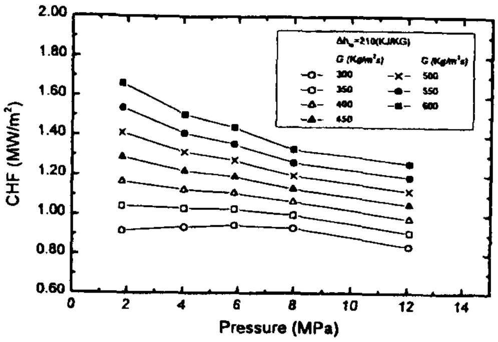

Fig. 4. Effect of Pressure in CHF

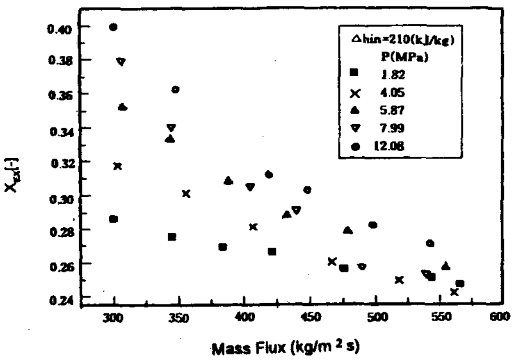

Fig. 5. Parametric Trends of Exit Quality on CHF with Mass Flux

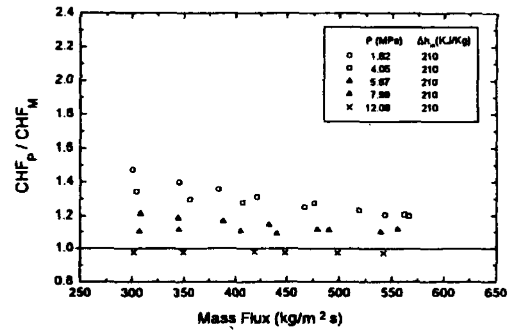

Fig. 6. Prediction Accuracy of Doerffer Correlation

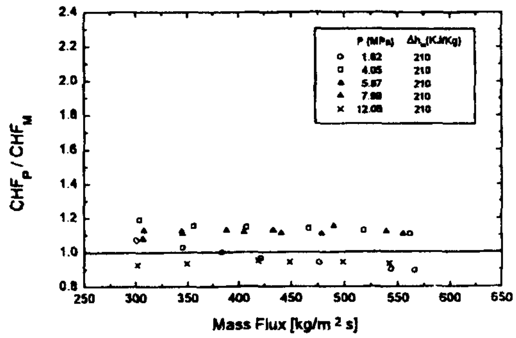

Fig. 7. Prediction Accuracy of Bowring Correlation

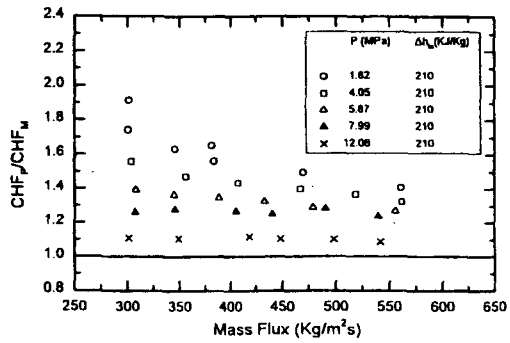

Fig. 8. Prediction Accuracy of Katto Correlation