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Prediction of Critical Heat Flux in a Tube with Non-uniform Axial Heat Flux Distribution

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Abstract

The performance of axial flux distribution factor, K_5 of the 1995 Groeneveld CHF look-up table in predicting CHF with non-uniform heat flux distributions was evaluated. A total of 856 tube CHF data having various non-uniform axial flux distributions(AFD) were used in this analysis. The results showed that K_5 factor of the look-up table from the boiling-length-average(BLA) approach provide a reasonable prediction of the AFD effect on CHF, but do slightly overpredict the measured CHF for certain critical qualities and flux peak shapes. The prediction accuracy can be improved using a modified BLA approach in conjunction with the look-up table. It predicts the CHF power for the compiled data with an average error of 1.5% and a standard deviation of 10.3%. It also provides a reasonable prediction of CHF locations.

1. Introduction

One of the most critical requirements in the design of nuclear reactor is to determine the allowable power level to avoid Critical Heat Flux(CHF) during normal reactor operation as well as the anticipated occurrences of transients. In accident conditions, it is also one of important criteria for judging the fuel integrity. Aside from flow conditions, one of the most important factors affecting the CHF is the axial heat flux distribution (AFD). Nuclear reactors generally have a variety of axial heat flux shapes that change with fuel burnup. Moreover, local heat flux peaking may occur for a number of reasons, e.g., end effects in short fuel bundles, use of control rods, fuel densification etc. Hence, many researchers have investigated the effect of heat flux profile and heat flux spike on CHF, and several correction factors have been suggested. These correction factors and models enable reactor designers to utilize existing CHF data and correlations for uniform AFDs for the design of nuclear reactors where different non-uniform AFDs prevail. However, there is no general analytical method available for the prediction of CHF for non-uniform heat flux profiles.

At present, the 1995 Groeneveld CHF look-up table is one of the most popular methods for predicting CHF in reactor safety codes. The look-up table covers a broad range of conditions, and employs several CHF multipliers to account for various separate effects of geometry and flow conditions. Among them, the AFD correction factor, K_5, defined as the ratio q_{local}/q_{BLA} where q_{BLA} is the boiling-length-average heat flux, has been used for quality region (X_e>0) in the look-up table, and can have a considerable effect on the prediction results. However, this method may not be the optimum method for determining CHF conditions for a non-uniform AFD for all conceivable conditions. Hence, the main purpose of this paper is to assess the efficacy of predicting the AFD effect with the BLA approach in conjunction with the CHF look-up table using the compiled tube CHF database as a basis for the comparison.

2. Data Sources

A total of 856 CHF data for tubes with non-uniform heat flux distributions were compiled from the literature. A summary of the CHF data used in this analysis is given in Table 1; the data sets cover AFDs with inlet, middle, outlet peaks and with a smooth variation or with a step change in heat flux. For comparison, all data sets except Becker[1] and Keeys[2] include a set of reference CHF data obtained for the same or similar size geometry with a uniform AFD.

Analysis of the AFD effect requires accurate measurements of the CHF or critical power as well as measurement of the axial CHF location. It is often difficult to determine the precise initial CHF location for a non-uniform AFD since conditions close to CHF can exist over a wide length within tolerance of experimental power, say ± 2%, and instrumentation to detect initial CHF occurrence is frequently sparsely located along the heated length. Hence, the uncertainty in CHF location can be considerable.

Lee[3,4,5] and Swenson[6] occasionally reported CHF to occur at more than 2 thermocouples; the middle point was assumed as the initial CHF location in this analysis (T/Cs were installed every 8~10 cm for Lee' s tests and every 15.24 cm for Swenson' s tests). Casterline' s data[7] can have larger uncertainties in initial CHF locations since they were detected by two ways, voltage taps and thermocouples separated more than 30 cm. Todreas[8] used an aluminum tubular test section which had a low melting point: the CHF location was assumed to correspond to the failure location. Note that the temperature spike at CHF depends on the CHF type and the failed location may not always be the initial CHF location. In Zenkevich' s tests[9], the CHF was assumed to occur at the top of a hot patch. Bertoletti data[10] with high inlet qualities showed large uncertainties; his data with $X_{in} > 0.4$ are not considered in this analysis. Since Becker' s test[1] were designed for measuring post-dryout temperatures, the initial CHF locations were not reported but were deduced from the reported temperature distributions. The section downstream of the CHF location was not considered in Becker's study because heat input after CHF location usually has no effect on CHF[2,3,9]. Kinoshita[11] obtained CHF at highly subcooled conditions in a very short tube with step change of heat flux. Only 4 out of 13 non-uniform data reported in his paper are within the range of look-up table application. His data, however, may be helpful to assess the applicability of the look-up table to highly subcooled CHF conditions.

3. Analysis

3.1 Boiling Length Approach

The boiling length approach was originally proposed by Bertoletti[12]. It assumes that, for a given flow and pressure, there is a unique empirical relationship between the critical quality and the boiling length. Others such as Lahey and Moody[13] followed the same approach although they used different relationship. The boiling length approach implies that the CHF is independent of the upstream AFD and thus has some similarity with the overall power hypothesis, except that the boiling length approach can predict the location of CHF. A variation of the boiling length approach was proposed by Groeneveld [14] who used a multiplier K_5 to modify the CHF for uniformly heated channels to make it applicable to non-uniform AFDs. Effectively this method, also known as the boiling-length-average heat flux approach (or q_{BLA}) approach, simply states that the CHF occurs when the boiling-length average heat flux, exceeds the CHF, where q_{BLA} is defined as

$$q_{BLA} = L_B^{-1} \int_{z=z_{sat}}^{z=z_{chf}} q''(z)dz \tag{1}$$

This was incorporated in the K_5 factor as

$$CHF_{nu} = K_5 * CHF_u \quad \text{where } K_5 = \frac{q_{local}}{q_{BLA}} \tag{2}$$

In Eq.(1) the boiling length L_B is usually defined as a length from the inception of the bulk boiling (Xe=0) to the CHF location as $L_B = l_{chf} - l_{sat}$. For negative qualities no boiling length is present and K_5 is equal to unity, i.e. the local conditions approach is used.

3.2 Prediction Method and Analysis Procedure

The thermal design of nuclear reactors requires a certain margin to CHF, which is usually described by the CHFR (Critical Heat Flux Ratio) and the CHFPR (Critical Heat Flux Power Ratio). The CHFR is based on the local condition concept while CHFPR is based on inlet condition. They are related to the direct substitution method (DSM) and heat balance method (HBM), respectively. Details of these two concepts and their applications have been described by Groeneveld[15] and Siman-Tov[16] .

In general, to predict CHF for non-uniform heat flux distributions, the CHF vs. X_e or X_e vs. L_B correlations based on uniform AFD data are employed. The two are equivalent, but the CHF vs. X_e is used in this analysis because of the look-up table structure. That is, the heat flux vs. quality curve of the channel is increased until it becomes tangent to the CHF line predicted by the 1995 CHF look-up table for a given pressure and mass flux and geometry, as shown in figure 1, thus predicting the initial CHF and CHF location. Note that the predictions using the DSM and HBM give the same results because heat balance is maintained in both cases.

In assessing prediction methods for non-uniform AFDs, accurate prediction of CHF with uniform AFD is essential. Hence, the prediction of the 1995 look-up table for uniform heat flux distribution is first checked against corresponding uniform CHF data. If there are some noticeable differences in the prediction, corrections are applied to the CHF look-up table. Then the CHF for non-uniform AFDs are predicted by the corrected 1995 Groeneveld look-up table with/without $K_{5.}$

4. Results and Discussions

The CHF data can depend on the test sections as well as test loops characteristics, and may not be consistent with each other. For example, the heat flux is usually calculated from the measured voltage and/or current, and the common assumption that the temperature coefficient of resistivity (TCR) is near zero as is the case for Inconel test section. However, some earlier test sections were constructed of stainless steel, aluminum or nickel that have high TCRs. Because of their variation in resistivity (from the highly subcooled region to saturated region near the outlet) erroneous values of CHF will be obtained if the local CHF is based on the average TCR, e.g., Casterline[7] reported that the variation in TCR can affect the local CHF by 8% on average. This will have an effect on the results of Lee[5], Swenson[6], Casterline[7] and Todreas[8] who used test sections made of aluminum, stainless steel or nickel.

1) Uniform AFD

The CHF prediction results for the uniform AFD using the 1995 CHF look-up table are given in the second column of Table 1 for DSM and HBM (in brackets), while the parametric trends in the predicted-to-measured CHF ratios are shown in figure 2 for DSM (Becker’ s data were left out of figure 2; they were are well predicted by both methods since they were used in the construction of the look-up table). As expected the deviation from the look-up table by HBM is much smaller than that by DSM[15]. In general, for the data sets of this study, the look-up table is in reasonable agreement with the measured CHF. In the Baek’s analysis[17] the look-up table slightly overpredicts the data as L/D increases and underpredicts with a decrease of mass flux, especially for G < 1000 kg/m^{2}s. For these cases where there is a clear bias in the prediction, the look-up table was corrected as indicated in section 3.2. When the parameter range of the uniform CHF data does not cover that of non-uniform data, or when the uniform data are not measured, the 1995 look-up table is used as the basis for comparison with the non-uniform AFDs.

2) Non-uniform AFD

The CHF predictions of the look-up table with and without K_5 factor are shown in table 1 and figures 3 to 4 for AFDs with inlet and middle peaks. Results for AFDs with an outlet peak show a similar trend. The predictions without the factors (i.e. using the local conditions approach) generally shows good agreement at high subcoolings (X_e <-0.2), where local conditions are dominant, but overpredict the CHF power for most other data except Casterline data[7]. The overprediction is around 10 % on average, but 25% for the inlet peak Becker data. The CHF was generally predicted to occur more upstream than the measured locations.

The predictions of the look-up table with the K_5 factor show better agreement in CHF power and CHF locations as well, but the critical power is still slightly overpredicted, particularly for higher qualities and AFDs with an outlet peak. The results suggest that small corrections to K_5 factor would improve the prediction of the non-uniform AFD effect.

In the boiling region, all data except Casterline[7] and some of Todreas[8] are overpredicted on average. It is noted that for the Becker and Swenson data, the K_5 factor overpredict the critical power as the heat flux peak moves to exit and the axial form factor increases. Todreas data show a relatively large uncertainty, which is probably due to uncertainty in the measurements since CHF was defined as actual failure of test section, not by thermocouples (Todreas reported a reproducibility of 10% in CHF power measurements and a large variation in CHF location). Casterline[7] and Lee[4] have similar test conditions and geometry (except the heat flux gradient near the exit). However, their prediction results are very different. For Casterline’s data, the predicted CHF locations were downstream from the measured locations and correspondingly the CHF was underpredicted. Two possible explanations can be suggested for this inconsistency: (i) Instrumentation; Casterline used both a Wheatstone bridge and TCs to detect CHF (most of his CHFs were detected by the bridge), while Lee used TCs only. Casterline defined the CHF as the point at which measurable temperature instabilities were observed. This can be detected at an early stage by the

Wheatstone bridge and may have enabled detection of CHF at more downstream locations where temperature excursion are modest and the critical power is low. (ii) Difference in heat flux near the exit; Lee used a much higher heat flux at the exit than Casterline. This may affect the prediction of K_5 which uses the BLA approach. One weakness in the q_{BLA} approach is that it may not predict the correct trends for cases where the local heat flux is very low or very high. To correct for this, Groeneveld[18] has recommended the limits of $0.3 < K_5 < 3.0$. Note also that the heat input after CHF location has an insignificant effect on the local CHF[3, 9, 19].

In the subcooled region, K_5 provides reasonable predictions for the data of Lee[5] and Todreas[8] and good agreement with Zenkevich data[9]. The results imply that the local condition approach is acceptable in the subcooled region. Kinoshita data[11] seems to indicate that a correction may be necessary for the AFD effect for highly subcooled conditions. But the scarcity of his data and the very short heated length used (L/D=10) makes it difficult to draw any firm conclusions.

5. Improvement of AFD Correction Factor, K_5

The experiments clearly demonstrate that the AFD affects both the CHF and its location, and it has been shown that correction factor of K_5 of the look-up table can provide a reasonable estimate of the AFD effect. Further improvements to the prediction of the AFD effect will be considered below.

5.1 Integration Starting Point for q''_{BLA}

Instead of the X_e=0 point other locations along the heated channel may be used as the starting point for q''_{BLA} , i.e. channel inlet, onset of nucleate boiling (ONB), onset of significant void (OSV), saturation and onset of annular flow (OAF) locations. They all can affect the CHF because the distributions of void, bubble boundary layer thickness and film flow rate are important to the CHF phenomena. Actually, Tong [20], Hwang[21], Bowring[22], Groeneveld[14] and Lee[5] all used different lower limits of integration. Hence, the influence of those locations on the prediction of K_5 in conjunction with the 1995 Groeneveld CHF lookup table was assessed for several selected sets of data, and the results are shown in table 2. ONB, OSV and OAF locations were predicted by Jens-Lottes, Saha-Zuber and Taitel-Dukler models, respectively [23]. It can be seen that the results are not significantly changed except for the channel inlet case, which imply that the lower limit of integration for K_5 does not have a significant effect on the prediction of CHF for non-uniform heat flux distribution. However, X_e =0 is preferred because it shows slightly better results and is the easiest to evaluate.

5.2 Correction to K_5

As was shown above, K_5 based on the boiling length starting at X_e=0 provides a reasonable prediction of the AFD effect. A further comparison, of the ratio measured to predicted K_5 values using the compiled database, is shown in figure 5 as a function of G and X_e. Figure 6 presents this ratio vs. quality for Swenson[6] and Becker[1] data with different axial flux profiles at a pressure of 140 bar. Generally, the correction factor is known to be dependent on the quality, mass flux and flux shape. These figures show a small but systematic trend of quality and flux shape, especially for outlet peaks. The trend for mass flux and axial form factor is less clear. To correct for these trends a modification to K_5 was derived, based on a best fit of the data of figure 5. The equation for the modified K_5 factor is,

$$K_5^{'} = K_5[(1+0.176Xe+0.483Xe^2)(1+0.241Y^5)] \quad , \ Xe > 0.0 \qquad (3)$$

$$K_5^{'} = 1.0 \quad , \ Xe \le 0.0$$

where, $$Y = \int_0^{Z_{q''_{\max}}} q''(z)dz \Big/ \int_0^{L_h} q''(z)dz$$

Using the modified K`$_5$ of eq (3), the non-uniform AFD data were recalculated and the results are shown in figure 3 c) and 4 c). The new predictions of AFD effect show better agreements with the measured data except for Casterline[7] and Todreas[8]. As described previously, Todreas data are subject to large uncertainties and Casterline data used a different method for detecting CHF. Better predictions for CHF power and CHF location were also noted. The resulting error statistics for the modified K_5 are summarized in the last column of table 1. In general, the use of eq. (3) results in a further improvement in the prediction of the AFD effect on CHF.

6. Summary and Concluding Remarks

1) If possible, the prediction accuracy of the look-up table at conditions of interest should be compared to the uniform heat flux distribution data before being applied to the evaluation of the CHF for non-uniform heat flux distribution.

2) The CHF power for non-uniform heat flux distribution can be up to about 25% lower than that for uniform heat flux distribution, and the magnitude depends on the quality and the flux peak shape. K_5 factor may overpredict the measured CHF slightly.

3) X_e=0 is recommended for the lower limit of integration for the boiling-length-average heat flux, required to evaluate the AFD correction factor K_5.

4) The local conditions approach may be used (i.e. the correction factor K_5=1.0) to predict the CHF for non-uniform AFDs and subcooled conditions (probably up to the onset of annular flow).

5) The AFD effect can be predicted with a reasonable accuracy using the K_5 factor although they may slightly overpredict the measured CHF depending on quality and AFD. The modified K_5 of eq. (3) provides an improved prediction of the AFD effect with a mean of 1.015 and STD of 0.103 for a total of 856 data with non-uniform AFDs.

6) For very large variation in heat flux, upper and lower limit should be applied to K_5, especially near the outlet of channel where the heat flux may approach zero. It is suggested that K_5 should be within the limit $0.3 < K_5 < 3.0$.

7) The correction to K_5 is based on tube data for the range of conditions covered in our database. Caution should be exercised when extrapolating beyond data base and applying to bundle geometries.

Nomenclature

Symbols		**Subscripts**	
CHFPR	Predicted to measured CHF power ratio	BLA	Boiling length average
CHF	Critical heat flux	c, CHF	Critical heat flux
G	Mass flux	in	Inlet
P.F	Axial Peaking factor $= q''_{\max} / q''_{avg}$	nu	Non-uniform AFD
q''	Heat flux	sat	Saturation
q''_{BLA}	Boiling length average heat flux	u	Uniform AFD
X_e,	Equilibrium quality		
Z $q''_{\max}$	Location where heat flux is maximum		

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Table 1. Range of CHF data and Statistics of results for predicted to measured CHFPR for uniform and non-uniform heat flux distributions

Source	**Uniform**	**Non-uniform**					
		Profiles	**Geom**[c]	**Test Cndtns**[c]	**w/o K_5**	**K_5**	**new K_5**
Swenson (1963)	m=1.084(1.037)[a] σ =0.137(0.045)	P.F=1.23 ~1.96 (i, m, o)[b]	D=10.6 ~11.3 L=1.83	P=137.9 G=678~1763 Xc=-0.05~0.47	1.089 (0.064)	1.023 (0.061)	0.990 (0.047)
Lee (1963)	m=1.041(1.011) σ =0.041(0.022)	P.F=1.27 ~1.45 (m)	D=9.73 L=1.83	P=69~112 G=2007~4082 Xc=0.03~0.43	1.087 (0.058)	1.015 (0.032)	0.993 (0.038)
Lee (1965)	m=1.088(1.021) σ =0.191(0.033)	P.F=1.4 (m)	D=9.47 L=3.66	P=66~71 G=2010~4100 Xc=0.17~0.47	1.130 (0.063)	1.023 (0.024)	0.990 (0.021)
Lee (1966)	m=0.971(0.994) σ =0.122(0.045)	P.F=1.67 (i)	D=22.1 L=1.19	P=109~113 G=328~1345 Xc=-0.04~0.51	1.094 0.106	1.062 (0.101)	1.053 (0.107)
	m=0.861(0.931) σ =0.209(0.109)	P.F=1.62 (i, o)	D=28.3 L=1.19	P=108~125 G=336~1360 Xc=-0.11~0.44	1.196 (0.191)	1.037 (0.141)	1.014 (0.113)
	m=0.969(0.980) σ =0.085(0.051)	P.F=1.17 (m)	D=15.9 L=1.00	P=86~125 G=1038~3399 Xc=-0.12~0.17	1.139 (0.065)	1.084 (0.047)	1.076 (0.046)
Becker (1992)	m=0.992(0.999) σ =0.242(0.045)	P.F=1.6 ~2.04 (I, m, o)	D=15.0 L=7.00	P=10~160 G=500~3000 Xc=0.07~0.93	1.148 (0.151)	1.108 (0.109)	1.062 (0.096)
Todreas (1965)	m=0.903(0.974) σ =0.133(0.043)	P.F=1.26 ~1.95 (i, m, o)	D= 5.4 L=0.76	P=4.3~9.03 G=652~2742 Xc=0.07~0.64	0.995 (0.132)	0.928 (0.082)	0.871 (0.078)
Casterline (1964)	m=1.248(1.000) σ =0.204(0.059)	P.F=1.57 (m)	D=10.2 L=4.88	P=69 G=1315~6850 Xc=0.08~0.63	0.816 (0.056)	0.749 (0.068)	0.730 (0.073)
Zenkevich (1969)	m=0.870(0.932) σ =0.099(0.052)	P.F=1.9 (m)	D= 7.9 L=0.53	P=100~180 G=994~2022 Xc=-0.96~0.38	1.021 (0.069)	1.026 (0.072)	1.023 (0.068)
Bertoletti (1963)	m=1.305(1.172) σ =0.218(0.122)	P.F=1.2 (m)	D= 8.1 L=0.64	P=69 G=1090~3915 Xe=-0.02~0.56	1.039 (0.079)	1.026 (0.061)	0.969 (0.073)
Keeys (1971)	-	P.F=1.4 (m)	D=12.7 L=3.66	P=69 G=720~4060 Δhi=0.15~0.75	1.188 (0.035)	1.062 (0.013)	1.014 (0.030)
Kinoshita (1998)	m=0.769(0.793)	P.F=0.51, 0.79 (m)	D= 6.0 L=0.06	P=6, 11 G=4796~9070 Tin=40 °C	0.908 (-)	1.057 (-)	0.908 (-)
Total	m=0.989(0.988)		856 (= # of data)		1.103 (0.150)	1.047 (0.110)	1.015 (0.104)
	σ =0.194(0.089)		187(i)		1.198 (0.180)	1.061 (0.123)	1.027 (0.113)
			550(m)		1.073 (0.124)	1.033 (0.097)	1.007 (0.099)
			119(o)		1.089 (0.132)	1.084 (0.132)	1.032 (0.106)

[a] value in ( ) is by HBM

[b] i, m, o mean inlet, middle and outlet peaks, respectively.

[c] unit : D (mm), L (m), P (bar), G (kg/m^2/s)

Table 2. Error Statistics of CHFPR results with different integration points for non-uniform heat flux distributions

Source	Starting point of integration				
	inlet	ONB	OSV	Xe=0	OAF
Swenson (1963)	1.109 (0.138)	1.071 (0.120)	1.033 (0.104)	1.023 (0.061)	1.030 (0.039)
Lee (1963)	1.051 (0.097)	0.996 ().096)	0.993 (0.071)	1.019 (0.028)	1.030 (0.027)
Lee (1965)	1.054 (0.024)	0.997 (0.163)	0.998 (0.139)	1.023 (0.024)	1.003 (0.142)
Becker (1992)	1.134 (0.098)	1.130 (0.100)	1.119 (0.104)	1.099 (0.105)	1.095 (0.101)

* Mean value
** Standard deviation

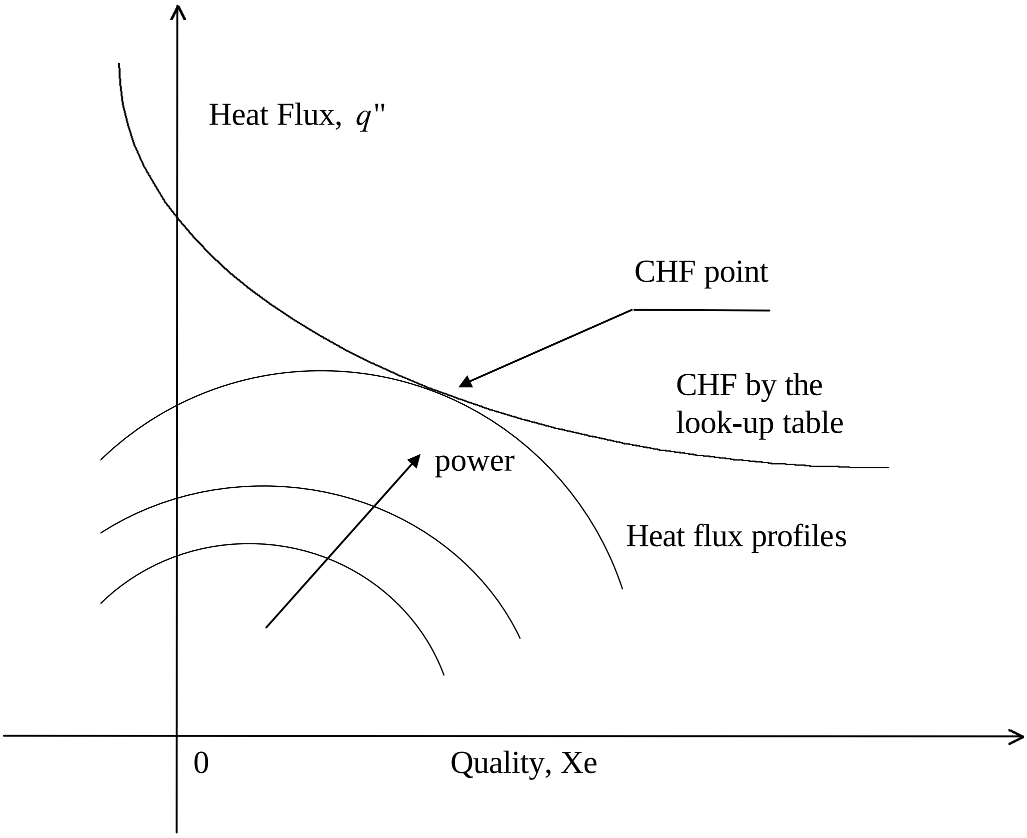
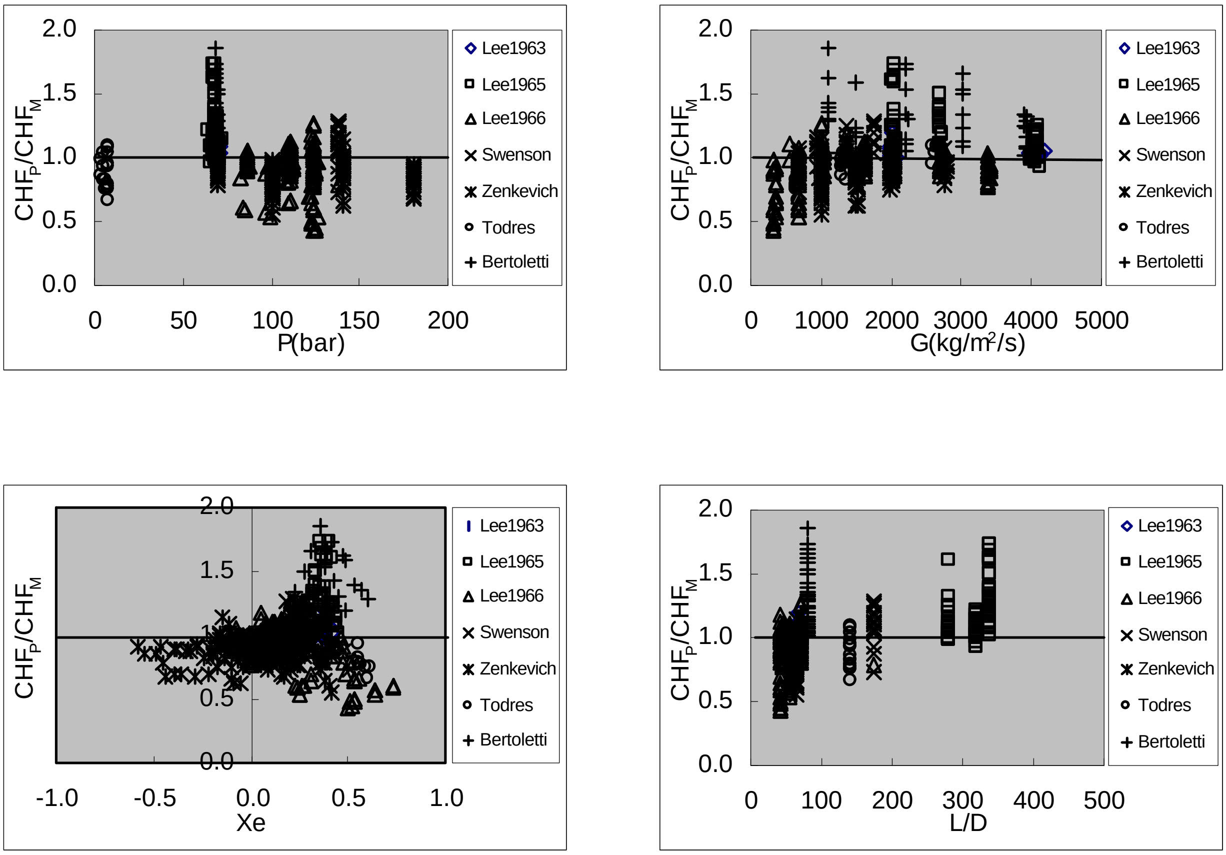
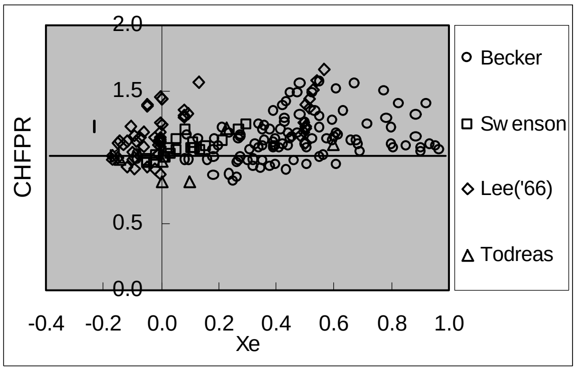


Figure 1. Prediction of CHF and its location for non-uniform heat flux distribution

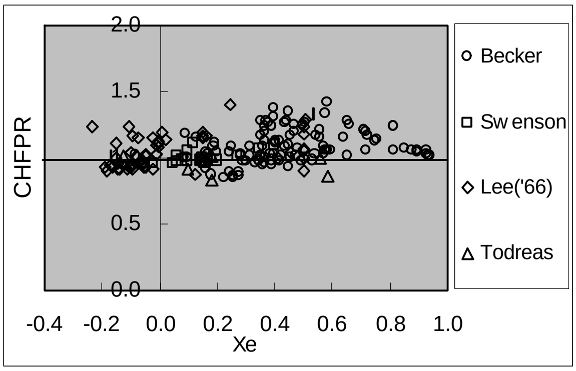


(Mean=0.986, STD=0.194)

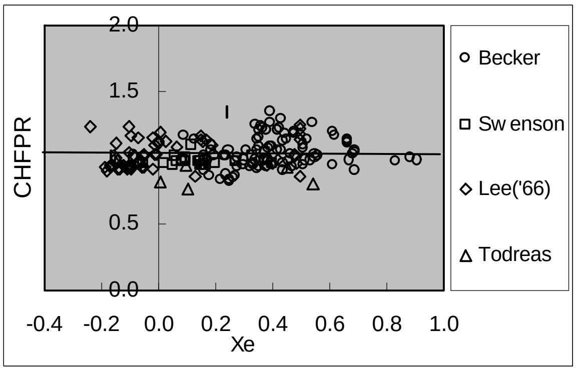
Figure. 2 Predicted/measured CHF ratios vs. P, G, Xe and L/D for a uniform heat flux distribution(DSM)



a) with K5 (Mean=1.061, STD=0.123)

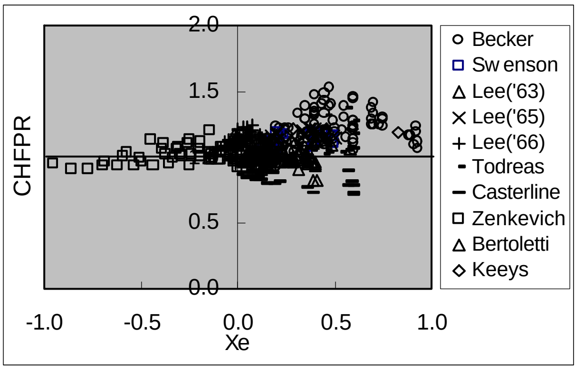


b) with K5 (Mean=1.061, STD=0.123)

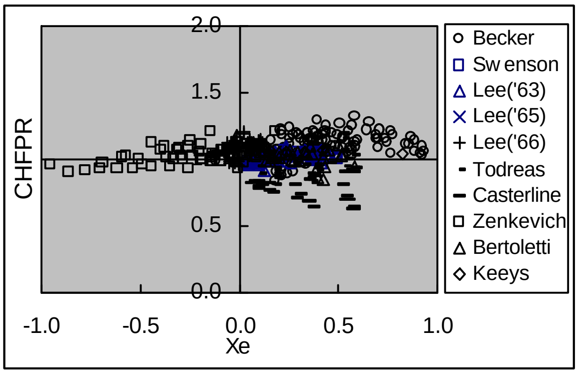


c) with corrected K5 (Mean=1.027, STD=0.113)

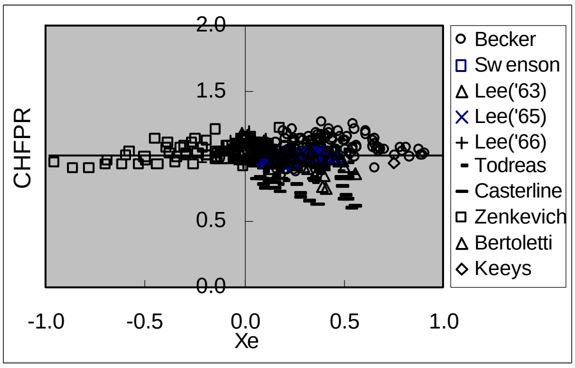
Figure. 3 Predicted/measured CHF power ratios for AFDs with inlet peaks



a) with K5 (Mean=1.033, STD=0.124)



b) with K5 (Mean=1.033, STD=0.097)



c) with corrected K5 (Mean=1.099, STD=0.099)

Figure. 4 Predicted/measured CHF power ratios for AFDs with middle peaks

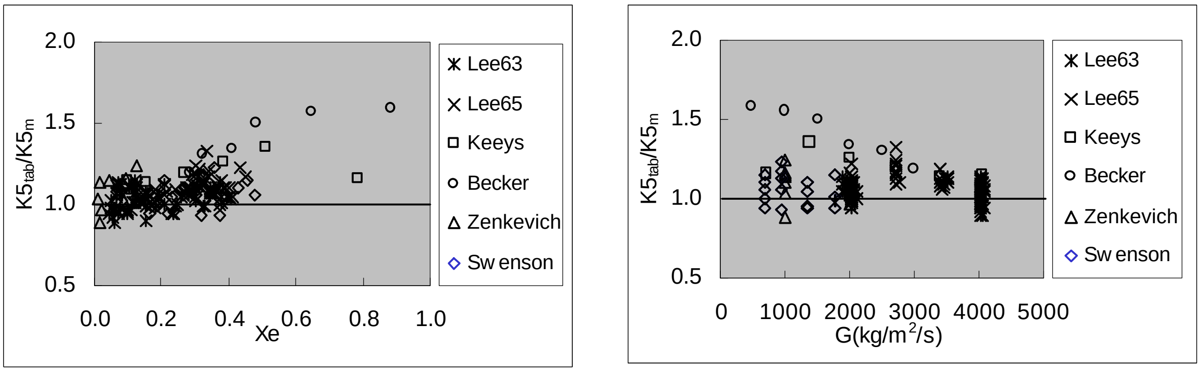
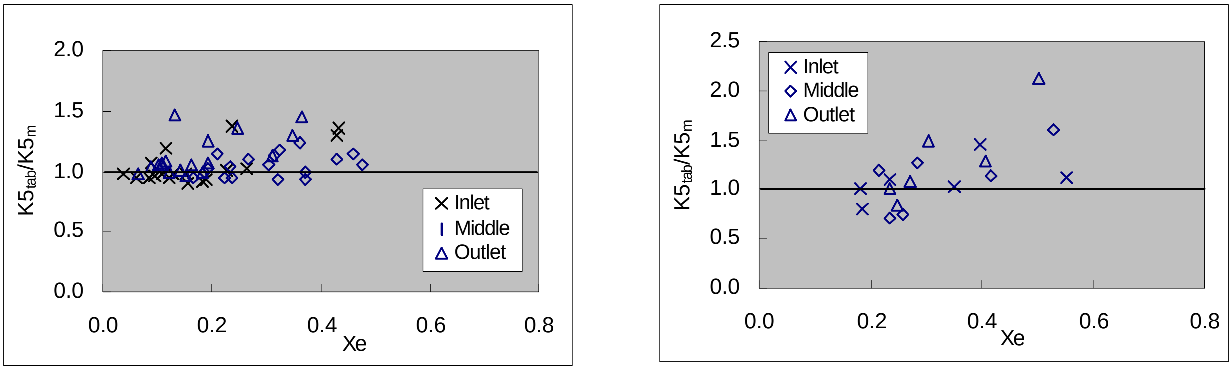


Figure 5 Predicted/measured K5 factor ratios vs. Xe and G



a) Swenson(1963) data

b) Becker(1992) data

Figure 6 Predicted/measured K5 factor ratios for different AFDs at P= 140 bar