Trend Analysis for Low Pressure Low Flow Round Tube CHF

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ABSTRACT

Critical Heat Flux (CHF) is one of the most important factors during the operation of nuclear power plant. Currently, due to the lack of experimental data, most of the CHF correlations are limited to high pressure conditions. There are insufficient CHF data in the range of medium to low pressure conditions to cover accidental or transient conditions during the depressurization process from high pressure to low pressure, then to the development of natural circulation passive cooling. Recently, there is renew interest in examining the rod bundle CHF under high quality condition, especially the one involved with low pressure and low flow rate thermal hydraulic conditions.

Under low pressure and low mass flow conditions, the dependency of CHF on other system parameters is different from that of high pressure and high flow conditions. Large density difference between liquid and steam at low pressure condition contributes to high slip ratio and rapid gas expansion, which leads to channel obstruction and flow instability in subchannels and often results in CHF with significantly different mechanisms from steady state conditions. Given present insufficient research, parametric trends of the CHF in terms of mass flux, pressure, subcooling, exit quality, as well as ratio of heated length to diameter are analyzed using data from various sources with the aim of not only presenting trends of CHF with different parameters, but also revealing some underlining mechanisms behind the fundamental phenomena. Several typical empirical correlations' parameter trends are also analyzed in the paper. They are then compared with experimental data. Parametric trend of the prediction by these methods were compared with the CHF data to select the most feasible method for CHF analysis at low pressure and low flow. Comparison results illustrate the necessity of extending the pressure and flow range of CHF correlations to cover the low pressure and low flow conditions. Based on this study, future research directions are recommended.

KEYWORDS

Critical Heat Flux（CHF）; CHF mechanistic model; Low pressure low mass flow; CHF correlation

1. INTRODUCTION

In a system involved in boiling heat transfer, the Critical Heat Flux (CHF) is the heat transfer limit beyond which sudden deterioration of heat transfer mechanism occurs. This event may result in a sudden rise of surface temperature in a heat flux controlled system, or a drastic decrease in power transferred in a temperature controlled system. In a nuclear reactor system, the critical heat flux (CHF) is the heat flux at which a boiling crisis occurs that causes an abrupt rise of the fuel rod surface temperature and, subsequently, a failure of the cladding material. Design of a water cooled reactor requires a sufficient safety margin with regards to the critical heat flux. In the recent year, since the Fukushima accident, the concerned thermal-hydraulic conditions have been extended from the high pressure (over 10 Mpa) high flow range to relatively medium and low pressure conditions, especially for the conditions involving low flow and/or high quality. For the third generation and other advance reactors involving passive cooling features, accurate prediction of critical heat flux under the low pressure and flow conditions has been recognized and become particularly important. The CHF at low pressure and low mass flow (LPLF) condition is important in relation to the commercial nuclear reactor in accident conditions, loss of coolant accidents (LOCA) of light water reactor and thermal safety performance analyses of power reactors or research reactors are concerns of many researchers in recent years. However the correlations and mechanistic models developed mainly based on the high pressure data are usually used for the CHF at LPLF condition in spite of the different CHF characteristics, because the experimental data are very limited and the phenomenon is not well understood. Under low pressure and low mass flow conditions, the dependency of CHF on other system parameters is different from that of high pressure high flow conditions, especially in the cases of parallel path in subchannel systems. Vapor-to-liquid specific volume ratio at 0.1Mpa is about 1600, which is 260 times that at 15Mpa. Large density difference between liquid and steam at low pressure condition contributes to high slip ratio and rapid gas expansion, which leads to channel obstruction and flow instability in subchannels and often results in CHF with significantly different mechanisms from steady state conditions.

There have been significant works on CHF at LPLF condition (Mishima et al., 1985[1]; Chang et al., 1991[2]; Moon et al., 1996[3]; Kim et al., 1998[4]). Chang et al.[5-7] reviewed the previous work and conducted experimental study and parameter trend analysis on the CHF in vertical tube at low flow low pressure. The works focused on extreme low pressure low flow conditions of $0.1 \le P \le 0.95$MPa, $20 \le G \le 300$kg.m^{-2}.s^{-1}, D=6, 8, 10, 12mm. Chun et al.[8] studied the effect of pressure on CHF in uniformly heated vertical annulus under low flow conditions. Olekhnovitch et al.[9-11] performed experimental research on CHF in vertical tube at low and medium pressure. The conditions was pressure $0.3 \le P \le 4.0$MPa while mass flow $1000 \le G \le 6000$kg.m^{-2}.s^{-1}. The mass flow range was mostly under medium and high flow. Groeneveld et al.[12-14] and Tanase[15] developed the widely used CHF look-up table 1995, 2005 and 2006. As analyzed by Shan et al.[16], 1995 & 2005 look-up table had defect in low flow region. 2006 look-up table[14] replaced or changed part of data or equations in $0 < G < 500$ kg.m^{-2} s^{-1} and $X < 0$. Still, most data in low flow region are established by linear interpolation however. Hence, this paper focuses on parameter trend of low pressure low flow tube CHF experimental data.

2. PARAMETRIC TRENDS OF CHF

2.1. Parametric Trends for fixed exit condition

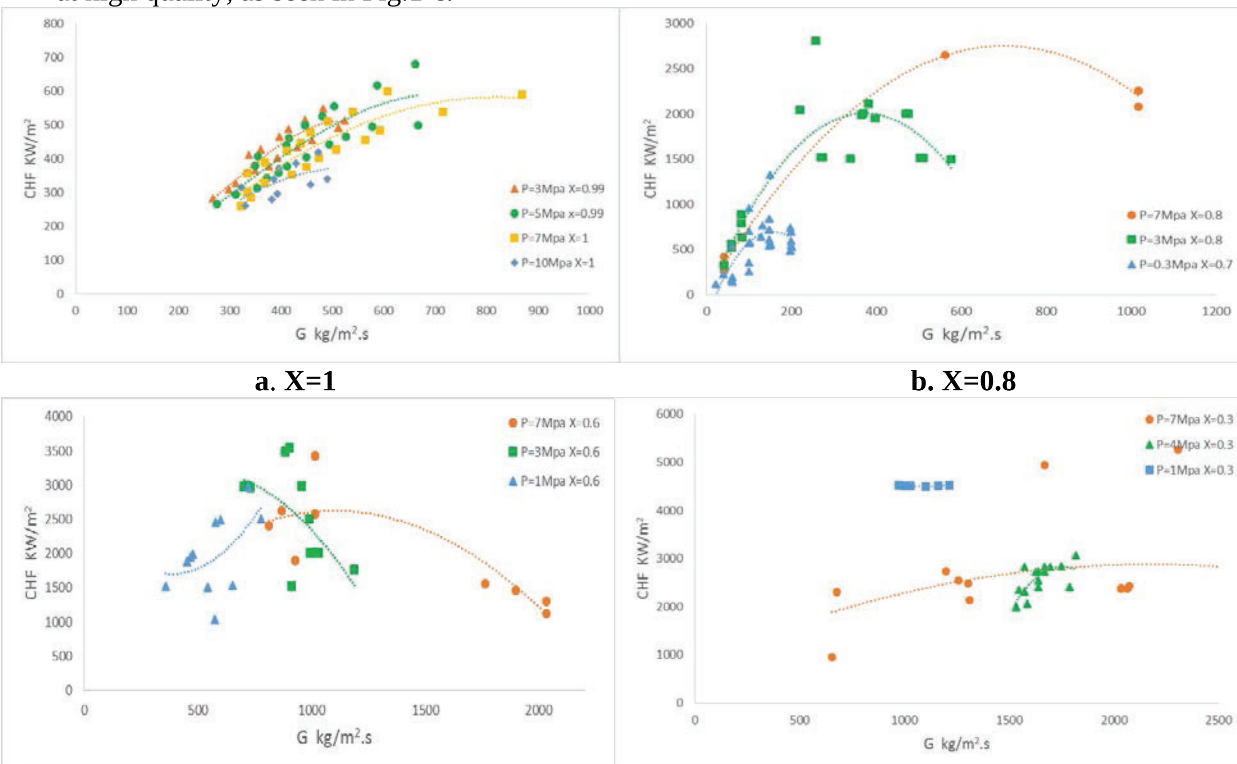
In this paper, CHF values have been examined using experimental data as well as proven empirical model to reveal the dependency of CHF value on various parameters, including mass flux, exit quality, and pressure.

Important parametric trends are summarized as follows:

(1) Mass flux

The effects of mass flux effect are shown separately (Fig.1) for different quality conditions to investigate the difference between the departure from nucleate boiling (DNB) and the liquid film dryout (LFD). The mass flux effect on the high-quality CHF appears to be much more complex.

For most of the quality range (X=0.8 and 1), as the mass flux increases, the CHF increases pass a maximum, then gradually level off (Fig.1-a, X=1) or even slightly decreases (Fig.1-b, X=0.8). It is noted, however, at the quality of X=0.6, the mass flux effect is contrary to what is generally observed at high quality, as seen in Fig.1-c.



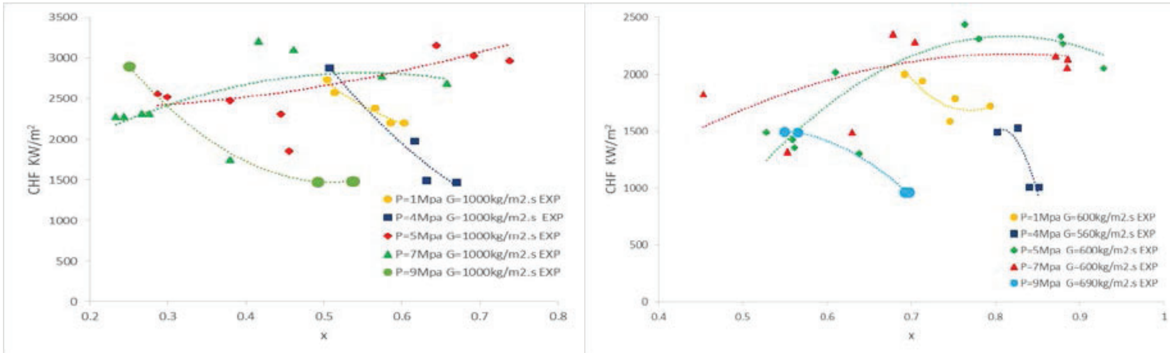
a. X=1 **b. X=0.8**

c. X=0.6 **d. X=0.3**

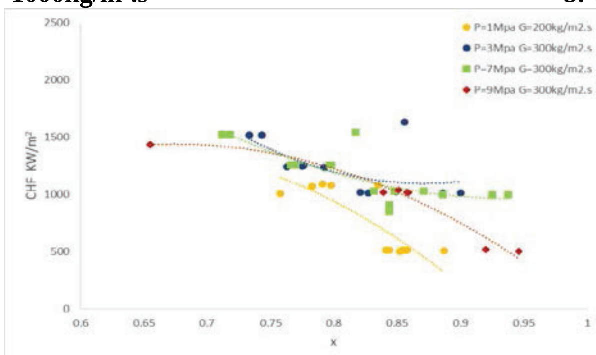
Fig. 1 Mass flux effect for fixed exit conditions (X=0.6)

(2) Exit quality

The exit quality effect on CHF is examined by plotting CHF versus exit quality (X) for a given flow rate under various low to medium pressure ranges, from 1 to 9 Mpa. Fig.2showed the effect of exit quality on the CHF for three mass fluxes. As shown in Figure 2-c, at low mass flux (G<300 kg/m^2.s), the CHF decreases with increasing exit quality, but the trend becomes obscure in the very high quality region (Figure 2-a, G=1000 kg/m^2.s). For the intermediate flow rate, e.g. for the mass flux larger than 600 kg/m^2.s, the effect of exit quality on the CHF depends on the pressure. For some cases (P=4Mpa, G=1000kg/m^2.s; P=1Mpa, G=1000kg/m^2.s; P=4Mpa, G=560kg/m^2.s), there is a sharp decrease of the CHF for a small increase in quality, which was called “limiting quality phenomenon”. While for other medium pressure (P=5Mpa and 7Mpa), there seems a slight trend of CHF increasing with increase in quality as shown in Fig.2-a and Fig2-b.



a. G=1000kg/m².s **b. G=600kg/m².s**

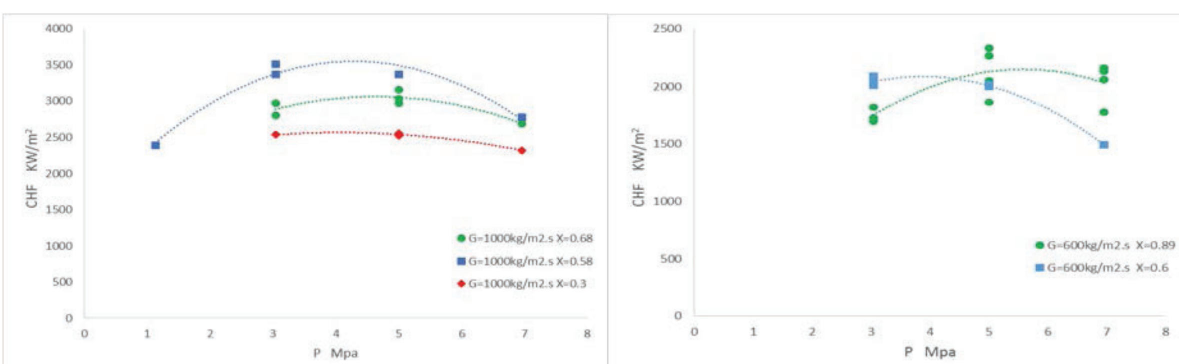


c. G=300kg/m².s

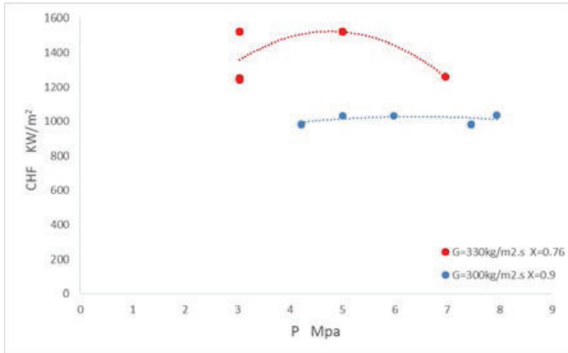
Fig. 2 Effect of exit quality on the CHF

(3) Pressure

Fig.3 show the effect of system pressure on the CHF with constant mass flux under various exit quality conditions. For the high mass flux (Figure 3-a, G=1000 kg/m².s), at the very low pressure range (1 to 3 Mpa), CHF increases with the increase of pressure. This CHF value reaches a peak value at medium pressure around 3 to 5 Mpa, then gradually decreases as pressure increase from 5 to 7 Mpa. Similar trends were observed at medium mass flux (see Figure 3-b, G=600 kg/m².s). However, in the low mass flux ranges (Fig.3-c, G=300 kg/m².s), the trends show CHF remained constant as the pressure increase from 3 to 7 Mpa.



a. G=1000kg/m2.s **b. G=600kg/m2.s**



c. G=300kg/m2.s

Fig. 3 System pressure effect for fixed exit pressure

2.2. Discussion

(1) Effect of mass flux

In the high quality range, the flow in a tube tend to have annular flow regime. In this flow regime, the liquid film thickness has significant impact on the heat transfer efficiency.

At the quality of 60 percent, the critical heat flux decreases as the mass flux increasing. The film thickness (at constant quality) has been found to decrease with increasing velocity for high-pressure adiabatic, heated flows [17, 18], and low-pressure adiabatic flows [19, 20]. Since the critical heat flux is strongly dependent on the film thickness, it would be expected that the critical heat flux would decrease with increasing velocity, Fig.3, which results in a decreasing liquid film thickness. The opposite trend in the present data can again be explained by the stabilizing effect of the higher vapor velocity on the film.

The general trends of the flow-regime boundaries are as shown in Fig.4. The flow regimes which may be encountered in flows in tubes with vertical upflow can be described in the order of increasing gas or vapor content. If very little gas or vapor is involved, the flow will be characterized by isolated vapor or gas bubbles dispersed rather uniformly in the continuous liquid phase. This is known as "bubbly flow". More bubbles appear with an increase of vapor or gas until the bubbles begin to touch one another and agglomerate. As more bubbles agglomerate, the gas begins to flow in long cylindrical, bullet-shaped bubbles, between the bubbles are slugs of liquid and hence "slug flow". Further increase of the gas content destroys the stability of the bubbles, producing "churn flow" or "semi-annular flow" in which slugs of liquid separate adjacent gas bubbles only temporarily. As the gas content continues to increase, the liquid flows on the wall as an annular film and the gas or vapor flows in the center of the tube. This geometry is called "annular flow". "Fog flow" or "dispersed flow" then follows where the gas or vapor phase occupies the entire tube but small drops of liquid are dispersed within it. This flow is also called "mist flow"[21]. It is seen in the maps that the bubbly flow and a large part of the slug flow regime occurs in the subcooled region, while fully developed annular flow exists at 2-4 percent quality.

At high quality, where the flow pattern at the exit of the tube is distinctly annular, changes in the trends are to be expected. There should be little effect of slug flow since the vapor velocities are generally high, and the slug region is far removed from the tube exit. On the other hand, the vapor velocity is now high enough to cause significant entrainment. In Fig.1-a and Fig.1-b, it is seen that the critical heat flux reaches a maximum and then decrease.

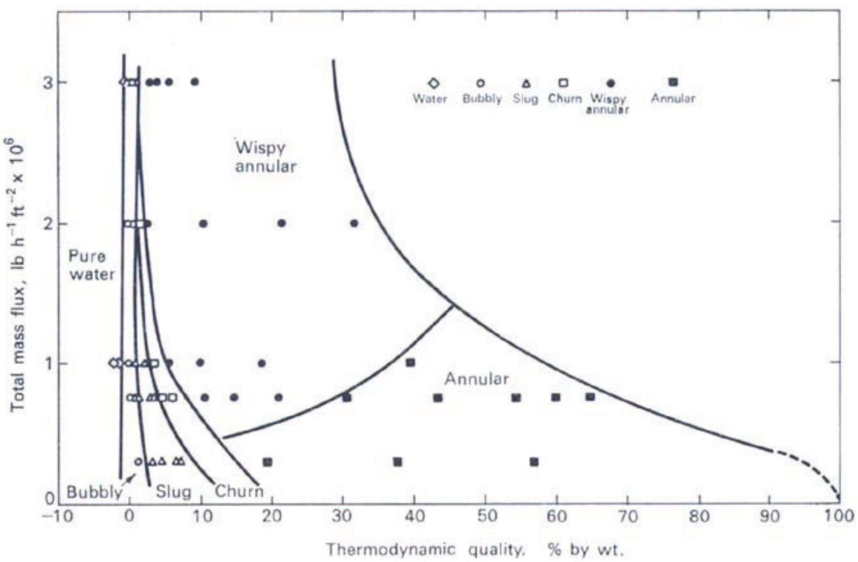


FIG. 2.6. Results of Bennett *et al.* (1965) for flow patterns produced by boiling in a $\frac{1}{2}$ in. bore tube at 1000 p.s.i.a.

Fig. 4 Flow regime map [21]

(2) Effect of exit quality

At the lower pressures, there is a very slight tendency for CHF to increase with increasing quality, Fig.2-a and Fig.2-b. There seems two major factors (the liquid film thickness as well as the stability on the liquid film) contribute to the liquid film effect on the heat transfer phenomena. At higher quality, the vapor velocity is higher. The increasing vapor velocity would tend to stabilize the annular film [19]. The experiments by Andeen and Griffith [22] have demonstrated that the unsteady momentum fluxes in annular flow do, in fact, decrease as the quality is increased. Of course, the film thickness decreases with increasing quality; however, the improved liquid film stability would tend to overweigh this. In addition to this quality effect, it is also reasonable to assume that there would be a greater tendency for the disturbances to be damped out as the slug region becomes farther removed from the tube exit. Both of the effects could explain the observed increase in CHF in the quality region.

For some cases (P=4Mpa, G=1000kg/m^2.s; P=1Mpa, G=1000kg/m^2.s; P=4Mpa, G=560kg/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 phenomenon (LQP)" which was discussed by Bennett [23], Katto [24], Levitan [25], Kirillov [26], Kim[4], and many others. LQP usually occurs in the intermediate steam quality region, CHF around the limiting quality is due to dryout of a liquid film in the absence of replenishment from the core of an annular-mist (dispersed-annular) flow.

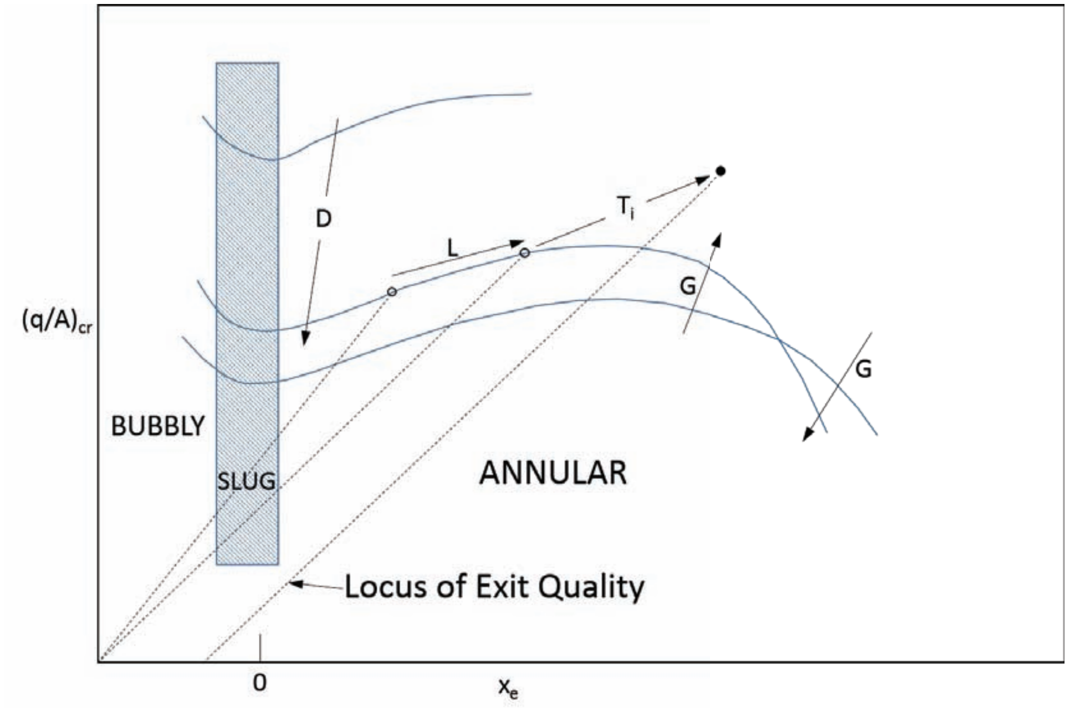


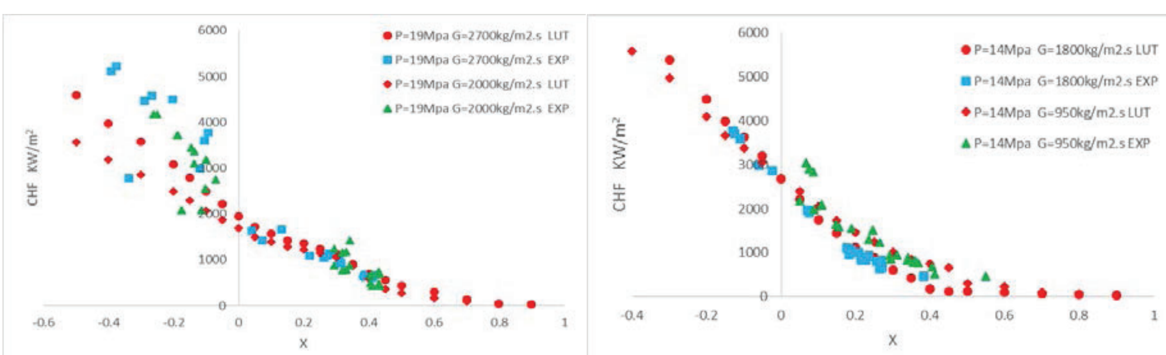
Fig. 5 Summary of trends of low-pressure critical-heat-flux data [19]

2.3. Parametric Trends of CHF Predicted by the Exiting CHF Prediction Methods

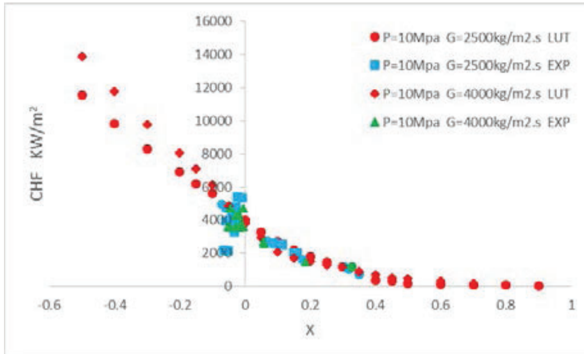
There are several CHF correlations which are claimed to cover LPLF conditions (Bowring, 1972 [27]; Katto and Yoshiro, 1984 [28]; Hall, David D and Mudawar, Issam, 2000[29]). The 2006 CHF look-up table of Groeneveld et al.[30] is based on local conditions while others are based on inlet conditions. The CHF table by Groeneveld et al. is compared because it is usually used in several best-estimate thermal hydraulic system codes.

2.3.1. Parametric Trends of CHF Predicted by the Look up Table at the High Pressure and High Mass Flux Conditions

The experiment data show highly consistent with the parametric trends of CHF predicted by the Look up Table at the high pressure and high mass flux conditions except for the high subcooled region (Fig.6).



a. P=19Mpa **b. P=14Mpa**



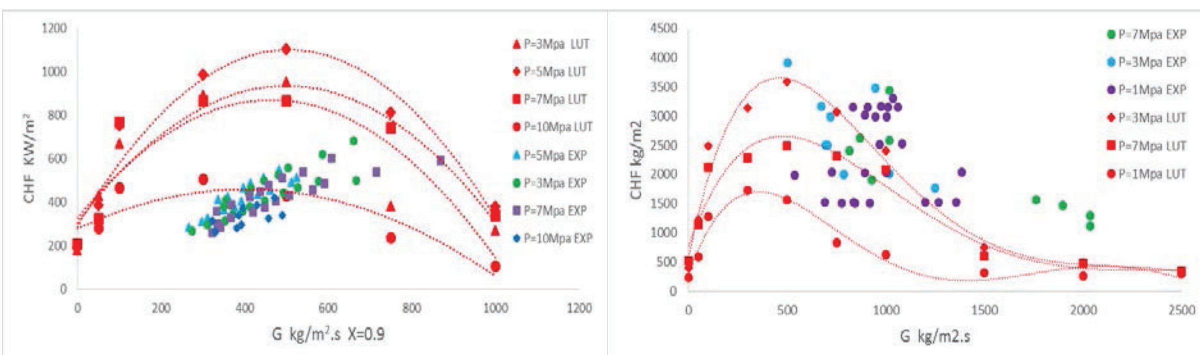
c. P=10Mpa

Fig. 6 Parametric trends of CHF predicted by Look up Table

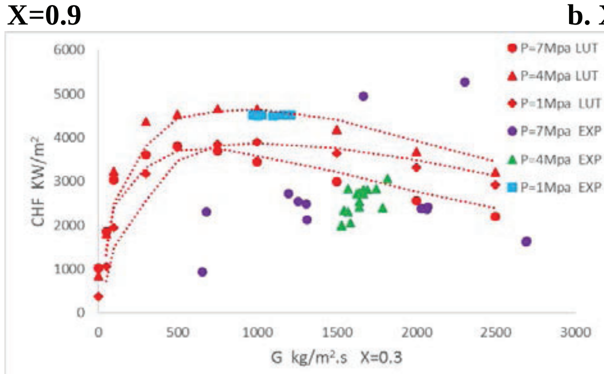
2.3.2. Parametric Trends of CHF Predicted by the Look up Table at the Low Pressure and Low Mass Flux Conditions

a). Mass flux

As shown in Figures7, all of the conditions show same CHF-G trend, as the mass flux increases the CHF increases, passes a maximum, and then gradually decreases. At the condition of X=0.6, the trend of experimental data is distinctly different from the CHF look-up table, Fig.1-c and Fig7-b.



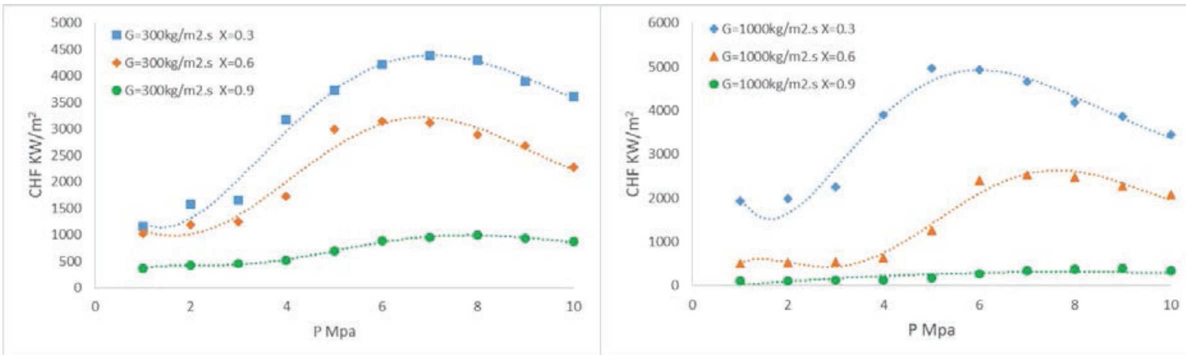
a. X=0.9 **b. X=0.6**



c. X=0.3

Fig. 7 Mass flux effect for fixed exit conditions (Look up table)

b). Pressure effect
Groeneveld et al.'s table shows similar pressure effect on CHF with the experimental data, while the CHF in the table peaked at higher pressure (Fig.3 and Fig.8).



a. G=1000kg/m^2.s **b. G=300kg/m^2.s**

Fig. 8 System pressure effect for fixed exit pressure (Look up table)

c). Exit quality
The trend of CHF-X shows great difference with the experimental data trend. All of the correlation and table just show gradual decrease in CHF value with the increase of exit quality.

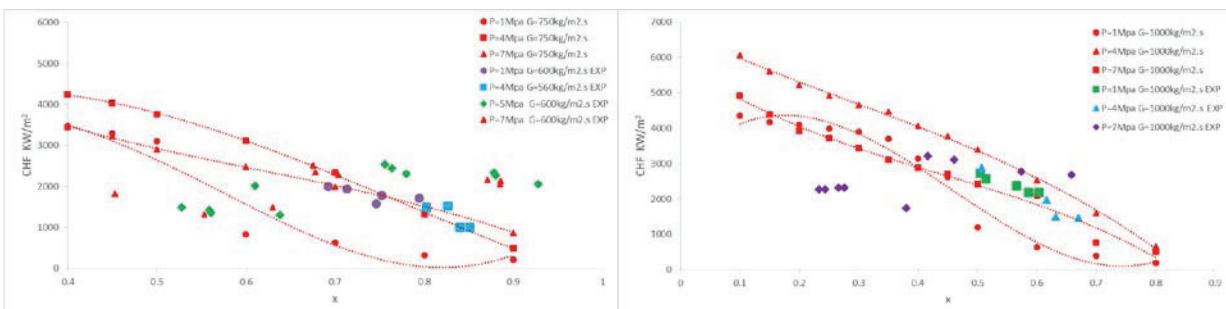


Fig. 9 Effect of exit quality on the CHF (Look up table)

3. CONCLUSIONS

The study of parametric trends of CHF was carried out under the condition of low pressure (<10Mpa) and low mass flux (<1000kg/m^2.s) based on CHF data obtained from various experiments.

Important results are as follows:
1. At high pressure and high mass flux conditions, the experimental data is highly consistent with the parametric trends of CHF predicted by the Look up Table except for the high subcooled condition.
2. The highly subcooled condition need for further research in view of the distinct difference between experiment data and Look up Table trend at the high pressure and high mass flux condition.
3. Parametric trend analysis of CHF for fixed exit condition show significant difference with those of previous studies with exception of the pressure effect. This indicates the need for special treatment of LPLF conditions.

4. At quality about 60 percent, the critical heat flux decreases as the mass flux increases.
5. As contrast to most of literature, the critical heat flux increases with increasing quality at several operation conditions.

More experiments are required for extension of the data base, identification of mechanisms and clarification of the parametric effects including the pressure, mass flux, quality and geometrical effects.

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