RESEARCH OF THE BUNDLE CHF PREDICTION BASED ON THE MINIMUM DNBR POINT AND THE BO POINT METHODS

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ABSTRACT

There are two ways in the development of CHF correlation in rod bundles: one is based on round tube CHF correlations, considering the effects of spacers and CHF promoters, effects of cold walls, etc. The other one is to develop the correlation directly using the rod bundles CHF experimental data which includes two methods: the minimum DNBR point method and the BO point method. In this study, the local thermal-hydraulic parameters at DNB occurrence point of each set of bundle CHF data were obtained by using the subchannel code ATHAS. Both of the minimum DNBR point and the BO point methods were then applied to develop a new CHF correlation for rod bundles. The so-called "three-step method" was used to determine the shape of the correlation and the non-linear regression analysis method was applied to determine the coefficients of the correlation. Based on the large database of CHF tests, a new CHF correlation named the ACC correlation has been developed. The analysis and assessment results indicate that the ACC correlation can fit the experimental data well with high prediction accuracy and correct parametric trends. Compared with the minimum DNBR point method, the BO point method is recommended to predict the risk of DNB because it is more reasonable and conservative with better predication rate. Coupled with subchannel code ATHAS, this correlation can simulate the thermal-hydraulics performances of rod bundles exactly.

KEYWORDS

Bundle CHF Prediction; The minimum DNBR point method; The BO point method; Sub-channel code ATHAS

1. INTRODUCTION

The local heat transfer coefficient drops steeply and the heat transfer becomes deteriorated near the critical heat flux point due to a large number of bubbles gathering on the wall acting as a barrier to heat flow from a heated surface. This phenomenon is known as boiling crisis and the heat flux there is called the critical heat flux [1]. According to different flow patterns and qualities, the boiling crisis can be divided into Departure from Nucleate Boiling type and Dry-Out type [2].

The risk of departure from nucleate boiling is one of the limiting constraints on PWR operation. Departure from nucleate boiling (DNB) results in a sharp degradation of the convective heat transfer between the fuel rod cladding and the reactor coolant. Thus, accurate prediction of CHF is a key issue for light water reactor thermal-hydraulics design.

CHF prediction methodology [3] can be categorized as the analytical (or theoretical) methods and the empirical methods. Analytical models are developed by considering specific physical mechanisms leading to the CHF. There is no conclusive evidence of governing CHF mechanisms until to now. Among various types of models that have been proposed, the bubble coalescence model [4~6] and the liquid sub-layer dry-out model [7~9] have been showing the most promising results for DNB prediction. Empirical methods are mainly based on the experimental data bases and known parametric trends of the data [10]. Three categories of empirical methods are being used: (a) empirical correlations, (b) look-up table methods, and (c) artificial neural network and other information processing techniques. In view of the detailed physical mechanisms leading to the CHF is not sufficiently understood, empirical approaches will keep their values in practical applications.

Overall, there are two ways in the development of CHF correlation in rod bundles [11]: one is based on round tube CHF correlations, considering the effects of spacing devices and CHF promoters, effects of cold walls and non-uniform heat flux, etc. The W-3correlation is a typical representative. The other one is to fit correlation directly using the rod bundles CHF test data, which includes two methods [12]: the minimum DNBR point method and the BO point method. The minimum DNBR point method optimizes all the coefficients of CHF correlation based on local parameters at minimum DNBR points and the examples are WRB-1, WRB-2 and WRB-2M correlations. The BO point method optimizes all the coefficients of CHF correlation based on local parameters at BO points. FC-98 correlation is developed using BO point method by FRAMATOME. The process of the minimum DNBR point method is shown in Fig.1.

China is now developing fuel assembly with independent intellectual property rights, so the bundle CHF prediction is a very important issue. Both of the minimum DNBR point and the BO point methods are applied in this paper to develop a new CHF correlation named the ACC correlation to match with the subchannel code ATHAS.

2. DEVELOPMENT OF ACC CORRELATION

2.1. Introduction of test data

The CHF in rod bundles cannot be predicted analytically so it is empirically correlated as a function of local thermal-hydraulic conditions, geometry, and power distribution. Therefore, experiment measurements are performed for the determination of the CHF. Arranging 5×5 rod bundles and different test configuration status considering the rod bundle and cell geometry, the rod radial peaking values, the heater rod axial flux shape, the axial locations and form losses of spacer grids, etc, the critical heat flux tests were performed on the test loop located in Nuclear Power Institute of China (NPIC).

The data from each CHF observation within a test consist of the variables of test section power, flow, inlet temperature, pressure and CHF location (rod and axial location). The test data are considered covering a wide range of geometries and reactor conditions. Table 1 gives the parameters range of experimental database. The range of applicability of the correlation is determined in accordance with the domain covered by the variables in the database.

Table 1 Database experimental range

Variable	Minimum value	Maximum value	Unit
Pressure	9.31	17.00	MPa
Mass velocity	0.92	4.04	Mg/(m^{2}s)
Local quality	-0.08	0.40	decimal

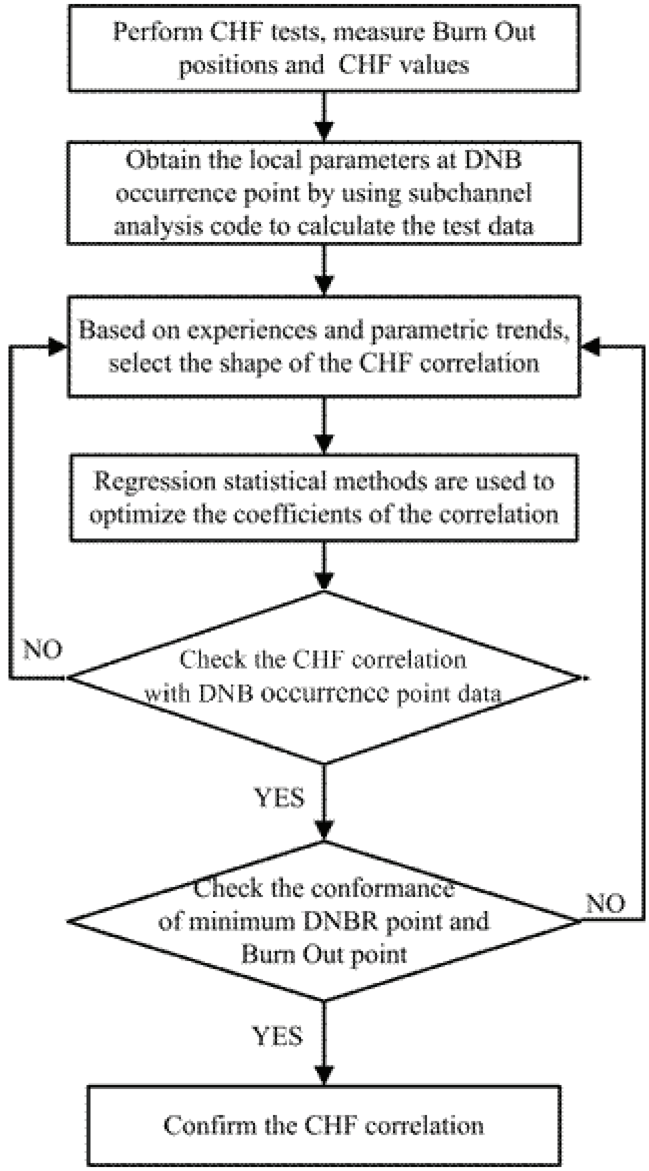

Figure 1 The process of the developing method

2.2. Local parameters calculation

ATHAS [13] is a subchannel code developed in Xi'an Jiaotong University. The code has been designed to be general enough to accommodate itself to calculate with different geometries and orientations. These include single subchannel of different shapes, and multiple subchannels of CANDU-PHWR, PWR and BWR designs, in both vertical and horizontal orientations. As well, the code can calculate a variety of different fluids, including single- and two-phase heavy water, light water, various Freons, and two-phase air-water. The operating conditions can be either supercritical pressure or subcritical pressure condition.

In this paper, the local thermal-hydraulic parameters (p, G, X) axially along the test section heated length are obtained using ATHAS code to calculate each set of bundle data. A detailed description of ATHAS modeling is presented in table 2.

Table 2 ATHAS modeling assumptions

Sub-channel code	ATHAS
Thermal equilibrium model	Liquid/vapor thermal equilibrium
Single-phase friction factor	$f=0.184Re^{-0.2}$
Two-phase friction factor multiplier	Homogeneous flow model
Two-phase form loss multiplier	Homogeneous flow model
Single-phase heat transfer correlation	Dittus-Boelter correlation
Mixing model	Carlucci thermal/momentum and void drift mixing
Cross flow resistance factor	0.5
Number of sub-channels	36

2.3. Determine the shape of ACC correlation

In this paper, the so-called "three-step method" is used to determine the shape of ACC correlation:
(a) Considering the impact of local parameters (p, G, X) at DNB occurrence point as a whole, i.e. $q_{CHF} = a(p,G,X)$,
(b) Dealing with the effects of spacing grids and cold walls, etc. which contain the geometrical parameters as a whole, i.e. $q_{CHF} = b(p,G,X,d_g,g_{sp},D_e,H)$, and
(c) Assigning a non-uniform heat flux factor (FNU) to correct non-uniform heat flux distribution.

Thus, the format of ACC correlation is:

$$q = \frac{a(p,G,X) + b(p,G,X,d_g,g_{sp},D_e,H)}{FNU}$$

The FNU is calculated with the Tong method [11]:

$$FNU = \frac{C}{\left[q''_{local}(l_{DNB})\right]\left[1-e^{-Cl_{DNB}}\right]}\int_0^{l_{DNB}} q''(z)e^{-C(l_{DNB}-z)}dz$$

Where,

$$C = \frac{b_1\left(1-x_{DNB}\right)^{b_2}}{G^{b_3}}$$

2.4. Determining the coefficients

The non-linear regression analysis method is applied to determine the coefficients of the ACC correlation. Firstly, the traditional thermal-hydraulic parameters (p, G, X) were investigated using the uniform heated CHF data without guide-tube. Then the uniform heated length CHF data with guide-tube were used to correlate the effect of cold walls. The whole set of uniform axial flux configuration data were used in order to optimize the coefficients associated with the variables of the effect of spacer grids as having an effect on the CHF. Since the characteristic groupings and their coefficients were determined on the basis of tests with uniform axial flux shape, the whole set of non-uniform axial flux configuration data were used to determine the non-uniform flux factor.

2.5. M/P database statistics and prediction rate

Having determined the shape and the coefficients, then the ACC correlation has been determined. We define that,

P_1: predicted CHF value at the minimum DNBR point with the minimum DNBR point method
P_2: predicted CHF value at burn out point with the BO point method
M_1: measured CHF value at the minimum DNBR point with the minimum DNBR point method
M_2: measured CHF value at burn out point with the BO point method

Then a database of the M/Ps can be formed. Table 3 summarizes the statistics on the M/P values calculated from separate databases. Obviously, compared with M_2/P_2, the whole M_1/P_1 data has the average closer to 1 and the smaller standard deviation. It is impossible to predict the burn out position accurately, which lead to the M_2/P_2 data with larger standard deviation. The probability density function distributions are presented in Fig. 2.

Table 3 M/P database statistics with ACC correlation

Test	Number of data points	M_1/P_1 data		M_2/P_2 data	
		Average	Standard deviation	Average	Standard deviation
1	88	1.062	0.060	1.052	0.063
2	60	1.005	0.055	1.046	0.074
3	76	0.948	0.048	0.979	0.049
4	70	1.014	0.089	0.981	0.091
5	72	0.987	0.045	0.977	0.037
6	65	1.045	0.052	1.024	0.109
7	75	0.974	0.060	0.935	0.093
8	65	0.958	0.049	0.927	0.081
All	571	1.002	0.073	0.991	0.088

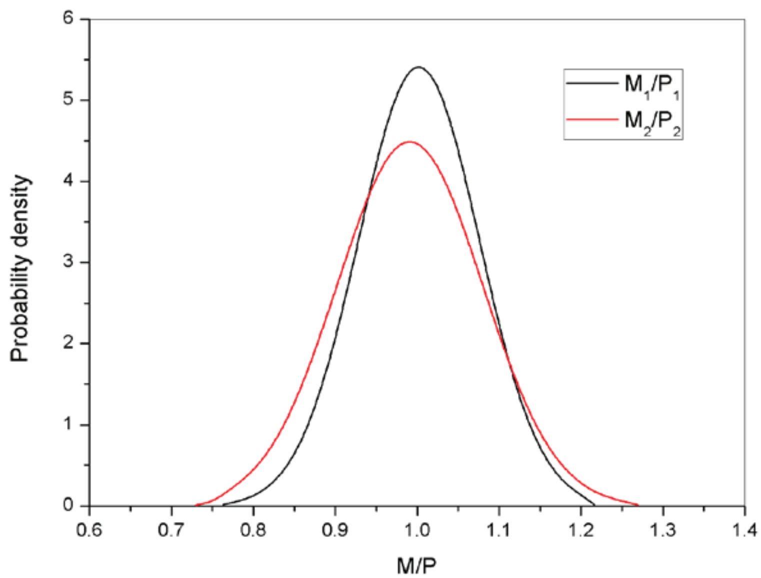

Figure 2 The probability density function distribution

It should be noticed that for each point of the CHF test series a comparison was made between the CHF measured at the experimental BO location and the CHF calculated at the elevation where the P/M ratio is minimum. Whenever the relative difference between the M/P was less than 4%, the predicted location was considered as accurate. The predication rate in table 4 defines the ratio of accurate predicted BO locations to the total number of CHF tests within a test series.

Table 4 The predication rate of the two methods

Test	Axial flux shape	Type of Cell	The minimum DNBR point method prediction rate	The BO point method prediction rate
1	Uniform	Typical	80%	82%
2	Uniform	Typical	82%	84%
3	Uniform	Typical	90%	90%
4	Uniform	Typical	100%	100%
5	Uniform	Guide Tube	85%	88%
6	Cosine	Typical	74%	79%
7	Cosine	Typical	71%	76%
8	Cosine	Guide Tube	66%	72%
All	-	-	81%	84%

As the minimum DNBR point method uses the calculated parameters at the DNB occurrence point which deviate the real CHF test data, it may be insecurity. Comparatively, the BO point method is more reasonable and conservative with better predication rate. So the BO point method is recommended to predict the risk of DNB.

2.6. Determining DNBR design limit

The difference between the measured critical heat flux, M, and the predicted critical heat flux P, is due to several factors:

(1) measurement uncertainties for pressure, mass velocity, inlet temperature and power,
(2) subchannel computer code models,
(3) regression error,
(4) except for the local and geometrical parameters defined in CHF correlations, there are other unidentified parameters that affect the CHF occurring, etc.

The sum of all these components has a normal distribution, a realistic assumption based on the statistical response of empirical uncertainties and the central-limit theorem. The D' statistical test method [14] rejects the hypothesis of a normal distribution if calculated D' value is outside minimum or maximum predefined values. Application of the D' test on the M/Ps of the whole ACC database indicates that the hypothesis of a normal distribution of the M/Ps is accepted.

With the normal distribution, the DNBR limit is established from the Owen theory [15]:

$$C = \frac{1}{\overline{x} - k\left(\beta, \gamma, \nu\right) \times s}$$

Where,

$\overline{x}$ = estimation of the mean of the M/P population

s = estimation of the standard deviation of the M/P population

$k\left(\beta, \gamma, \nu\right)$ is the Owen coefficient corresponding to the probability β, for the proportion γ and degrees of freedom ν.

Based on the statistics at the minimum DNBR point, the DNBR limit is 1.15, while at the BO point, it is 1.18.

3. ASSESSMENT OF ACC CORRELATION

3.1. M/P data analysis

The distributions of M/P as a function of independent variables pressure, mass velocity and quality at the minimum DNBR locations as well as the experimental Born Out locations are shown in Fig. 3 to 5, respectively. The figures show that there is no systematic bias as a function of independent variables pressure, mass velocity and quality in the whole application within the M/P data distribution at the minimum DNBR locations as well as the experimental Born Out locations.

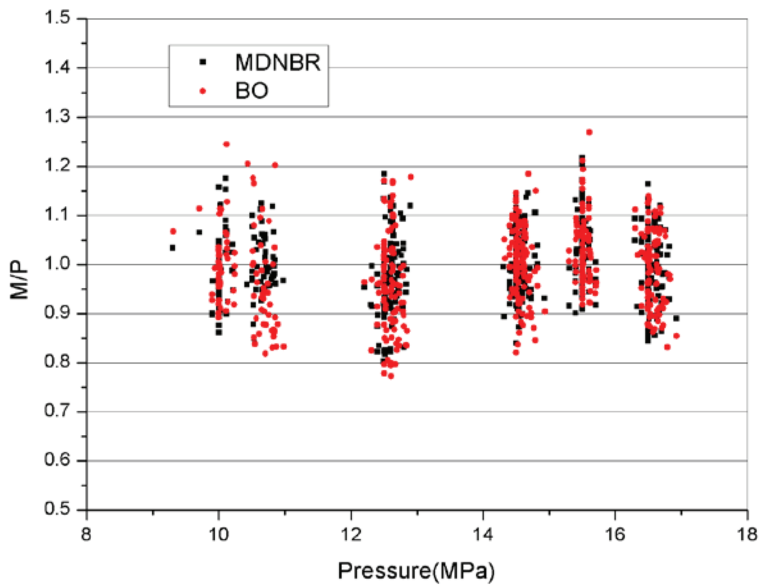

Figure 3 M/P vs. pressure

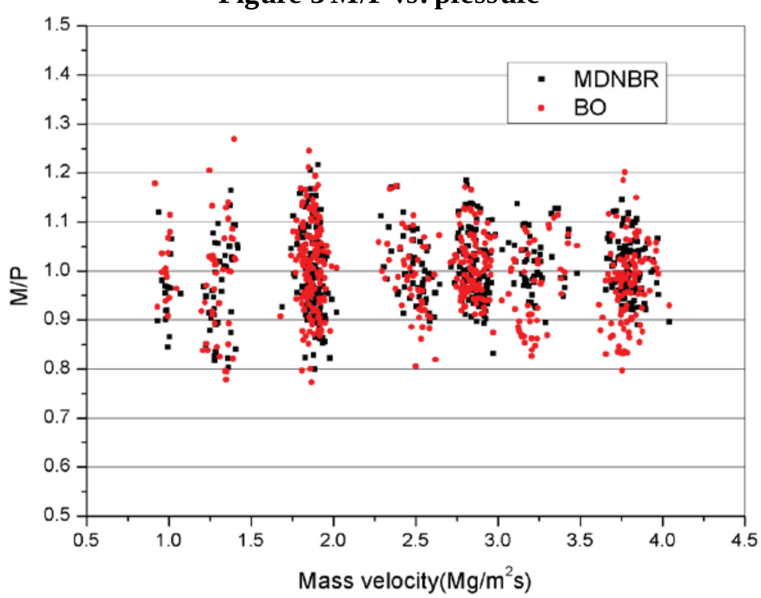

Figure 4 M/P vs. mass velocity

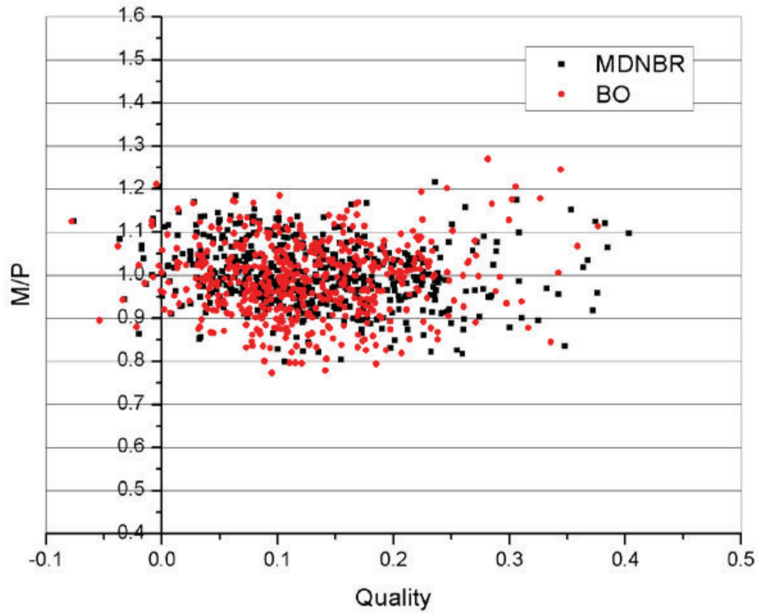

Figure 5 M/P vs. quality

The comparison of predicted CHF and measured CHF is shown in Fig. 6. The distributions of heat fluxes calculated with the ACC correlation are well distributed along the 45^o line with measured CHF.

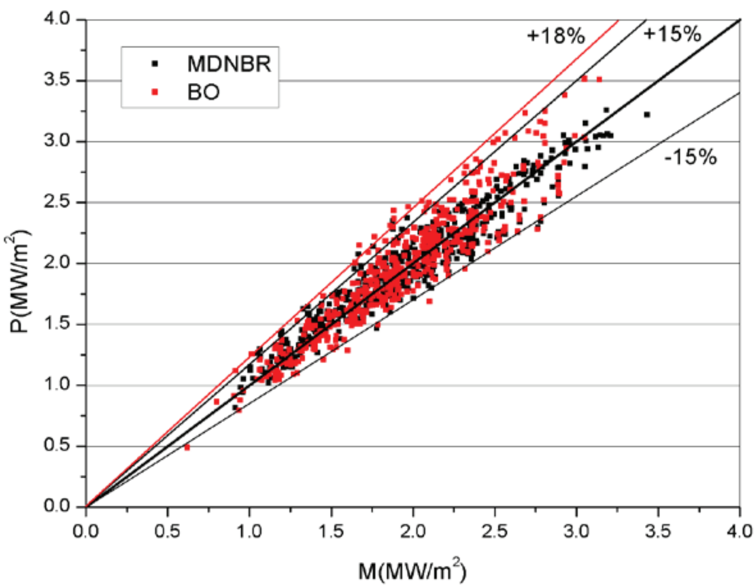

Figure 6 Predicted CHF as a function of measured CHF

3.2. Parametric trends analysis

The parametric trends of the CHF vary according to the thermal-hydraulics conditions determined by the combination of the various ranges of pressure, mass velocity, quality and geometrical parameters.

Numerous studies [16-23] show that, at high pressure, high mass velocity, medium subcooling and small equivalent diameter, typical of PWR operating conditions, the parametric trends can be briefly summarized as follows:

(1) CHF decreases with increasing pressure,
(2) CHF increases with increasing mass velocity,
(3) CHF decreases with increasing quality.

In typical PWR operating conditions, the heat flux predicted by the ACC correlation as a function of independent variables pressure, mass velocity and quality are shown in Fig. 7 to 9, respectively. The figures show that the parametric trends of ACC correlation are consistent with the physical mechanisms and known parametric trends of the data. Overall, with high prediction accuracy and correct parametric trends, the ACC correlation developed in this paper can be used to predict the risk of the DNB for PWR fuel assemblies.

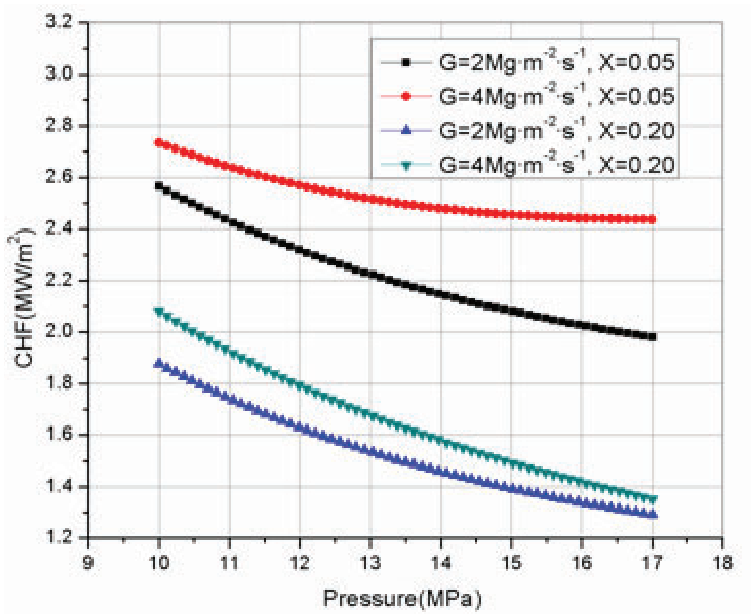

Figure 7 CHF as a function of pressure

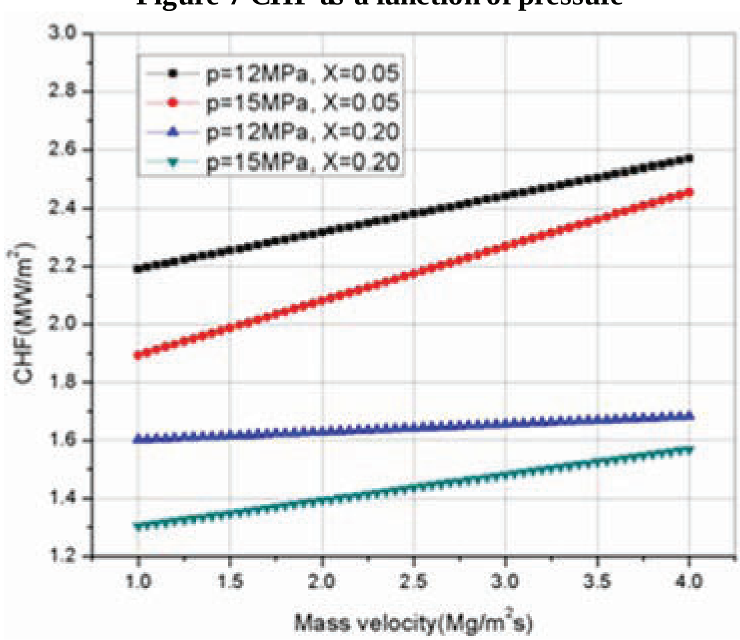

Figure 8 CHF as a function of mass velocity

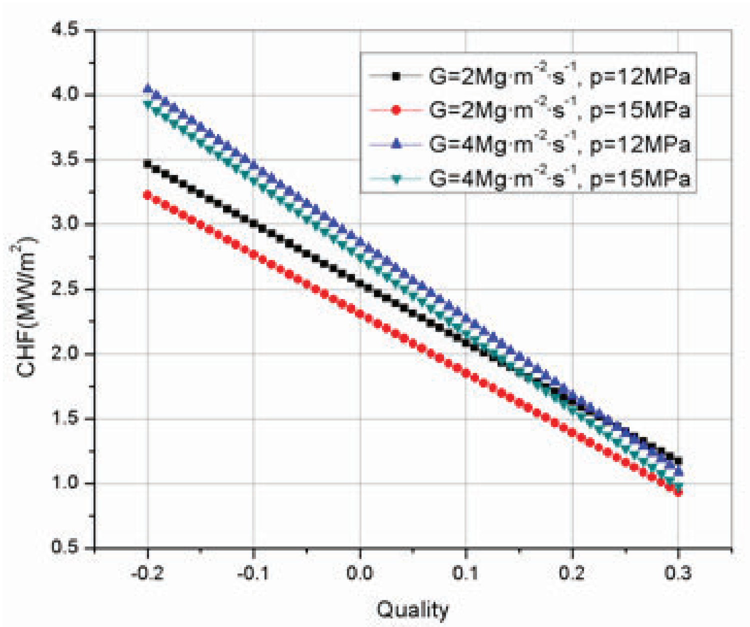

Figure 9 CHF as a function of quality

4. CONCLUSIONS

Based on the large database of CHF tests representative of thermal-hydraulic characteristics of the PWR fuel assemblies, the ACC correlation has been developed based on the minimum DNBR point and the BO point methods to calculate the risk of DNB. This correlation is applicable over a large range reactor conditions. The analysis and assessment results indicate that:

(a) The ACC correlation can fit the experimental data well.
(b) There is no systematic bias as a function of independent variables pressure, mass velocity and quality in the whole application within the M/P data distribution at the minimum DNBR locations as well as the experimental Born Out locations.
(c) The parametric trends of ACC correlation are consistent with the physical mechanisms and known parametric trends of the data.
(d) Compared with the minimum DNBR point method, the BO point method is recommended to predict the risk of DNB because it is more reasonable and conservative with better predication rate.
(e) Coupled with subchannel code ATHAS, this correlation can simulate the thermal-hydraulics performances of rod bundles exactly.

NOMENCLATURE

ABBREVIATIONS	
ATHAS	Advanced Thermal-Hydraulics Analysis Sub-channel
ACC	ATHAS CHF Correlation
AFS	Axial Flux Shape
BO	Born Out
CHF	Critical Heat Flux
DNB	Departure From Nucleate Boiling
DNBR	Departure From Nucleate Boiling Ratio
FNU	Non Uniform Flux Factor

NOMENCLATURE	
d_g	Distance (m) between the point of calculation and the first upstream mixing grid position
g_{sp}	Distance (m) between two consecutive mixing grids
D_e	Equivalent diameter
H	Heated length
M	Measured local CHF
P	Predicted CHF
p	Pressure (MPa)
G	Mass velocity (Mg/(m^{2}s))
X	Thermodynamic quality

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