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Parametric Trends of CHF and the Assessment of CHF Prediction Methods Based on Experimental Data at Low Pressure and Low Flow

Hong-Chae Kim, Won-Pil Baek and Soon Heung Chang

Department of Nuclear Engineering
Korea Advanced Institute of Science and Technology
373-1 Kusung-dong, Yusong-gu
Taejon, Korea 305-701

ABSTRACT

Recently, a series of experiments on critical heat flux (CHF) under low pressure (< 9.5 bar) and low flow (G < 277 kg/m^{2}s) condition have been accomplished in KAIST. As a result, a total of 513 CHF data for water flow in vertical round tubes were obtained at various stable conditions. Tests have been conducted in the following conditions: diameter of 6, 8, 10 and 12 mm; heated length of 0.3 ~ 1.77 m; pressure of 1.0 ~ 9.5 bar; mass flux of 20 ~ 277 kg/m^{2}s; and inlet subcooling of 50 ~ 654 kJ/kg. Based on the data, parametric trends are examined from two different points of view: fixed inlet condition and fixed exit condition. Parametric trends are generally consistent with previous understandings but complex effects of system pressure and tube diameter are observed. Several empirical correlations and mechanistic model applicable to LPLF conditions are assessed with the measured data; the correlations of Baek et al.(1997) and Shah (1987), and the annular flow model of Katto (1984) show good prediction accuracy. Parametric trends of the prediction by these methods were compared with the CHF data to select most useful method for CHF analysis at low pressure and low flow.

1. Introduction

The critical heat flux (CHF) condition causes a drastic reduction of heat transfer coefficient and sometimes involves a physical failure of a heated surface. Understanding of the CHF phenomenon and reliable CHF prediction models are necessary to design various heat transfer units including nuclear reactors, fossil-fueled boilers, fusion devices, etc. The research on CHF has been extensively carried out over the last four decades, mainly with the development of water-cooled nuclear reactors. Now many aspects of the CHF phenomenon are well understood and reasonable prediction models have been developed. However, due to the complex nature of the phenomenon, CHF is still the subject of the most active research and the application area is expanding.

Interests on the CHF at low pressure and low flow (LPLF) conditions have been continuously increased with respect to accident conditions of light water reactors and normal and transient conditions of research reactors. The CHF phenomenon becomes more complex at LPLF conditions due to the important role of buoyancy forces, flow instabilities, the large specific volume of vapor, the effect of loop design parameters, etc.

There have been significant works on CHF at LPLF conditions (Lowdermilk et al., 1958; Mishima et al., 1985, 1987; Weber and Johannsen, 1990; Chang et al., 1991; Baek et al., 1995), focusing on experimental investigations. Kirillov (1994) presented the state-of-the art understandings of the LPLF CHF including the works by Russian investigators.

Reliable stable-flow CHF models should be developed and validated based on sufficient number of experimental data over the range of interests. However, existing CHF data bases do not properly cover all the LPLF conditions and the data are concentrated on atmospheric pressure conditions, see Groeneveld et al. (1996). An exact understanding of parametric trends is important to develop reliable prediction models. There have been some works on parametric trends of CHF (Collier and Thome, 1994; Hewitt, 1982; Moon et al., 1996). Collier and Thome used a set of experimental data for the CHF trends analysis and Hewitt's analysis was based on an empirical correlation. However, because the experimental data used in the analysis generally have limited ranges of system parameters, recently, Moon et al. investigated the CHF behavior by applying artificial neural networks (ANNs) to CHF data bank for upward flow of water in uniformly heated vertical round tubes. From their analysis they drew some important conclusions; 1) The effect of tube diameter on the CHF at fixed local (or exit) quality appears to be quite different according to the CHF mechanisms. The CHF decreases with the diameter for the low-quality CHF, whereas little or reversed effect is observed for the high-quality CHF. 2) The effect of mass flux on the high-quality CHF at fixed local conditions shows a complex trend. 3) The importance of the length effect in the correlations using local conditions is observed. In spite of these works, some aspects are still obscure and need further clarification. Parametric trends of the LPLF CHF have not been adequately addressed by previous workers, in particular for the effects of pressure, diameter, length, and critical quality.

In this work, parametric trends are analyzed from two points of view: (a) fixed inlet conditions and (b) fixed exit conditions, based on CHF experimental data and available CHF prediction methods at LPLF were assessed including parametric trends analysis of them.

2. Parametric Trends of CHF

2.1 Parametric trends for fixed inlet conditions

(a) Mass flux. The CHF increases with the increase of mass flux for fixed D, L, P and Δh_i; however, the rate of increase somewhat decreases with increasing mass flux (Fig. 1). The mass flux effect becomes larger for test sections with small L/D. It is noticeable that the CHF data for the same L/D value lie nearly on a single line except small L/D data. Overall trends are consistent with the previous findings.

(b) Diameter. The CHF increases with increase in diameter for fixed L, P, G and Δh_i, as reported in Chang et al. (1991) (Fig. 2). The diameter effect becomes stronger for shorter heated length. However, for the same L/D, diameter effect didn't appear. This, with the findings of Fig.1, suggests that the length-to-diameter ratio is more important parameter than the diameter or heated length alone.

(c) Heated length. The longer tube shows the lower CHF for fixed D, P, G and Δh_i; however, the effect decreases and becomes negligible as the length becomes large (Fig. 3). All data for two diameters show nearly same trends and values except for small L/D condition and this supports the above suggestion.

(d) Inlet subcooling. The effect of inlet subcooling is shown in Fig. 4. Though the effect is not large, it is clear that the CHF increases with the increase in inlet subcooling. The effect becomes small as the heated length increases. Most of the previous investigators have been reported that the inlet subcooling effect is negligible for LPLF conditions (Mishima et al., 1985; Chang et al., 1991; Bergles, 1977). It is thought that the inlet subcooling effect exists for any cases but decreases as mass flux decreases and as the heated length increases (no effect at zero flow).

(e) Pressure. It is generally known that CHF increases with the increase of pressure, goes through a maximum, then decreases with pressure (Collier and Thome, 1994; Bergles, 1977). Pressure effect observed in the present tests is illustrated in Fig. 5. The CHF slowly increases with increase in pressure for higher mass fluxes but the effect becomes negligible at lower mass fluxes.

2.2 Parametric trends for fixed exit conditions

Because both the exit quality and critical heat flux are dependent variables in CHF tests, it is difficult to represent the parametric trends for fixed exit conditions from an experimental data base. For given mass flux, pressure and tube geometry, exit quality can only be changed by varying inlet subcooling; however, this is not easy at low pressures because the inlet subcooling cannot be controlled in a wide range. Therefore, available data plots are somewhat limited and the data which have similar qualities have been represented by the same quality line in figures. Important parametric trends are as follows:

(a) Mass flux. The effect of mass flux effect is shown in Fig. 6 for three diameters (D = 6, 8, 12 mm). The CHF increases with the increase of mass flux. Moon et al. (1996) described that the CHF at high quality conditions increases with mass flux in the very low mass flow region, then sharply decreases to a minimum and then gradually increases. The 1995 CHF look-up table of Groeneveld et al. (1996) also shows the similar trend. Therefore the present work confirms the findings of Moon et al. (1996) and Groeneveld et al. (1996).

(b) Exit quality. The CHF generally decreases with the increase of exit quality for fixed D, L, P, G (Fig. 7). However, this effect seems to diminish at qualities higher than a threshold which depends on mass flux and pressure. At G = 60 kg/m^{2}s, CHF is nearly constant over the range of $0.675 < X < 0.79$. For some cases (D = 6 mm, P = 700 kPa, G = 200 kg/m^{2}s and D = 12 mm, P=300 kPa, G = 130 kg/m^{2}s), there is a sharp decrease of the CHF for a small increase in quality. It corresponds to the concept of "limiting quality" which was discussed by Bennett et al. (1967), Katto (1982), Levitan et al. (1975), Kirillov (1994), and many others. The authors postulated that CHF around the limiting quality is due to dryout of a liquid film in the absence of replenishment from the core of annular-mist (dispersed-annular) flow.

(c) Pressure. Figure 8 shows the pressure effect on the CHF for various diameter, heated length and mass flux. The observed trends are very similar to that for fixed inlet conditions. The CHF is not affected significantly by pressure at LPLF conditions, but increases with the increase of pressure at higher mass fluxes. This trend is also shown in the plot of Moon et al.(1996).

(d) Heated length to diameter ratio (L/D). The CHF prediction models based on local conditions ignores the effect of *L/D*. As the L/D effect exists for short tubes, the local-condition correlations generally use only the CHF data of relatively large *L/D*. For example, the 1995 CHF look-up table of Groeneveld et al. (1996) used the CHF data of $L/D \geq 80$. Figure 9 illustrates the effect of *L/D* for tubes of $D = 6$ and 8 mm. The CHF decreases with the increase of *L/D* but the rate of decrease also decreases with the increase in *L/D*. For the 6mm tube (P = 100 kPa, G = 100 kg/m^{2}s, X = 0.74 - 76), the CHF for $L/D = 150$ is around half that of $L/D = 75$. This confirms that $L/D \geq 80$ is not sufficient for selection criterion of data base for local condition-type correlation (Baek et al., 1997). The effect of L/D becomes smaller for the larger tube.

(e) *Tube diameter.* The CHF has been generally considered as a decreasing function of tube diameter at fixed local conditions, and based on that understanding the 1995 CHF look-up table (Groenoveld et al., 1996) assumed the following relationship:

$$\frac{CHF_D}{CHF_{D=8mm}} = \left(\frac{D}{8}\right)^{-1/2} \tag{1}$$

where CHF_D is the CHF for a diameter of interest, $CHF_{D=8mm}$ is the CHF for an 8mm tube and D is the tube diameter in millimeters. Figure 10 shows two kinds of plots: one based on the same heated length and the other based on the same L/D. The CHF increases with the increase of diameter for a fixed heated length as previously noted by Moon et al. (1996). This means that heated length-to-diameter effect exists and Eq. (1) can not be used for this condition even though all the data have L/D > 80. However, there is no apparent effect of tube diameter for fixed heated length-to-diameter ratio.

2.3 Discussion

2.3.1 Effect of exit quality

In the Fig. 7, some data show the rapid fall in a narrow range of exit quality called "limiting quality" and some data for low mass flow are nearly independent of exit quality. The limiting quality phenomenon occurs at a higher mass flux as diameter decreases.

It is generally known that the limiting quality phenomenon is related to the flow pattern transition from macro-film annular flow to micro-film dispersed annular flow condition. And at low velocity conditions, there is an argument that the hydraulic forces are insufficient to remove the macro-film as the droplet entrainment and the limiting quality phenomenon may not occur. However, the limiting quality phenomenon can take place at low flow under the condition of low pressure where steam-to-water specific volume ratio is very high and this makes high steam velocity sufficient to cause entrainment even at low flow. However, at very low flow, this phenomenon may not occur.

2.3.2 Effects of heated length and diameter

Figure 9 shows that the *L/D* effect exists even for longer tubes ($L/D > 100$) though the effect decreases as *L/D* increases. Therefore, the data for very long tubes should be used for development of local condition correlations. However, long tubes can produce only high-quality CHF data and short tubes should be used to produce low- and intermediate-quality data. In this regard, development of a L/D correction factor and its application to development of local condition correlations is a useful approach.

Lee et al. (1998) presented the threshold L/D based on KAIST CHF data bank, above which the length effect can be ignored:

$$\left(\frac{L}{D}\right)_{th} = 252.86\left(\frac{\sigma\rho_f}{G^2 D}\right)^{0.135}\left(X + 0.25\left(\frac{\rho_f}{\rho_g}\right)^{0.189}\right) + 10.0 \tag{2}$$

For D = 8 mm, P = 100 kPa, G = 100 kg/m^{2}s and X = 0.80, the threshold L/D, $(L/D)_{th}$, is calculated as 447.0 from above correlation.

Kataoka et al. (1982) suggested a correlation for the equilibrium heated length-to-diameter ratio at which entrainment and deposition rates become equal:

$$\left(\frac{L}{D}\right)_{eq} \cong 440 We_I^{0.25} / \mathrm{Re}_f^{0.5} \tag{3}$$

where, $$We_I = \frac{\rho_g j_g^2 D}{\sigma}\left(\frac{\Delta\rho}{\rho_g}\right)^{1/3} \text{ and } \mathrm{Re}_f = \frac{\rho_f j_f D}{\mu_f}. \tag{4}$$

Though some upstream effects always exist in annular or annular-mist flow regimes, the equilibrium heated length-to-diameter ratio can be a useful measure over which the upstream effect is not so large. For the above condition, $(L/D)_{eq}$ value is calculated as 212.8. There is a significant difference between predictions by Eqs. (2) and (3). Further data would be required for clarification of the threshold L/D.

Figure 10 deserves further attention. It shows the increase of CHF with D for fixed L, but no apparent trend of CHF with D for fixed L/D. When we are interested in the diameter effect for fixed exit conditions, we usually consider the situation where upstream effects are negligible. In this respect, the trend for fixed L/D would have more meaning. However, a definite conclusion should be avoided because most of the data in our work have upstream effects.

3. Assessment of the Existing CHF Prediction Methods

3.1 Comparison between CHF data and the predictions of the CHF prediction methods

There are several CHF correlations which are claimed to cover LPLF conditions (Bowring, 1972; Katto and Ohno, 1984; Shah 1987; Weber and Johannsen 1990; Chang et al., 1991; Baek et al., 1995; Groeneveld et al., 1996; Baek et al., 1997). The 1995 CHF look-up table of Groeneveld et al. (1996) and the correlation of Baek et al. (1997) are based on local conditions while others are based on inlet conditions. Each correlation is assessed twice: with the whole data and with the data within the applicable range. Assessment results are shown in Table 1 with the number of data used in assessment.

It is found that all the correlations overpredict the CHF to some extent. The correlation of Shah (1987) shows the best prediction capabilities and that of Baek et al. (1997) and Groeneveld et al. (1996) predict CHF with the reasonable average and RMS errors. The 1995 CHF look-up table also shows a reasonable accuracy. The 1995 CHF look-up table and Baek et al.(1997)'s correlation were developed based on CHF data with L/D > 80 to delete the heated length effect on CHF. The assessment conducted for all data including that for L/D < 80 shows that prediction errors are not much different from those of long tubes. For the inlet type correlations, all correlations, except Bowring (1972)'s correlation, show similar error for the both two cases; within range and whole range. Katto et al. (1984)'s correlation has relatively higher prediction error.

It is notable that some correlations (The 1995 CHF look-up table, 1996; Bowring, 1972; Katto et al., 1984; Weber and Johannsen, 1990) show relatively high average errors but have small standard deviations. They could be modified for better predictions.

Some liquid film dryout (LFD) models have been suggested by many authors (Whalley et al, 1978; Levy et al, 1981; Katto, 1884 and others) to predict CHF at annular flow condition. All these models are based on hydrodynamic history effects using constitutive equations for the entrainment and deposition of liquid droplets. All of these models are known to be successful in predicting annular flow CHF. However, the validations are mainly conducted for high pressure and high velocity conditions. In this work, Katto's model was assessed to see the applicability of annular flow model at low pressure and low flow. The assessment result is also shown in Table 1. From the result, the model can predict all 513 CHF data with average error and RMS error of 1.3 % and 12.5 %, respectively. The model is better than any other CHF correlations and table except Shah's correlation.

3.2 Parametric Trends of CHF Predicted by the CHF Prediction Methods

Even though some CHF correlations and the annular flow model have good accuracy statistically, if they predict CHF trend badly, they would give quite poor prediction at out of the assessment range. From this, parametric trends of the predictions by CHF correlations (Baek et al., 1997; Shah, 1987) and annular flow model (Katto, 1984) showing good prediction accuracy were investigated and compared with CHF data. The CHF table by Groeneveld et al. (1996) was also compared because it is expected that it will be used in several best-estimate thermal hydraulic system codes. The exit quality is dependent variable and can be different very much with the prediction. On account of that, just the parametric trend for fixed inlet conditions were analyzed as follows:

a) Mass flux. As shown in Fig. 11, all of the prediction methods show increasing trend of CHF with increase in mass flux. Groeneveld et al. (1996)'s table and Katto (1984) model show similar CHF trend generally underpredicting CHF as mass flux increases at small L/D. Baek et al. (1997) and Shah (1987)'s correlations trace CHF trend very well.

b) Diameter. All prediction methods have similar trend with CHF data for same heated length (Fig. 12). However, for same L/D, most of the methods show decreasing function with the increase of diameter except Baek et al. (1997) correlation, while experimental data show negligible diameter effect. Baek et al. correlation has complex CHF trend with diameter.

c) Heated length. All methods have good agreement with the trend of CHF data (Fig. 13). Baek et al.'s and Shah's correlation show better trend accordance with data, while Groenevel et al.'s and Katto's model under predict CHF at small L/D.

d) Inlet subcooling. All methods predict the inlet subcooling effect very well for two different cases (Fig. 14).

e) Pressure effect. Groeneveld et al.'s table and Katto's model show similar pressure effect on CHF with the data (Fig. 15). However, all methods overpredict CHF for short tube. According to Shah's correlation, CHF slowly decreases with the increase of pressure and Baek et al.'s correlation shows complex trend.

As shown in Fig. 8, limiting quality phenomenon appears at some conditions. To see whether the CHF correlations and model can predict this phenomenon or not, CHF trends for exit quality are investigated with varying inlet subcooling (Fig. 16). According to Fig. 16, only Katto's model shows the limiting quality phenomenon for 6 mm tube. However, different from the data, this phenomenon doesn't appear for larger diameter (D = 12 mm) in any prediction methods. All of the correlations and table just show gradual decrease in CHF value with the increase of exit quality.

From the result of the analysis, it can be concluded that Katto (1984)'s model and Groeneveld et al. (1997)'s table show good agreement with the CHF trends of the data even though these underpredict CHF for short tubes.

5. Conclusions

The study for parametric trends of CHF was carried out under the condition of low pressure (≤ 9.5 bar) and low mass flow (≤ 277 kg/m^2s) based on CHF data obtained from experiment in KAIST. With a total of 513 CHF data, available CHF prediction methods for LPLF condition were assessed quantitatively and qualitatively.

Important results are as follows:

1. The observed parametric trends of CHF data based on fixed inlet conditions generally agree with those of previous studies with exception of the pressure effect. For a relatively high mass flux, the CHF increases with increase in pressure. However, for relatively low mass fluxes, the pressure effect is negligible, except for the case of the short heated length.
2. Parametric trends analysis of CHF for fixed exit condition shows that L/D effect does not disappear even for long tube (L/D > 200) even though the effect becomes smaller for the longer tube. The diameter effect is shown differently according to geometric conditions: CHF increases with the increase of diameter for fixed heated length, while no apparent diameter effect is shown for fixed L/D.
3. Assessment results of the CHF prediction methods with measured CHF data showed that all prediction methods overpredicted the CHF value. The correlation of Shah (1987) shows the best prediction accuracy, and Baek et al. (1997) correlation and Groeneveld et al. (1996)'s table also show good accuracy.
4. According to the parametric trend analysis of the CHF prediction methods, Katto (1984)'s model and Groeneveld et al. (1997)'s table show good agreement with the CHF trends of the data even though these underpredict CHF for short tubes.
5. Annular flow model (Katto, 1984) predicts CHF pretty well and shows reasonable performance for whole range of parameters. This can be a useful method to predict CHF value and trends at various conditions at LPLF condition.

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Table 1. Assessment results of CHF correlations and look-up table

Correlation type	Table/Correlation	Assessment method	No. Data	Avg. error (%)	RMS error(%)
Local type	Groeneveld et al. (1996)	HBM	438 (a)	11.6	14.1
			513 (b)	10.3	15.9
	Baek et al. (1997)	HBM	438 (a)	5.5	12.9
			513 (b)	4.8	13.7
Inlet type	Bowring (1972)	Fixed inlet	169 (a)	12.1	13.2
			513 (b)	17.8	22.3
	Katto and Ohno (1984)	Fixed inlet	470 (a)	25.2	27.9
			513 (b)	26.1	29.3
	Weber and Johannsen (1990)	Fixed inlet	217 (a)	13.9	22.3
			513 (b)	13.5	19.3
	Chang et al. (1991)	Fixed inlet	493 (a)	10.5	25.0
			513 (b)	12.0	26.9
	Baek et al. (1995)	Fixed inlet	493 (a)	9.4	20.3
			513 (b)	10.6	21.6
Mixed type	Shah (1987)	Fixed inlet	513 (a)	3.2	10.4
			509*	2.7	8.6
Annular flow model	Katto (1984)	Fixed inlet	513	1.0	12.4
			509*	0.3	10.2

(a) the data within the applicable range of each correlation
(b) the whole set of data
* without early occurred CHF data

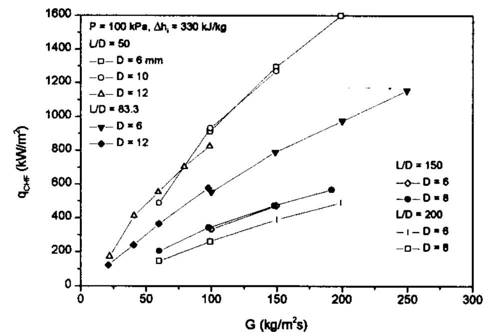

Fig. 1 Mass flux effect on CHF for fixed inlet condition

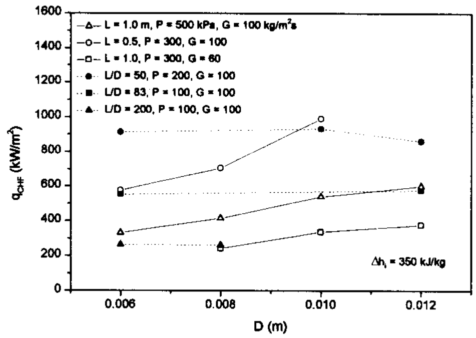

Fig. 2 Diameter effect on CHF for fixed inlet condition

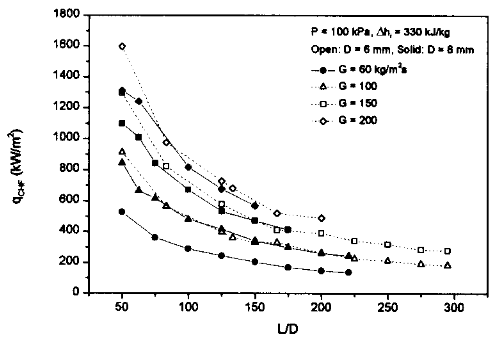

Fig. 3 Heated length effect on CHF for fixed inlet condition

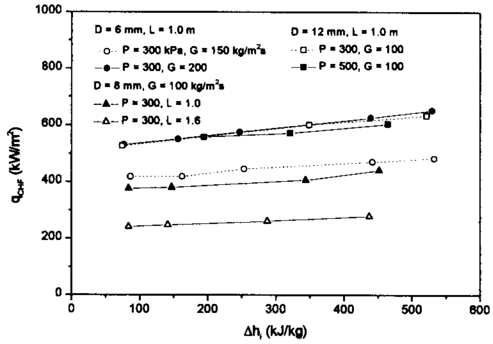

Fig. 4 Inlet subcooling effect on CHF for fixed inlet condition

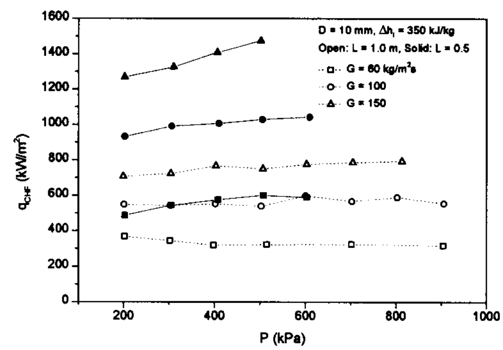

Fig 5. Pressure effect on CHF for fixed inlet condition

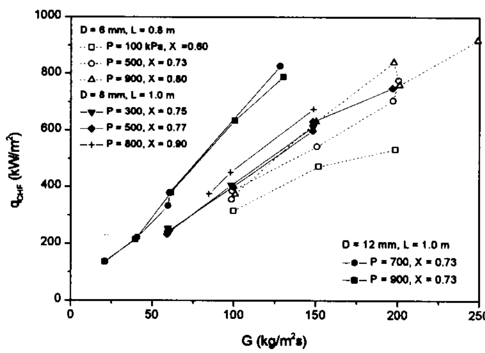

Fig. 6 Mass flux effect on CHF for fixed exit condition

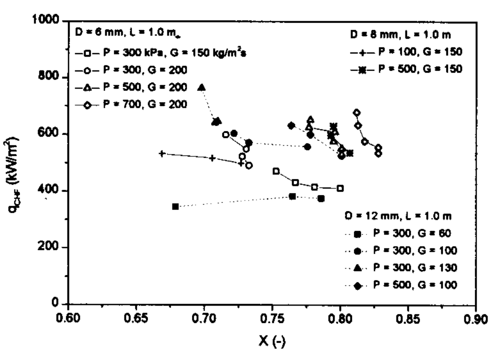

Fig. 7 Exit quality effect on CHF for fixed exit condition

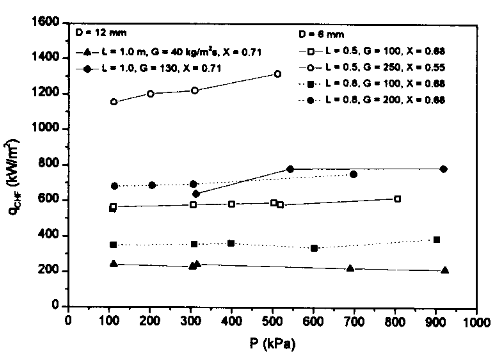

Fig. 8 Pressure effect on CHF for fixed exit condition

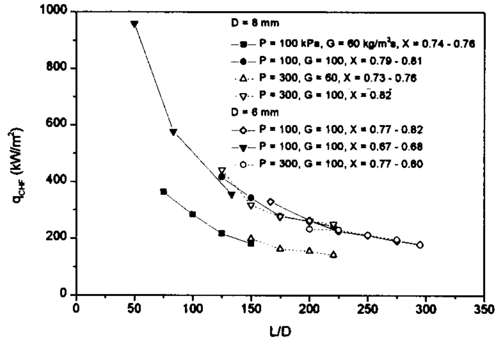

Fig. 9 L/D effect on CHF for fixed exit condition

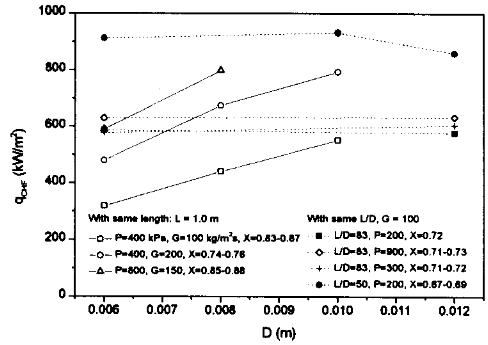

Fig. 10 Diameter effect on CHF for fixed exit condition

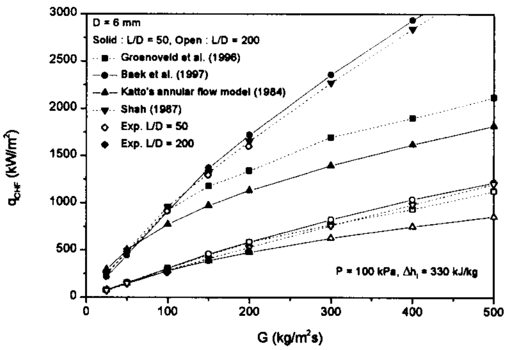

Fig. 11 Mass flux effect of the CHF prediction methods

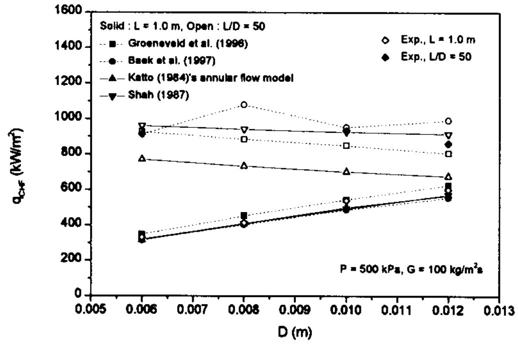

Fig. 12 Diameter effect of the CHF prediction methods

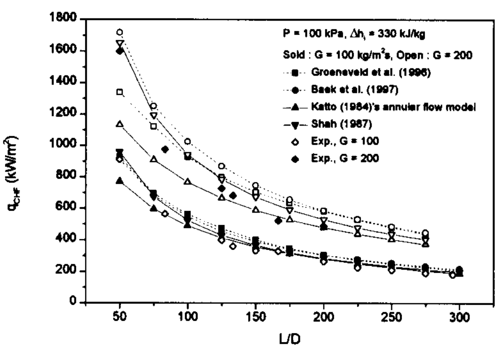

Fig. 13 Heated length effect of the CHF prediction methods

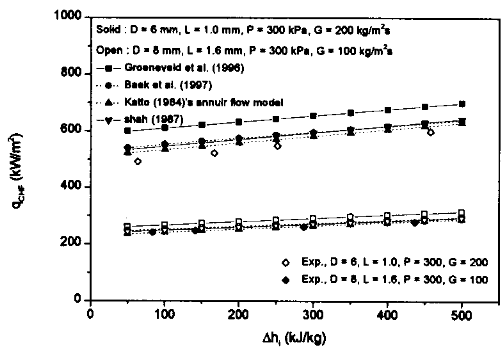

Fig. 14 Inlet subcooling effect of the CHF prediction methods

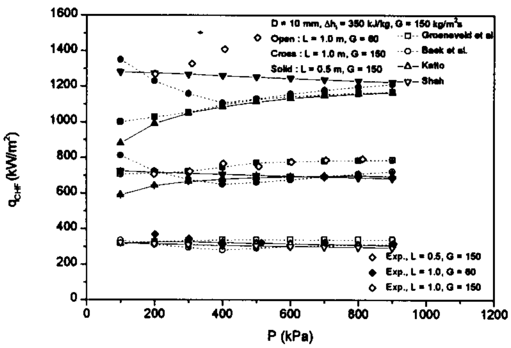

Fig. 15 Pressure effect of the CHF prediction methods

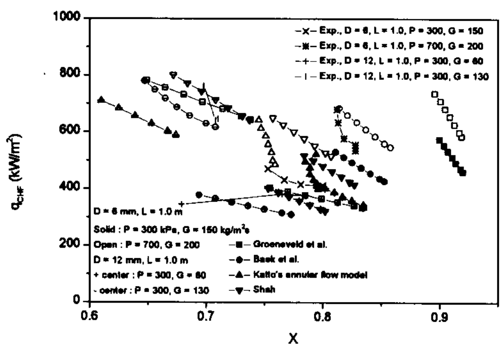

Fig. 16 Exit quality effect of the CHF prediction methods