# Study on CHF Correlation for PWR at Low Pressure Conditions Based on Stepwise Regression Analysis

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**ABSTRACT**

Constrained by limited loop experimental data, the development of the CHF correlation for the PWR fuel assembly at low pressure conditions is a typical microscopic statistical problem with small sample, but has the requirement of high prediction accuracy. The format of CHF correlation is studied in terms of the DNB mechanism and the experimental data of the PWR fuel assemblies at low pressure conditions. A new CHF correlation is obtained using the essential variables of DNB which is suitable for low pressure conditions. Stepwise regression analysis is used to optimize the format and coefficients of the CHF correlation. BO method is used to develop the CHF correlation because it can reflect directly the original test data. A very simple switch variable has been introduced to replace the F factor for the non-uniform heat flux shape so that the complex integral calculations are greatly eliminated. The analysis and evaluation results indicate that the correlation matches well with the experimental data. This CHF correlation can be used for the prediction of DNB in the thermal-hydraulic design of PWR at low pressure conditions.

**Keywords**

DNBR; BO; CHF correlation; small sample; stepwise regression

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# 1. INTRODUCTION

The safety and economy are two pursuits of the modern nuclear power plant design. The critical heat flux (CHF) on the occurrence of the departure from nucleate boiling (DNB) is the major limitation for the design goals of PWR nuclear power plant. The total target of the thermal-hydraulic design for reactor cores is to provide a suitable heat transfer capability in accordance with the heat production of reactor core thermal distribution, that is to say, 1) providing appropriate thermal removal for reactor coolant system, normal residual heat removal system or the emergency core cooling system, 2) retaining a certain margin of safety. Thus the critical heat flux (CHF) of the reactor core is increased as high as possible under a prerequisite of ensuring the security of reactor. The design bases of the reactor core thermal hydraulics are that the departure from nucleate boiling (DNB) and the fuel melt do not occur in the core. Not happening of DNB means that the probability of nonoccurrence of DNB at the limiting fuel rod is 95% at least, and with 95% confidence level in normal operation, operational transients and transient events with any medium frequency (i.e. accident conditions in the event classification) during their whole process.

In order to improve the CHF performance of the reactor core under the accident conditions, a lot of researches have been done on CHF in the nuclear thermal-hydraulic industry [1-9] in the past few decades. Because there are not any satisfied analytical descriptions for the CHF thermal-hydraulic model, there are no choices but relying on the help of appropriate loop experimental data to obtain CHF correlation which is dependent on the fluid parameters and geometric structure of the fuel assembly in the reactor core by mathematical fitting method. Due to the limitation of the experimental conditions, the low pressure experimental data under the accident conditions is little, so most of CHF correlations are based on those experimental data obtained at high pressure conditions. Hence, the research of CHF correlation based on the low pressure condition is very important for the safety of nuclear power plant.

Constrained by the limited loop experimental data, the critical heat flux correlation of fuel assemblies in PWR under low pressure conditions is a typical microscopic statistical problem with both small sample and very high forecast accuracy. This study explores a special processing method to solve the problem above.

The development of CHF correlation for fuel assemblies includes two methods [4], i.e. BO method and minimum DNBR method. The BO method is based on the loop experimental data at the burn-out (BO) location to optimize all the coefficients of CHF correlation and then determines the DNBR design criteria. The progress of this method is shown in Figure 1. The minimum DNBR method optimizes all the coefficients of CHF correlation based on minimum DNBR location data and then determines the DNBR design criteria. The BO method is chosen in this study because BO location data is the data directly obtained from loop experiments without any modification and then having intuitive persuasiveness and being relatively conservative.

The technical route of this study is: first, researching the essential variables which led to a DNB occurrence according to the DNB occurrence mechanism and the basic format of a CHF correlation based on the experimental data for the main type fuel assembly for PWR respectively; then a new DNB CHF correlation under low pressure conditions based on the DNB essential variable is developed by optimizing the structure and parameters of the correlation using stepwise regression methods.

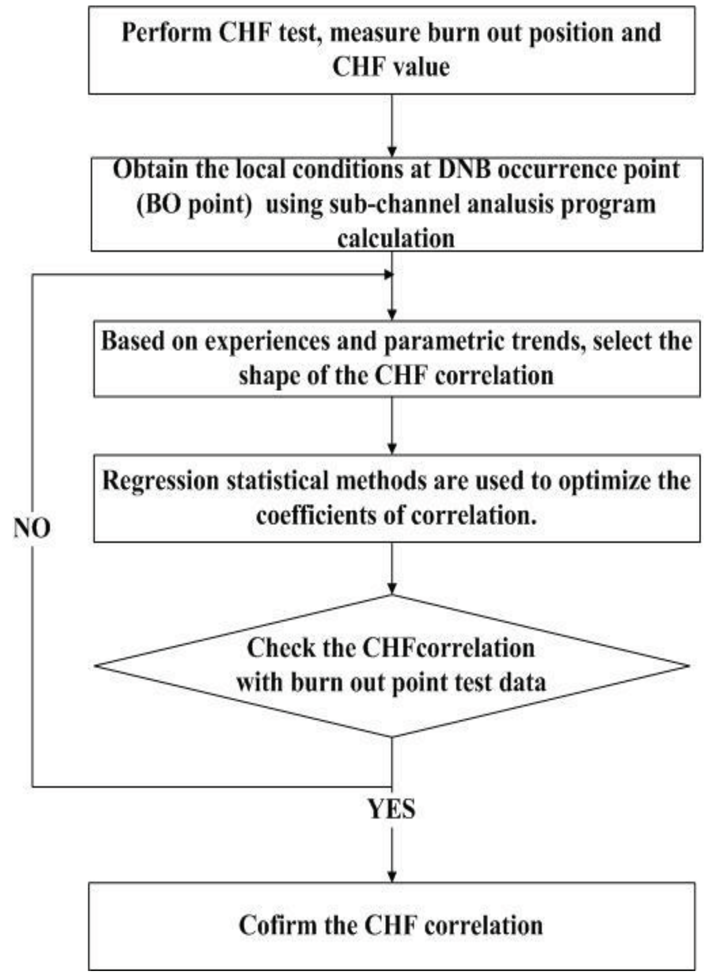


**Figure 1. BO Method CHF Correlation Development Process**

## 2. STUDY OF CHF ESSENTIAL VARIABLES BASED ON DNB OCCURRENCE MECHANISM

Figure 2 shows the thermohydraulic status of the fluid inside a round tube when the departure from nucleate boiling (DNB) occurs. DNB could occur at the subcooled boiling or nucleate boiling flow regions. The bubble layer is along the wall and the middle is the mainstream of the liquid. On the near wall surface, void fraction reaches a maximum. When the bubble layer breaks away from the wall surface, stagnant liquid is formed beneath the bubble layer. The high heat flux through the wall leads to the formation of a stagnant vaporized film covering on the wall which results in the local heat transfer deterioration and with that the wall temperature rises rapidly and the fluid comes into film boiling from the nucleate boiling. It can be concluded that the fundamental cause of DNB is that the increasing of the quality alone the wall leads the assembling of bubbles into a steam film, i.e., the local quality (BO point) is the most important factor to the DNB occurrence. Of course, the local pressure and fluid mass velocity at BO location are influential too. So the fluid local quality, pressure, mass velocity are obviously essential variables deciding the DNB CHF.

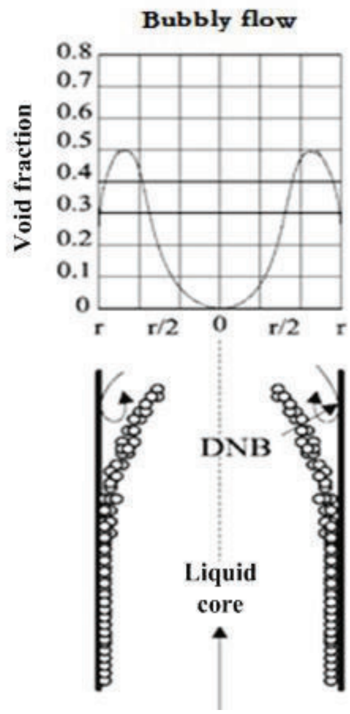


**Figure 2. Fluid thermohydraulic Condition in a tube on DNB**

The fuel assembly for the contemporary PWR generally adopts the rod bundle structure with mixing vane grids (Figure 3). The mixing vanes around the bundle grids make the fluid in sub-channel to be mixed up so thoroughly that the radial fluid state near grids is quite homogeneous on the axial sections (local quality, pressure, temperature etc.). As showing in Figure 2, the void fraction (directly relating with quality) of the fluid in the pipe is U type in radial, namely the quality near wall was significantly higher than that of the center but meanwhile local parameters calculated by sub-channel analysis code are average parameters across the sub-channel cross section. Assuming the swirling effect of mixing vanes is sufficient, through the upstream mixing vane, fluid average parameters across the cross sections calculated by sub-channel code are the same as the local fluid parameters near the wall. Then with the fluid flow, radial non-uniformity distribution (i.e. U distribution) increases gradually along axial direction. Therefore the distance between the location where DNB occurs (ie.BO point) to the nearest mixing vane upstream dg is obviously very important as a DNB essential variable.

The distance between grid spacers affects the CHF too. But considering of its correlation with dg (the distance from BO point to the nearest mixing vane upstream) in the actual experimental data, it isn't accounted as an essential variable.

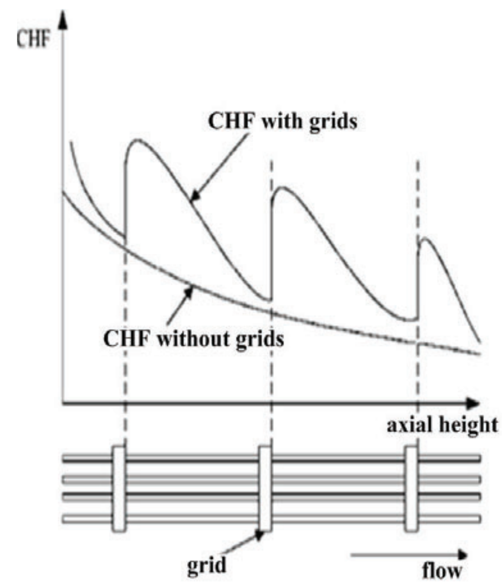


**Figure 3. CHF distribution of fuel assembly with mixing vane**

To sum up, the influence of CHF essential variables of DNB according to the importance weighting are the local quality X, the distance between the BO location to the nearest mixing vane upstream dg, fluid mass velocity and local pressure. Therefore, this study uses only the above four essential variables and their combination to constitute the CHF correlation base, eliminating the non-essential variables such as heating length, inlet parameters of fluid and so on, in order to develop a concise, accurate CHF correlation.

## 3. BASIC IDEA OF STEPWISE REGRESSION METHOD

The purpose of multivariate regression analysis actually is to establish the "optimal" regression correlation in order to predict or control the dependent variables. The factors associated with or possibly with the dependent variables are selected as independent variables to constitute the regression equation and using the multiple linear regression analysis method to analyze these problems. But not all the selected independent variables have significant influence on the dependent variable. Too many independent variables are selected into the correlation will, on the one hand increase the amount of calculation, cause multicollinearity problem on the other hand thereby impacting seriously the predicting ability of regression correlation. So, it is necessary to filter all independent variables so as to obtain the "best" subset of variables. Stepwise regression method is an effective method for the “filtering”.

The basic idea of stepwise regression is to add the variable into the model one by one and a significant test using F test must be made after each introduction of explanatory variables and t test also be made on every explanatory variables included in the correlation. The original introduced explanatory variables are removed whereas it is no longer significant due to the introduction of new explanatory variable. It is ensured that only significant variables are included in regression equation before introducing new variables in any time. This is a recursive process until there are neither significant explanatory variables to be added into regression equation nor un-significant explanatory variables to be removed from the regression equation and so it is ensured that the resulting set of explanatory variables is optimal.

According to the above idea, stepwise regression method can be used to eliminate the variables which caused the multicollinearity. The specific steps are as follows: first doing simple regression to the explained variable for each of the considered explanatory variables, and introduce the rest explanatory variables based on which has the maximum contribution to the explained variable. Through stepwise regression process, the final explanatory variables retained in the model are not only important but also have no serious multicollinearity.

## 4. DEVELOPMENT OF CHF CORRELATION AND RESULTS EVALUATION

### 4.1 Development of CHF Correlation for Low Pressure Conditions

The experimental data which be applied to develop the new correlation include both the axial uniform heated and non-uniform flux heated with cosine shapes, and the typical cell and thimble cell matrices. The experimental data ranges are shown in table 1. The test data are considered covering the low pressure transient and accident conditions of PWR reactor. The local perimeters at BO points are obtained by the calculation of the thermal-hydraulics sub-channel analysis computer program LINDEN which are developed by China Nuclear Power Technology Research Institute [11].

Using the essential variable for DNB (fluid local equilibrium quality X, the distance to the upstream nearest mixing vane dg, fluid mass velocity G and local pressure P) and the combined indexes of them as the independent variable, the following format of CHF correlation (called ALPC correlation) is obtained:

$$q_{loc} = A + B + C \tag{1}$$

Where A is the basic term for the CHF of the fuel assembly without the mid span mixing grids for uniform axial flux shape. B is the correction term for the CHF of the non-uniform axial flux shape obtained by regression of the loop experimental data with cosine axial flux shape. A very simple switch variable in this term has been introduced to replace the F factor[Error! Reference source not found.] for the non-uniform heat flux shape so that the complex integral calculations are greatly eliminated. C acts as the correction term for the CHF of the fuel assembly with the mid span mixing grids obtained by regression of corresponding test data. Because the location of burn-out point in the loop experiments is always located at the upstream end of grids, the experiment results of the variable dg (the distance between the BO point to the nearest upstream grid) can't provide sufficient information for the regression. Considering the complexity of the influence of dg on critical heat flux, individual revision had to be made on the fuel assembly with mid span mixing grids therefore.

Table 1 shows the meaning and applicable scope of variables in the ALPC correlation.

**Table 1. Meaning and applicable scope of variables of the ALPC correlation.**

| parameter | physical meaning | unit | scope |
|---|---|---|---|
| **P** | pressure | MPa | 2.07<p<10.00 |
| **G** | mass velocity | Mg·m-2·s-1 | 0.93<G<4.00 |
| **X** | equilibrium quality | - | 0.05<X<0.40 |
| **dg** | distance between BO point to nearest upstream grid | m | 0.22<dg<0.56 |

Predictive CHF (P) at DNB point can be calculated using the correlation ALPC and getting the ratio value M/P (M is the measured CHF value at the same DNB point). The statistical results show that the mean value of M/P is 1.0000, and the standard deviation is 0.0631, the DNBR design criteria is 1.1265.

Considering the small sample problem of this study (the sample size is only 248), the correlation ALPC uses only 8 coefficients that meet the requirements of sample size for small sample problem. Meanwhile the number of coefficient of the CHF correlations commonly used in current industry such as W-3[1] is generally 20 or so. So the research result is satisfactory.

Frequency histogram for M/P data and theoretical normal distribution function are presented in Figure 4. It looks accordant with the normal distribution basically. There are three data which are beyond 3 times of the standard deviation from the mean value. Considering of the ratio is M/P, it means the situations is conservative when the value is greater than 1. So only one datum is un-normal.

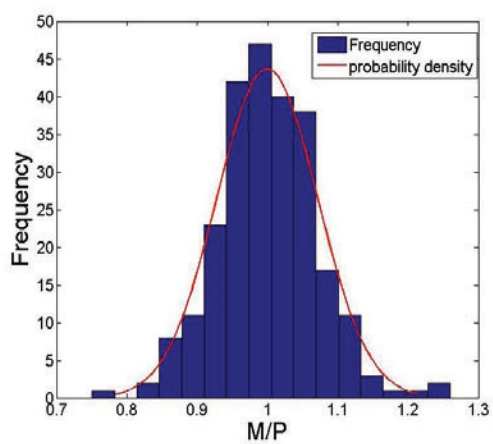


**Figure 4. Frequency Histogram for M/P and Theoretical Normal Distribution Function**

The fitting results of the correlation 1 for the axial uniform heating and the non-uniform heating style are shown in Table 2. It can be seen that there are almost no difference between the average value of the M/P for the non-uniform heating and that of the uniform and only the standard deviation is slightly larger than the uniform heating. This is in accordance with the objective of the experiment, because the non-uniform heating experiment is more complicated than the uniform and then the experimental uncertainty is higher. It can be concluded that the correlation 1 uses the non-uniform heating switch expression B to realize the fitting of the experimental data of the non-uniform heating without using the non-uniform heating correction factor of Tong's [8] .

**Table 2. M/P of non-uniform and uniform**

| Type of heating style | Mean value | Standard deviation |
|---|---|---|
| uniform | 0.9985 | 0.0631 |
| non-uniform | 1.0005 | 0.0680 |
| All | 1.0000 | 0.0631 |

The fitting results also show that CHF for thimble cell and typical cell has no essential difference because there isn't systematic difference between the ratio value M/P of typical cell and that of thimble cell (see Table 3) although there isn't additional amendment to the thimble cell. So there is no need to do any revision for thimble cells.

**Table 3. M/P of typical cell and that of thimble cell**

| Type of cell | Mean value | Standard deviation |
|---|---|---|
| Typical cell | 1.0018 | 0.0631 |
| Thimble cell | 0.9884 | 0.0559 |
| All | 1.0000 | 0.0631 |

## 4.2 ASSESSMENT OF ALPC CORRELATION

### 4.2.1 M/P data analysis

The distributions of M/P as a function of independent variables pressure, mass velocity and equilibrium quality are shown in Figures 5 to 7 respectively.

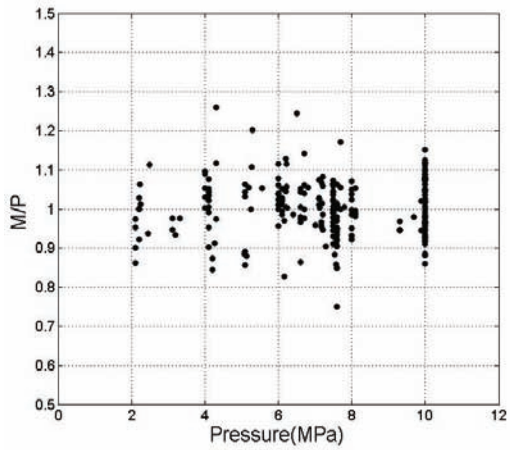


**Figure 5. M/P as a Function of Pressure**

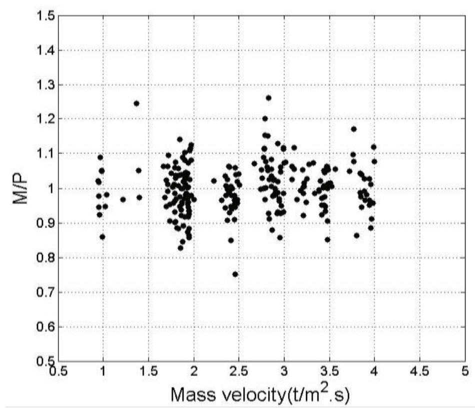


**Figure 6. M/P as a Function of Mass Velocity**

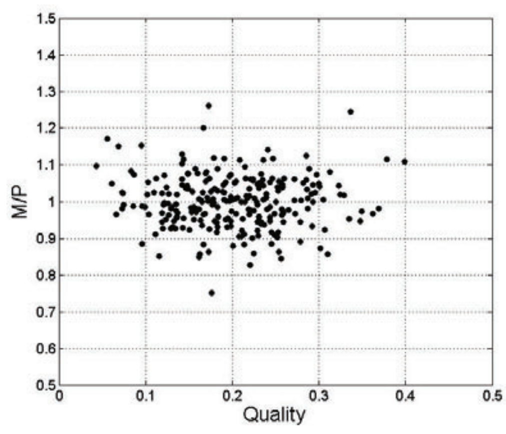


**Figure 7. M/P as a Function of Equilibrium quality**

Through statistical testing and visual inspection, it is clear that the M/P data distributions of ALPC correlation to the local parameters of P, G and X do not have any obvious skewing tendency. This will ensure the reliability of DNBR calculation limit value when ALPC is used.

The predicted CHF P as a function of the measured CHF M is shown in Figure 8. As seen in Figure 8, the distribution of the predicted CHF values of the ALPC correlation are well distributed along the 45$^o$ line with the measured CHF values, all of the test points almost fall into the ±15% limit line.

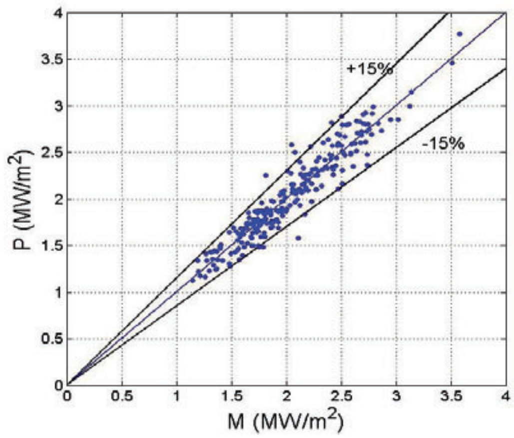


**Fig.8. M/P as a function of pressure**

The CHF correlation fits quite well with the loop experimental data. It can be used for the DNB prediction in the thermal- hydraulic design of the reactor core at low pressure conditions.

### 4.2.2 Parametric trends analysis

The parametric trends of correlation ALPC are showed in Figure 9-12 respectively. The parametric trends are coincident with the conclusion of researchers in the area i.e. (1) CHF decreases with increasing pressure, (2) CHF increases with increasing mass velocity, and (3) CHF decreases with increasing quality. (4) CHF decreases with increasing dg.

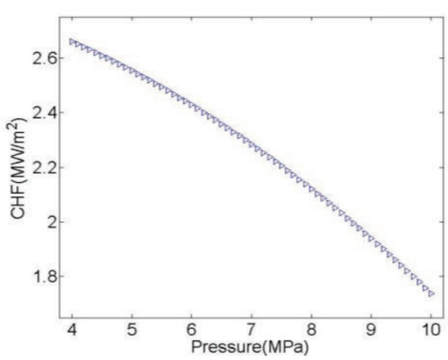


**Fig.9. CHF as a function of pressure**

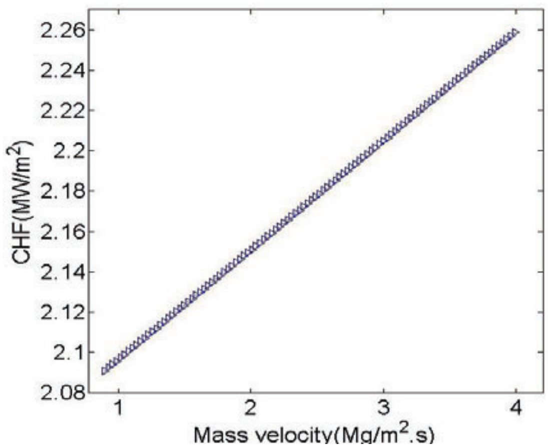


**Fig.10. CHF as a function of mass velocity**

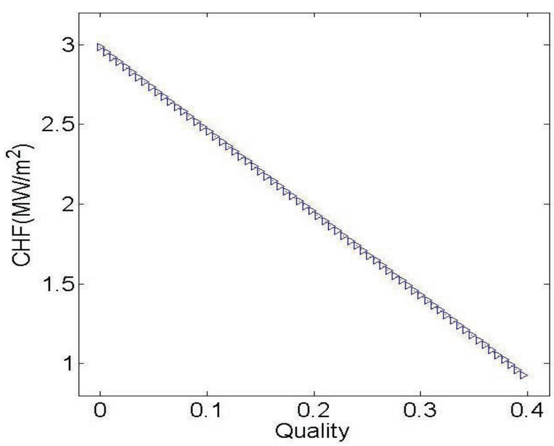


**Fig.11. CHF as a function of equilibrium quality**

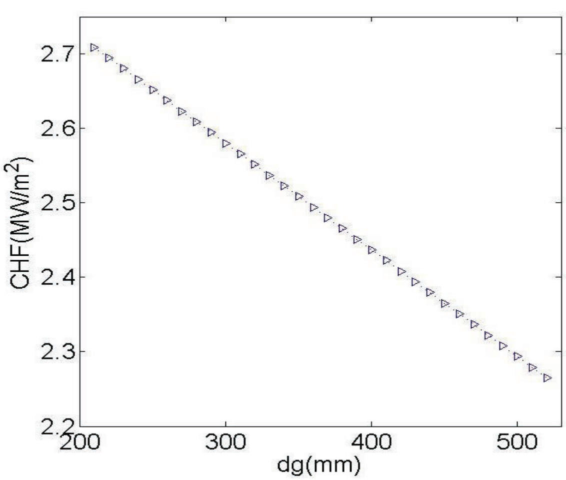


**Fig.12. CHF as a function of dg**

## 5. CONCLUSIONS

(1) The ALPC CHF correlation fits quite well with the loop experimental data so it can be used to predict CHF of DNB in the reactor core thermal-hydraulic design for low pressure conditions with adequate expected safety margins.

(2) By studying the essential variables which cause the occurrence of DNB, a new correlation using 8 parameters substituted for the current correlations using normally about 20 parameters. This work laid the foundation for study about the simplifying CHF correlation with high accuracy.

(3) Fitting results show that CHF for thimble cell and typical cell has no essential difference and there is no need to do any revision for a thimble cell.

(4) A very simple switch variable has been introduced to actualize non-uniform heating correction without using the TONG's non-uniform heat flux shape factor [3] so eliminating the complex integral calculations. The process of calculation is greatly simplified.

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