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Review of Critical Heat Flux Correlations for Upward Flow in a Vertical Thin Rectangular Channel

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1. Introduction

The flat-plate type of fuel firstly applied to the early nuclear reactor such as Shippingport, has been studied and used in many research reactors for a long time.[1] Compared with the general circular rod type of fuel, the plate fuel has higher ratio of heat transfer area to fuel volume and lower fuel temperature. So the plate fuel takes advantages of load following characteristics and robust material structure. From the view point of safety, this type of fuel has higher resistance to earthquake and external impact.

The cross section of coolant flow channel in the reactor core composed with the plate fuel is a thin rectangular shape. Thermal-hydraulic characteristics of this thin rectangular channel are different with those of general circular rod fuel bundle flow channel. Accordingly it could be thought that the CHF correlation in a thin rectangular channel is different with that in a circular channel, for which a large number of researches on CHF prediction have been carried out.

The objective of this paper is to review previous researches on CHF in a thin rectangular channel, summarize the important conclusion and propose the new simple CHF correlation, which is based on the data set under high pressure and high flow rate condition.

The researches on CHF in rectangular channel have been partially carried out according to the pressure, heated surface number(see Fig. 1), heated surface wettability effect, flow driving force and flow direction conditions.[2]

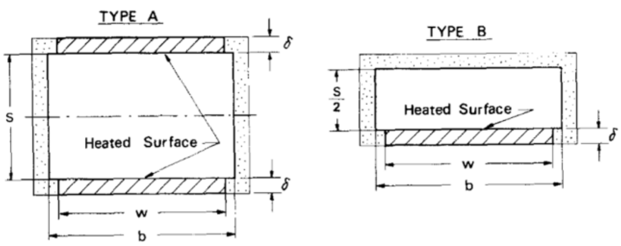

Fig. 1. Types of heated surface number in rectangular channel

In this paper, the CHF researches under forced upward flow in a vertical thin rectangular channel, both sides of which were heated will be mainly reviewed.

2. Review of Previous CHF Prediction Methods

2.1 Review of Empirical Correlation

An empirical correlation, a lookup table and a theoretical model are generally thought to be representative CHF prediction methods. Generally, an empirical correlation is derived from experimental data set through the regression analysis. In this paper, the restricted data set, which was extracted from some previous literatures is summarized in Table 1 and utilized in estimating the previous and new CHF correlation.

Table. 1. CHF Data Set in a Rectangular Channel

Channel Shape (s x b x L inch)	Pressure (psia)	Inlet Subc. (°F)	Data	Ref.
0.101 x 1 x 6	800, 1200, 2000	12~537	63	1958, DeBortoli
0.097 x 1 x 12-1/16	2000	8~555	103	
0.050 x 1 x 12-1/16	600, 2000	7~533	76	
0.097 x 1 x 27	600, 800, 830, 1200, 1215, 2000	9~592	138	
0.059 x 1 x 27	800, 1200, 1870, 2000	12~539	55	
0.078 x 2.25 x 72	600, 800, 1200, 2000	36~536	53	1958, Troy
0.097x 1x 12-1/16	2000	8~63	20	1958, Jacket
0.097 x 1 x 27	2000	9~66	13	
0.050 x 1x 12-1/16	2000	11~335	9	
0.50 x 2.1 x 37	~1000	17~191	45	1962, Tippets
0.25 x 2.1 x 37	~1000	13~190	33	
Total			608	

It is well known that Katto correlation has relatively higher accuracy of capacity to predict CHF in a thin rectangular channel among some CHF correlations through previous researches.

Fig. 2 shows the assessment result of Katto correlation and the RMS error is evaluated as 21.44 %. But Katto correlation has the limit that it was modified from the CHF correlation in a circular channel and the complicated proportional factor such as q_{c0} (zero-inlet subcooling CHF) and K should be defined and calculated depending on the flow rate region.

2.2 Review of Lookup Table

The lookup table of AECL is a large set of CHF experimental data points(about 33,000), which was normalized to the circular channel with 8 mm diameter.

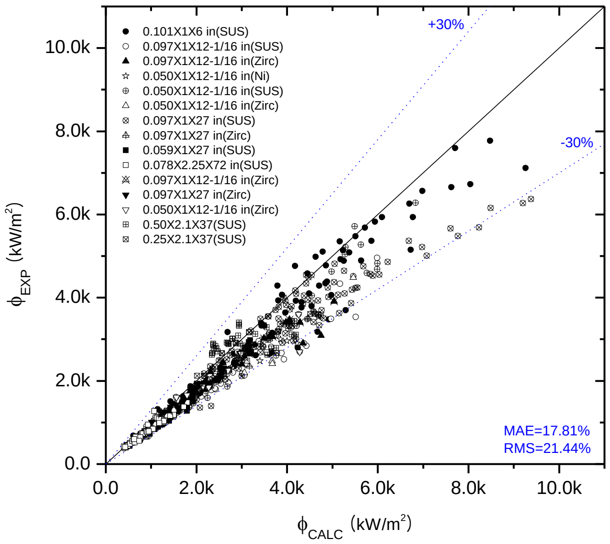

Fig. 2. Experimental vs Calculated CHF (Katto Correlation)

Groeneveld et al(2005)[5][6] supposed the correction factors, which are applicable to predicting CHF in a bundle of heated channels. The equation (1) is the supposed corrected equation.

$$q_{c,Tube} = K_1 \times K_4 \times q_{c,D=8mm} \qquad (1)$$

,where

$$K_1 = \begin{cases} (0.008/d_e)^{1/2} & ,if\ 3 \le d_e \le 25 \\ 0.57 & ,if d_e > 25 \end{cases}$$

$$K_4 = \exp[(d_e/l)\exp(2\alpha_h)] \qquad ,if\ (l/d_e) > 5$$

$$\alpha_h = X\rho_f / [X\rho_f + (1-X)\rho_g]$$

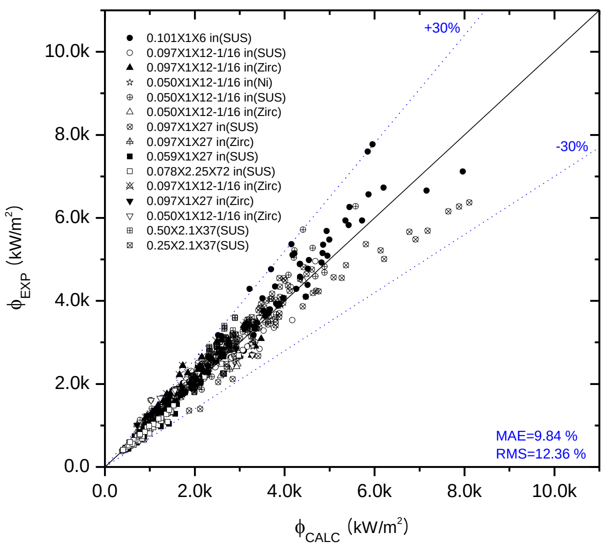

Fig. 3. Experimental vs Calculated CHF (Lookup Table)

The fig. 3 shows the assessment result of Lookup Table. RMS error(12.36%) is better than that of Katto correlation, which shows that lookup table could predict relatively well CHF in a rectangular channel if proper correction factors were applied. This conclusion coincides with the research of Pioro(1999)[4], which said that lookup table predicts well CHF in the noncircular channel under the high pressure condition.

2.3 Comparison with Low Pressure Correlation

From 1980's, JAERI has carried out the researches on CHF for upward and downward flow in a thin rectangular channel, which can be applied to the design of flat-plate type fuel in a research reactor. Sudo et al(1985)[7] and Sudo & Kaminaga(1993)[8] performed the related experimental researches and proposed their own CHF predicting equations. It is well known that their correlation has high accuracy of capacity to predict CHF under relatively lower pressure condition.

The above three CHF prediction methods are compared with each other according to pressure condition in fig. 4. Unlike other methods, there is almost no difference of pressure effect in Sudo & Kaminaga correlation. Besides, it relatively over-predicts CHF in lower flow rate and under-predicts in higher flow rate. Katto correlation and lookup table show similar trend of CHF prediction.

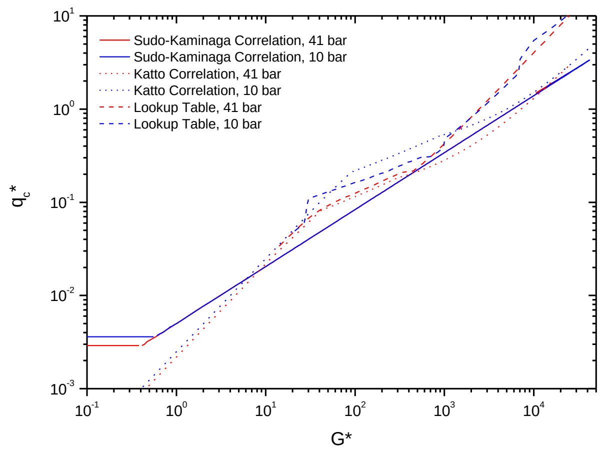

Fig. 4. Comparison of pressure effects among prediction methods

3. New Simple Correlation

3.1 Development Concept of New Simple Correlation

From the above review, it can be concluded that there is no universal prediction method for CHF in a vertical rectangular channel and the empirical correlation has as physically important meaning as ever. So, the more convenient empirical correlation, which has relatively lower prediction error than previous correlations is needed.

In this paper, it is assumed that the new CHF correlation would be the shape of linear equation of first order, X term of which is composed with the dimensionless numbers affecting CHF. The basic shape of the new CHF correlation is supposed as the following equation (2).

$$\left(\frac{A_h}{A}\right)^{C_0} q^* = C_1 (Bi)^{C_2} \left(\frac{\rho_g}{\rho_l}\right)^{C_3} \left(We_d^{-1}\right)^{C_4} \left(1+\frac{\Delta H_i}{H_{fg}}\right) G^* + C_5 \qquad (2)$$

The constant C_1 is slop of this equation and C_5 is the y interception. These could be found through the linear regression analysis.

3.2 Development Procedure of New Simple Correlation

The physical variables affecting CHF are summarized as the following dimensionless numbers. Weber number(We_d) is the ratio of surface tension to momentum in rectangular channel, density ratio(ρ_g/ρ_v) means the effect of pressure, the ratio of heated area to cross section area(A_h/A) is the effect of shape of channel and Biot number(Bi) is the ratio of conduction resistance to convection resistance, which means the heat transfer effect under CHF.

Each dimensionless number is added step by step as Fig. 5 and exponents of each term are decided by the least square method. This method has been used in the previous research such as Wright ea al(2008)[3]. The CHF prediction errors of each step equation are evaluated and summarized in table. 2.

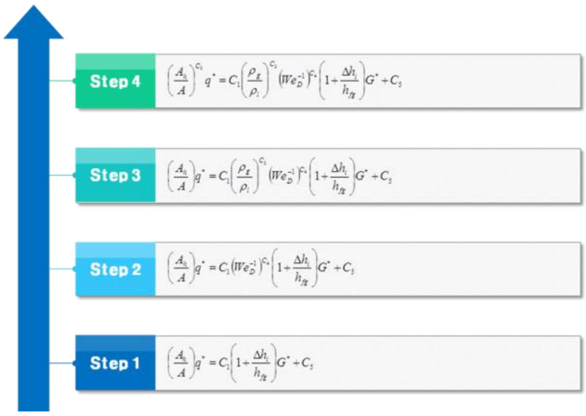

Fig. 5. Procedure of new simple correlation development

At step 4, the correlation is capable of predicting the CHF at the lower RMS error than that of Katto correlation.

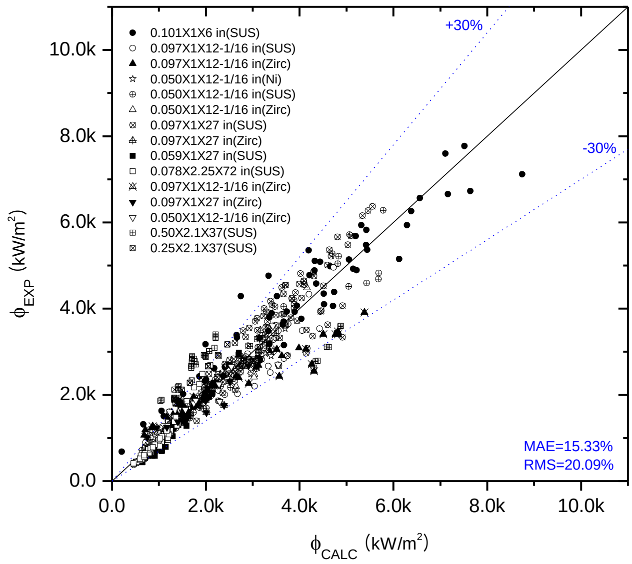

Fig. 6. Experimental vs Calculated CHF (New Simple Correlation)

Fig. 6 and 7 show the assessment results of this new simple correlation.

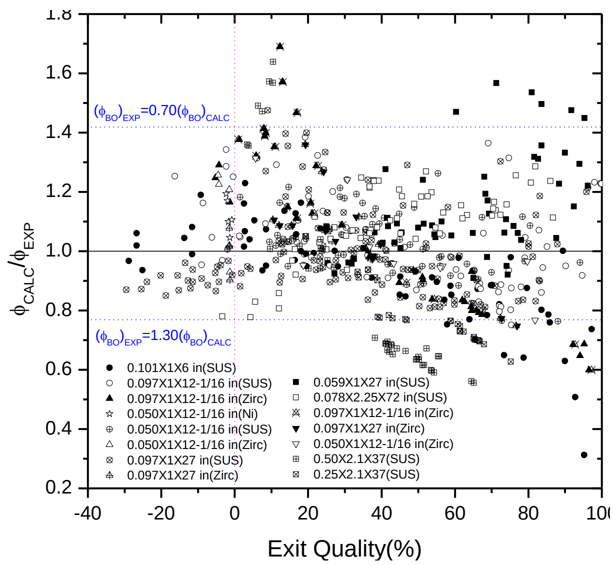

Fig. 7. Prediction ratio vs Exit quality (New Simple Correlation)

Table. 2. Summary of deriving procedure of new simple correlation

Correlations	C_0	C_1	C_2	C_3	C_4	C_5	*Mean Ratio*	*Stnd. Dev.*	*MAE*	*RMS*
Step 1	*1*	*0.2949*	*-*	*-*	*-*	*5.4269*	*0.8913*	*0.3683*	*0.3023*	*0.3838*
Step 2	*1*	*2.3463*	*-*	*-*	*0.205*	*-6.2487*	*1.0413*	*0.3132*	*0.2238*	*0.3157*
Step 3	*1*	*5.9666*	*-*	*0.180*	*0.253*	*-12.433*	*1.0731*	*0.3247*	*0.2383*	*0.3326*
Step 4(New Cor.)	*0.752*	*0.8988*	*-*	*0.149*	*0.238*	*-1.1604*	*1.0120*	*0.2007*	*0.1533*	*0.2009*
Katto Cor.	*-*	*-*	*-*	*-*	*-*	*-*	*1.1650*	*0.1370*	*0.1781*	*0.2144*
Step 5	*0.742*	*0.8561*	*-0.036*	*0.131*	*0.237*	*-1.1611*	*1.0033*	*0.1981*	*0.1520*	*0.1980*

At step 5, even though Biot number was added, the RMS error improvement is relatively small. Especially C_2 is very small and this means that the effect of Bi on CHF is small. So, it would be better to exclude Bi from CHF correlation under high pressure condition.

4. Conclusion

From the literature researches on CHF for upward flow in a vertical thin rectangular channel, some CHF prediction methods were reviewed and compared. There is no universal correlation which can predict CHF at all conditions, but generally, Katto empirical correlation is known to be useful at high pressure and high flow rate.

The new simple correlation was developed from the restricted data set, the CHF prediction capacity of which is better than that of Katto. Even though the prediction consistency of the new simple correlation is lower, MAE and RMS error decreased quite.

For the more development of the new simple CHF correlation, the more advanced regression analysis method and theoretical analysis should be studied in future.

Appendix A. Nomenclature

A	flow area of channel
A_h	heated area
d_e	hydraulic equivalent diameter
G	mass flux
G^*	dimensionless mass flux $G^* = G\Big/\sqrt{\lambda g \rho_g (\rho_l - \rho_g)}$
H_{fg}	latent heat of evaporation
ΔH_i	inlet subcooling enthalpy
l	length of heated plate
q	heat flux
q^*	dimensionless heat flux $q_c^* = q_c \Big/ h_{fg}\sqrt{\lambda g \rho_g (\rho_l - \rho_g)}$
X	quality
We	Weber number $We_d^{-1} = \sigma \rho_l \big/ G^2 d_e$

Greek symbols

ρ_l, ρ_f	density of liquid
ρ_v, ρ_g	density of vapor

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