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环形通道内液钠的临界热流密度的灰色相关分析和灰色模型的建立

GREY RELEVANT ANALYSIS OF SODIUM CRITICAL HEAT FLUX IN ANNULAR CHANNEL AND THE ESTABLISHING OF GREY MODEL

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摘　要

采用灰色系统理论，对在两台液钠沸腾实验回路上测得的实验数据，进行了影响钠沸腾临界热流密度 (CHF) 值因素的灰色相关分析，并用 GM (1，1) 模型对 CHF 进行了预测。选用 GM (1，h) 模型对 CHF 进行了建模。计算及预测结果与实验值符合较好。

Grey Relevant Analysis of Sodium Critical Heat Flux in Annular Channel and the Establishing of Grey Model

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ABSTRACT

Using grey systems theory and experimental data obtained from sodium boiling test loop in China, grey mutual analysis is done to some parameters influencing sodium CHF.The results of CHF are predicted by using GM (1, 1) model. The GM (1, *h*) model is made up for creating CHF model. The results are in good agreement with the experimental data.

With the development of nuclear power industry of China, fast breeder reactors have become an important research field. And the flow boiling characteristics of liquid sodium, especially the analysis and prediction of its critical heat flux (CHF), are the important aspects in the operation and safety analysis of fast breeder reactors. The factors that influence the value of CHF are complex, various and interactive. There also exist other uncertain factors. Having both definite and indefinite information is the characteristic of typical grey systems. Professor Deng Julong created grey system theory in 1982, specializing the systems mentioned above. The key contents of his theory are using minimum proceeded data (the number is 4) and partial differential models applicable to multi-dimension arrays. We can found a dynamic model of the system, including all related factors. Grey system theory has been successful in many scientific research fields. Using the theory for the first time, we analyze and study a lot of experimental data of the boiling characteristics of liquid sodium from the onset of nucleate boiling (ONB) to dryout, which were obtained at two sodium boiling experimental loops in China. We also compare the method with conventional data-processing method, the regression method.

1 CALCULATING PRINCIPLES

1.1 Grey relevant analysis method

Grey relevant analysis method is a way in which we can quantitatively describe and compare the developing trend of a system by determining the relevance degree and coefficient between reference arrays (mother arrays) and a certain number of comparison arrays (son arrays). The purpose of the method is to search for the main relationship among each factor in the system, find the important factors that influence the value of the object, thereby obtain its main characteristics, promote and guide the system to develop fast and effectively. The scale measuring the relevance degree between two systems or factors is called relevance degree. The specific calculating method is:

Data change firstly:

If the mother array $\{x_1(t)\}$ and the son array $\{x_j(t)\}$ exist, data change can be proceeded as Eq. (1).

$$x_i(t) = x_j(t)/\max(x_j(t)) \qquad i = 1, \ldots, N \tag{1}$$

Then the relevance coefficient of the two arrays at the $t = k$ moment can be calculated by using Eq. (2).

$$\xi_{1i}(k) = \frac{\Delta_{\min} + \rho\Delta_{\max}}{\Delta_{i}(k) + \rho\Delta_{\max}} \tag{2}$$

where Δ_{1i} (k) is the absolute difference between the two arrays at the k moment, that is:

$$\Delta_{1i}(k) = |x_1(k) - x_i(k)| \tag{3}$$

where $\Delta_{\min}$, $\Delta_{\max}$ is the minimum and maximum value among all the absolute differences , respectively .

ρ distinguishing coefficient , generally adopting 0.5.

Finally, calculate the relevant coefficient using Eq. (4).

$$r_{1i} = \frac{1}{N}\sum_{k}^{n}\xi_{1i}(k) \tag{4}$$

1. 2 Grey model-creating method

Grey system theory defines grey derivatives and differential equations on the basis of ideas such as relevance space and differential equation dynamic models through dispersed data. The essence is the differential equation fitting method. And the model is not definite, so it is called grey model, written as GM (Grey Model). The general expression is GM (n, h), which means a model created by n rank differential equations aiming at h individual variables. The specific methods are as following:

As for the following given time series

$$\{x_i^{(0)}(t)\}, \qquad i = 1, 2, \ldots, h; \quad t = 1, 2, \ldots, N$$

there exists a corresponding accumulating array

$$\{x_i^{(1)}(t)\}, \qquad i = 1, 2, \ldots, h; \quad t = 1, 2, \ldots, N$$

where,

$$x_i^{(1)}(t) = \sum_{k=1}^{t} x_i^{(0)}(k) \tag{5}$$

There exists an array that consists of the average value:

$$z^{(1)}(k) = 0.5x^{(1)}(k) + 0.5^{(1)}(k-1) \tag{6}$$

(1) If $n=1$ and $h=1$, the model becomes GM(1, 1), corresponding differential equation is given by

$$\frac{\mathrm{d}X^{(1)}}{\mathrm{d}t} + aX^{(1)} = u \tag{7}$$

Where,

$$\hat{a} = (a, u)^{T} = (B^{T} B)^{-1} B^{T} Y_{N} \tag{8}$$

$$Y_{N} = \left[X^{(0)}(2),\ X^{(0)}(3),\ \ldots,\ X^{(0)}(N)\right]^{T} \tag{9}$$

$$B = \begin{bmatrix} -Z(2) & 1 \\ -Z(3) & 1 \\ \vdots & \vdots \\ -Z(N) & 1 \end{bmatrix} \tag{10}$$

After getting the solution of Eq. (8), we can solve Eq. (7):

$$\hat{X}^{(1)}(t+1) = \left[\hat{X}^{(0)}(1) - \frac{u}{a}\right] e^{-at} + \frac{u}{a} \tag{11}$$

or

$$\hat{X}^{(0)}(t+1) = \hat{X}^{(1)}(t+1) - \hat{X}^{(1)}(t) \tag{12}$$

where,

$$\hat{X}^{(0)}(1) = \hat{X}^{(0)}(0) \tag{13}$$

The precision of grey model is usually tested by the method as following.

According to the array consisting of the results of Eq. (12)

$$\hat{X}^{(0)} = \left\{\hat{X}^{(0)}(1),\ \hat{X}^{(0)}(2),\ \ldots,\ \hat{X}^{(0)}(N)\right\} \tag{14}$$

Calculating remnant difference,

$$e(k) = X^{(0)}(k) - \hat{X}^{(0)}(k) \qquad k = 1, 2, \ldots, N \tag{15}$$

We get remnant difference vector:

$$e = (e(1), e(2), \ldots, e(N)) \tag{16}$$

Write the square difference of array $X^{(0)}$ and remnant difference array e as S_1^2 and S_2^2 respectively, that is:

$$S_1^2 = \frac{1}{N}\sum_{k=1}^{N}\left(X^{(0)}(k) - \overline{X}^{(0)}\right)^2 \tag{17}$$

$$S_2^2 = \frac{1}{N}\sum_{k=1}^{N}\left(e(k) - \overline{e}\right)^2 \tag{18}$$

where

$$\overline{X}^{(0)} = \frac{1}{N}\sum_{k=1}^{N} X^{(0)}(k) \tag{19}$$

$$\overline{e} = \frac{1}{N}\sum_{k=1}^{N} e(k) \tag{20}$$

then, calculate the ratio:

$$C = S_2^2 / S_1^2 \tag{21}$$

and small error probability:

$$p = P\{|e(k) - \bar{e}| < 0.6745S_1\} \tag{22}$$

The precision of this model is determined by C and p. In general, the precision is classified into four classes, shown in Table 1.

Table 1 Precision classes of this model

Precision classes	p	C
The first class (Good)	$0.95 \leqslant p$	$C \leqslant 0.35$
The second class (Qualified)	$0.85 \leqslant p < 0.95$	$0.35 < C \leqslant 0.5$
The third class (barely enough)	$0.70 \leqslant p < 0.80$	$0.5 < C \leqslant 0.65$
The fourth class (Not qualified)	$p < 0.70$	$0.65 < C$

Hence, the level of model precision is equal to the maximum of the levels that p and C fall, that is the level of model precision=max {level which p falls, level which C falls}. (23)

For example, if the precision of a GM (1, 1) model is 1st and 3rd levels according the value of p and C respectively, its precision should be max {1, 3} = 3, namely the 3rd level.

(2) If $n=1$ and $h \geqslant 2$, the model is GM (1, h), corresponding differential equation is:

$$\frac{dX_1^{(1)}}{dt} + aX_1^{(1)} = b_2X_2^{(1)} + b_3X_3^{(1)} + \ldots + b_hX_h^{(1)} \tag{24}$$

where,

$$\hat{\boldsymbol{a}} = (a, b_2, b_3, \ldots, b_h)^{\mathrm{T}} = (\boldsymbol{B}^{\mathrm{T}}\boldsymbol{B})^{-1}\boldsymbol{B}^{\mathrm{T}}\boldsymbol{Y}_N \tag{25}$$

In Eq. (25),

$$\boldsymbol{Y}_N = (X_1^{(0)}(2), X_1^{(0)}(3), \ldots, X_1^{(0)}(N))^{\mathrm{T}} \tag{26}$$

$$\boldsymbol{B} = \begin{pmatrix} -\frac{1}{2}(X_1^{(1)}(2) + X_1^{(1)}(1)) & X_2^{(1)}(2), \ldots, X_h^{(1)}(2) \\ -\frac{1}{2}(X_1^{(1)}(3) + X_1^{(1)}(2)) & X_2^{(1)}(3), \ldots, X_h^{(1)}(3) \\ \vdots & \vdots \\ -\frac{1}{2}(X_1^{(1)}(N) + X_1^{(1)}(N-1)) & X_2^{(1)}(N), \ldots, X_h^{(1)}(N) \end{pmatrix} \tag{27}$$

$$\hat{X}_1^{(1)} = \left(X_1^{(0)} - \frac{1}{a}\sum_{i=2}^{N} b_i X_i^{(1)}(k+1) \right) e^{-ak} + \frac{1}{a}\sum_{i=2}^{N} b_i X_1^{(1)}(k+1) \qquad (28)$$

2 EXPERIMENTAL DATA AND CALCULATION

We record the critical heat flux (CHF), mass flow rate (G), inlet subcooling (ΔT) and system pressure (p) as X_1, X_2, X_3, X_4 respectively . The last 3 parameters are the relevant factors of X_1. The data in Table 2 are obtained by experiment (Assuming that the geometric parameters are invariable during experiment).

Table 2 the value of CHF and related factors

i		1	2	3	4
CHF/10^5 W·m^{-2}	X_1	3.076	4.075	5.060	6.074
G/kg·s^{-1}	X_2	207.6	294.6	307.4	291.5
ΔT/℃	X_3	107.3	150.5	184.4	101.6
p/Pa	X_4	1070	1300	3400	40000

Normalizing the data by Eq. (1), we can obtain Table 3.

Table 3 Normalized CHF and relevant factors

i		1	2	3	4
CHF/10^5 W·m^{-2}	X_1	0.5064	0.6709	0.8331	1.0000
G/kg·s^{-1}	X_2	0.6753	0.9584	1.0000	0.9483
ΔT/℃	X_3	0.5819	0.8162	1.0000	0.5510
p/Pa	X_4	0.02675	0.0325	0.0850	1.0000

2. 1 Relevance degree calculating

Using Eq. (2), we can get relevance coefficient $\xi_{0i}(k)$, which is shown in Table 4.

Table 4 Relevance coefficient

i k	1	2	3	4
$\xi_{01}(k)$	0.6252	0.4532	0.6291	1.0000
$\xi_{02}(k)$	1.0000	0.8112	0.7665	0.4454
$\xi_{02}(k)$	0.4382	0.3695	0.3333	1.0000

The value of relevance degree can be calculated by Eq. (4).

$$r_{12} = 0.6769$$
$$r_{13} = 0.7558$$
$$r_{14} = 0.5353$$

From this, we can see $r_{13} > r_{12} > r_{14}$

Namely inlet subcooling affects CHF mostly, mass flow rate and the influence of system pressure is the smallest relatively. However, the non-dimension quantity class of their relevance coefficient is comparable, so they all play important roles on CHF under their respective unit measurements.

2. 2 Grey model-founding calculating

2. 2. 1 Found GM (1, 1) model

According to experiment, under the condition of p=3000 Pa, G=134.7～153.6 kg/(m^2 • s), the experimental data of ΔT and CHF is shown in Table 5.

Table 5 The experimental data of ΔT and CHF

		1	2	3
ΔT/℃	X_3	50	100	150
CHF/ MW·m^{-2}	X_1	0.18	0.27	0.305

According to Table 5, by using Eq. (1) we can get:

$$X^{(1)}(1) = X^{(0)}(1) = 0.18$$
$$X^{(1)}(2) = 0.45$$
$$X^{(1)}(3) = 0.55$$

From Eq. (9) and (10), we obtain

$$\boldsymbol{B} = \begin{bmatrix} -0.315 & 1 \\ -0.6025 & 1 \end{bmatrix}$$
$$\boldsymbol{Y}_N = [0.27 \quad 0.305]^{\mathrm{T}}$$

According to the experimental data, there are:

$$\hat{\boldsymbol{a}} = (a, u)^{\mathrm{T}} = (-0.124 \quad 0.234)^{\mathrm{T}}$$

From Eq. (7), we get

$$\frac{\mathrm{d}X^{(1)}}{\mathrm{d}(\Delta T_{\mathrm{SUB}})} - 0.124X^{(1)} = 0.234$$

From Eq. (11), we get

$$X^{(1)}(i+1) = 2.07\mathrm{e}^{0.124i} - 1.89$$

and

$$X^{(1)}(2) = 0.453$$

$$X^{(1)}(3)=0.762$$

From Eq. (12), we get

$$X^{(1)}(2)=0.273$$
$$X^{(1)}(3)=0.309$$

From Eqs. (15) and (22), there are

$$e\,(1)=0,\quad e\,(2)=0.003,\quad e\,(3)=0.004$$
$$\bar{e}=\frac{1}{3}[e(1)+e(2)+e(3)]=0.00233$$
$$S_2^2=\frac{1}{3}\sum_{i=1}^{3}[e(i)-\bar{e}]^2=2.9\times10^{-6}$$
$$\overline{X}=\frac{1}{3}(0.18+0.27+0.305)=0.257$$
$$S_1^2=\frac{1}{3}\sum_{i=1}^{3}\left[X^{(0)}(i)-\overline{X}\right]^2=0.00276$$
$$C=\frac{S_2}{S_1}=0.0103<0.35$$
$$|e(1)-\bar{e}|=0.00233<0.6145S_1$$
$$|e(2)-\bar{e}|=0.0007<0.6745S_1$$
$$|e(3)-\bar{e}|=0.0017<0.6745S_1$$
$$p=\{|e(i)-\bar{e}|<0.06745S_1\}=1$$

Table 1 shows that the precision of the model is high. According to the experimental data, under the condition that pressure is 3000 Pa and inlet subcooling is 90.5～105.9 ℃， there is Table 6.

Table 6 Experimental data of CHF and *G*

i		1	2	3
G/kg·s^{-1}	X_2	100	200	300
CHF/ MW·m^{-2}	X_1	0.2	0.32	0.38

From Table 6， we can also get GM (1， 1)model:

$$\frac{dX^{(1)}}{d(G)}-0.171X^{(1)}=0.258$$
$$\hat{X}^{(1)}(i+1)=1.78\,e^{0.171i}-1.58$$

Through model test:

$$C=0.066<0.35$$
$$p=\{|e(i)-\bar{e}|<0.6745S_1\}=1$$

We see the model is reliable.

According to experimental data, when inlet subcooling is 89.3～119.3 ℃, mass flow rate is 206.5～226.3 kg/(m^2 • s), we have Table 7.

Table 7 Experimental data of CHF and *p*

i		1	2	3
p/ Pa	X_4	10000	20000	30000
CHF/ MW·m^{-2}	X_1	0.375	0.405	0.43

Similarly, we obtain

$$\frac{dX^{(1)}}{d(p)} - 0.06X^{(1)} = 0.37$$

$$\hat{X}^{(1)}(i+1) = 6.58e^{0.06i} - 6.2$$

$$C = 0.042 < 0.35$$

$$p = \{|e(i) - \bar{e}| < 0.6745S_1\} = 1$$

So, the precision is good.

2. 2. 2 GM (1, 4) model

Using the data of Table 3, after the average value calculating of Eqs. (5) and (6), from Table 5, finally we obtain Table 8.

Table 8 The Results of accumulating and average value

i i	1	2	3	4
$\hat{X}^{(1)}(i)$	0.5064	1.1773	2.0104	3.0104
$\hat{X}^{(2)}(i)$	0.6753	1.6337	2.6337	3.587
$\hat{X}^{(3)}(i)$	0.5879	1.3981	2.3981	2.949
$\hat{X}^{(4)}(i)$	0.025	0.25925	0.14425	1.14425
$Z^{(1)}(i)$		0.84185	1.59385	2.5104

Thus, using Eqs. (26) and (27), we get

$$\boldsymbol{B} = \begin{bmatrix} -0.84185 & 1.6337 & 1.3981 & 0.05925 \\ -1.59385 & 2.6337 & 2.3981 & 0.14425 \\ -2.51040 & 3.5820 & 2.9491 & 1.14425 \end{bmatrix}$$

$$\boldsymbol{Y}_N = [0.665 \quad 0.833 \quad 1]$$

then, using Eq. (25), we have

$$\hat{\boldsymbol{a}} = (a, b_1, b_2, b_3, b_4)^T = (1.55, 0.55, 0.75, 0.76)^T$$

According to Eq. (24), the GM (1, 4) model becomes

Using Eq. (28), it is written as

$$\hat{X}_1^{(1)}(i+1)=\left[0.5064+0.353\,X_2^{(1)}(i+1)+0.482\,X_3^{(1)}(i+1)+0.489\,X_4^{(1)}(i+1)\right]e^{-1.55i}-$$

$$0.353\,X_2^{(1)}(i+1)-0.482\,X_3^{(1)}(i+1)-0.489\,X_4^{(1)}(i+1)$$

If we substitute CHF, ΔT, G and p for X_1, X_2, X_3 and X_4, the GM (1, 4) model can be written as

$$\mathrm{CHF}=\left(0.5064+6.98\times10^{-3}G+1.59\times10^{-2}\Delta T+7.43\times10^{-5}p\right)e^{-1.55i}-$$
$$6.99\times10^{-3}G-1.59\times10^{-2}\Delta T-7.43\times10^{-5}p$$

3 RESULTS

3.1 The GM (1, 1) model

3.1.1 If we predict X_1 (CHF) by X_3 (ΔT), then

$$i=3 \qquad \hat{X}^{(1)}(4)=1.113$$
$$\hat{X}^{(0)}(4)=0.351$$

However, we get the prediction value of 0.42 by multi-elements linear regression method. And the experimental value is 0.37.

3.1.2 If we use X_1 (CHF) and X_2 (G) to predict CHF, thus

$$i=3 \qquad \hat{X}^{(1)}(4)=1.393$$
$$\hat{X}^{(0)}(4)=0.463$$

Through multi-elements linear regression method, we have the prediction value 0.44, and the experimental value is 0.46.

3.1.3 If using X_1 (CHF) and X_4 (p) to predict CHF, we have

$$\hat{X}^{(0)}(4)=0.46$$

Through multi-elements linear regression method, we get the prediction value of 0.48, and the experimental value is 0.46.

Obviously, grey models predict more accurate than multi-elements linear regression method, referring to Fig. 1～3.

3.2 GM (1, 4)

Using multi-elements linear regression method, from experimental data, we get following equation.

$$q_{\mathrm{CHF}}=0.969G^{0.728}\Delta h_{\mathrm{in}}^{0.72}+0.035\rho_g h_{fg}\left[\frac{\sigma_g(\rho_f-\rho_g)}{\rho_g^2}\right]^{\frac{1}{4}}$$

where q_{CHF} is the critical heat flux 10^5 W/m^2;

G is mass velocity, kg/m^2·s;

$\Delta h_{in}=h_s-h_{in}$,

h_s is enthalpy of saturated state;

h_{in} is enthalpy of liquid at test inlet;

ρ_f is density of liquid;

ρ_g is density of gas;

$\rho_{fg}=\rho_g-\rho_f$, latent heat;

σ_g is gas surface tension.

the average dispersion

$$\sigma_{CHF}=\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[q_{CHF}-(q_{CHF})_i\right]^2\Big/\frac{1}{N}\sum_{i=1}^{N}(q_{CHF})_i^2}=19.7\%$$

By means of the GM (1,4) model above, we obtain

$\hat{X}_1^{(1)}(1)=0.5064$;

$\hat{X}_1^{(1)}(2)=1.1155$, by comparing with the original value of $\hat{X}^{(1)}(2)$, the relative error is 5.3%;

$\hat{X}_1^{(1)}(3)=2.0818$, by comparing with the original value of $\hat{X}^{(1)}(3)$, the relative error is 3.6%;

$\hat{X}_1^{(1)}(4)=3.2210$, by comparing with the original value of $\hat{X}^{(1)}(4)$, the relative error is 7%.

Then, using Eqs. (12) and (13), we have

$\hat{X}_1^{(0)}(1)=0.5064$;

$\hat{X}_1^{(0)}(2)=0.6091$, by comparing with the original value of $\hat{X}^{(1)}(2)$, the relative error is 9.2%;

$\hat{X}_1^{(0)}(3)=0.9663$, by comparing with the original value of $\hat{X}^{(1)}(3)$, the relative error is 16%;

$\hat{X}_1^{(0)}(4)=1.1392$, by comparing with the original value of $\hat{X}^{(1)}(4)$, the relative error is 13.9%.

When using grey GM (1, 4) model, the largest error is 16%, and the precision is fairly good . The comparison between calculating and experiment data is shown in Fig.4, where " Δ " and "*" represent the calculating values of multi-elements linear regression method and grey model method, respectively.

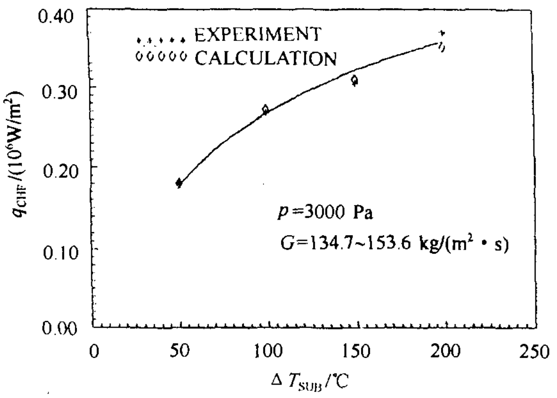

Fig.1 Influence of inlet subcooling on CHF

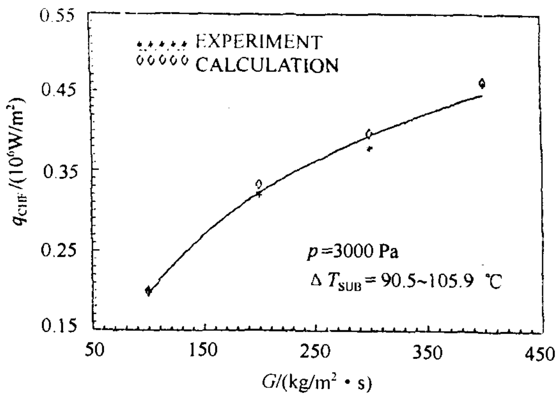

Fig.2 Influence of mass flow rate on CHF

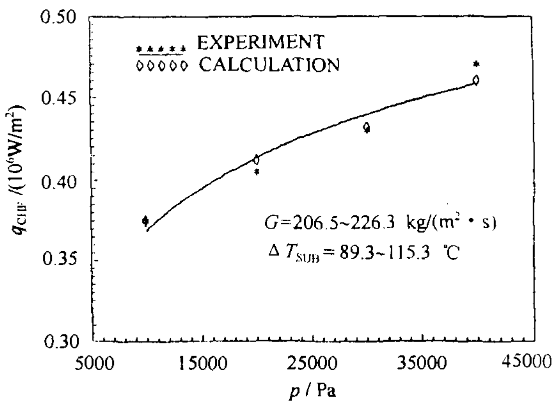

Fig.3 Influence of pressure on CHF

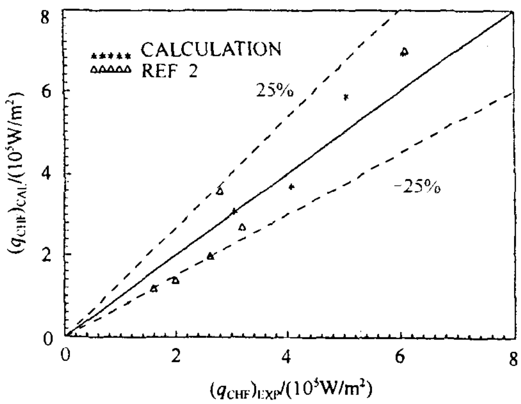

Fig.4 Calculating results of CHF are compared with experimental results

4 CONCLUSION

(1) The grey model can create more accurate models with less data, and can be created for many times and combined. Obviously, the grey model has advantage when lack of information, while information is sufficient, models can be created better because of successive feedback.

(2) The factors influencing sodium are complex. We can find out the main factors that affect the characteristics of liquid sodium by method of grey relevance degree, and create the model of liquid sodium boiling properly.

(3) We can predict the value of CHF accurately by creating GM (1, 1) model for sodium boiling, so appropriate measures can be adopted. The characteristics are: prediction for near future value is rather accurate, while far future value can be predicted only when model is created by adding new information.

(4) The chart of grey model-creating method is made up by discontinue points , so it reflects the real situation of experiment.

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