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A Study of the Heated Length to Diameter Effects on Critical Heat Flux

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ABSTRACT

An analytical and experimental investigation has been performed on the heated length-to-diameter effect on critical heat flux for fixed exit conditions. A L/D correction factor is developed by applying artificial neural network and conventional regression techniques to the KAIST CHF data base. In addition, experiment is being performed to validate the developed L/D correction factor with independent data. Assessment shows that the developed correction factor is promising for practical applications.

1. INTRODUCTION

The phenomenon of critical heat flux (CHF) provides an important limitation on the operation of water-cooled nuclear reactors and, consequently, has received a great deal of study. During the last four decades many researchers have conducted experimental studies on the CHF using various types of test sections under various conditions especially to obtain more accurate prediction and prevail the mechanism. As a result of those extensive studies, many aspects of the CHF have been understood and several CHF prediction methods have been developed based on experimental data.

There are several forms of CHF correlations. For uniformly heated tubes, most correlations can be classified into inlet condition type and local condition type correlations, among which local condition type correlations are more useful in practical applications. The CHF table based on the local conditions hypothesis, e.g. the 1995 CHF look-up table by Groeneveld et al.[1], is considered as one of the best and widely used CHF prediction methods. The local-condition correlations consider the CHF as a function of pressure, mass flux, channel cross-section geometry, and local quality, neglecting the effect of heated length. The heated length effect is significant for short tubes but decreases as the length-to-diameter ratio (L/D) increases. Therefore, it is common to use the CHF data of L/D > certain value in developing the local condition correlations. The 1995 CHF look-up table was developed based on the experimental data of $L/D \geq 80$. Only a few number of actual data were used for the region of low and intermediate pressure, low flow and low qualities. This is due to the fact that low-quality data cannot be obtained with long tubes for low flow conditions in steady-state CHF tests. However, the relevant conditions are still important in practical applications where CHF occurs during a transient.

An exact understanding of the L/D effect as a function of other operating conditions is important at least in two aspects: (a) to predict CHF in short channels by prediction models developed based on longer channels, and (b) to utilize the data for shorter channels in developing local-condition correlations. The latter can be achieved by converting the short tube data to representative long tube data with an appropriate L/D correction factor.

The main objectives of this study are to understand the parametric effect of heated length and to develop a reliable L/D-correction factor based on KAIST CHF data base and verify it with new experimental data.

2. BACKGROUND

Contrary to other parameters related to the CHF, little work has been done to identify the appropriate definitions for characteristic lengths that should be associated with CHF[2]. Based on results from forced convection, previous investigators have most frequently used the ratio of the heated length to the inside equivalent diameter of channel (L/D) as the characteristic dimensionless length.

Generally, the CHF decreases as the heated length increases for fixed inlet conditions because the exit quality increases with increasing length for a given heat flux; however, there are some different arguments in case of fixed exit conditions. Although many researchers have consented that there exist values of L/D beyond which it does not affect the CHF, it is not clear what this limiting value is. The limiting value of L/D can be several tens to several hundreds as a function of other parameters such as mass flux, quality, etc. It is shorter for low quality and/or high velocity conditions. There is also an indication that the limiting value does not exist and the CHF is always a decreasing function of L/D[3].

There are several L/D correction factors proposed in the literature. Groeneveld et al. [4] noted that the length effect is particularly noticeable if L/D<10 for subcooled burnout and L/D<100 for two-phase dryout. The factor was represented by

$$k_4 = \exp\left[\frac{D}{L}\cdot e^{2\alpha}\right] \qquad (1)$$

where, α is evaluated from homogeneous model(Eq. (2)) as follows:

$$\alpha = \frac{x}{x+(1-x)\frac{\rho_g}{\rho_f}} \qquad (2)$$

Another heated correction factor proposed by Sudo & Inakaki[5] for subcooled conditions is

$$K = 40(L/D)^{-1.2} \qquad (3)$$

It is applicable to low pressure(below 0.1Mpa) and very short tubes (L/D≤25).

The available correction factors have not been verified with experimental data of a wide operating range of conditions.

3. DEVELOPMENT OF L/D CORRECTION FACTOR

In order to qualify and assess the heated length effect for fixed exit conditions, various experimental CHF data with different heated lengths are needed. Not only those data are insufficient but it is also difficult to evaluate their complex behavior because of their different experimental conditions. In this study, an advanced information processing technique, artificial neural networks (ANNs), is introduced to overcome this problem. ANNs have the capability to learn complex relationships from a set of associated input-output. ANNs might provide a valuable alternative to current techniques for estimating the CHF as verified in Ref. 6. Trained by using a large number of experimental data from KAIST CHF data base, the networks predict the CHF values which are required for the development of the L/D correction factor at various flow and geometric conditions. The back-propagation neural network(BPN), one of the numerous ANNs, used in this study consists of one input layer, two hidden layers and one output layer. The CHF data used in learning step have the following ranges of parameters: diameter (D) = 0.006~0.012 m, heated length (L) = 0.1~6.0 m, pressure (P) = 100~20000 kPa, mass flux (G) = 100~9000 kg/m²s, exit quality(X) = -0.5 ~1.0. For fixed exit conditions, four dimensionless parameters (e.g., ρ_g/ρ_f, $\sigma\rho_f/G^2L$, L/D, X) are used at input layer. These parameters are normalized into the values between 0.1 and 0.9 to reduce the training time of the BPN. The network correlates these parameters until the desired output accuracy is acquired. Through the sufficient training step the constructed network can produce the reasonable output. The training results of the BPN are summarized in Table 1.

Table 1 Summary of the trained BPN

No. of the CHF Data		No. of hidden nodes		Network Error	Prediction result	
Training Data	Simulation Data	1st hidden layer	2nd hidden layer		Avg. error	R.M.S. error
7633	848	40	40	0.000290	-0.719%	15.487%

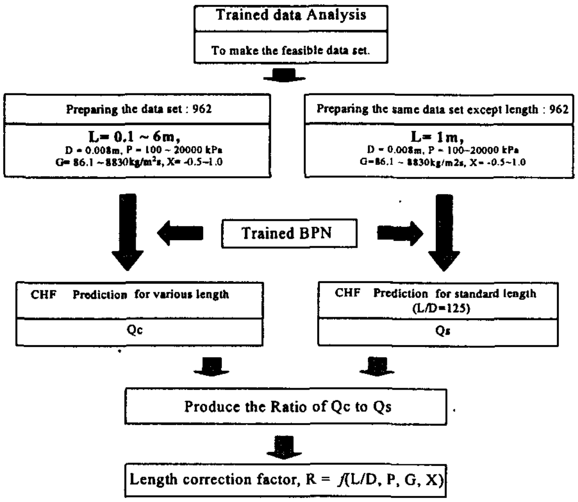

Fig. 1 The development procedure of L/D correction factor.

A schematic depiction of the development procedure of length correction factor is illustrated in Fig. 1. To prepare the feasible and meaningful data set, the analysis of CHF data used in the BPN was performed in detail. Then, the BPN predicted the CHF (Qc) for the prepared data set at various conditions except the diameter; the prepared data was fixed with 8mm inner diameter for fear of including the influence of diameter itself. With other parameters (D, P, G, and X) fixed in each data set, the heated length was only converted to a standard heated length(L=1m; L/D=125). For the converted data, The CHF(Qs) was re-predicted by the BPN. The ratio of Qc to Qs(R) calculated in this way would have a functional relation with other system parameters. Finally, with a statistical analysis tool (SASS), the length correction factor was developed showing a reasonable prediction result according to each system parameter (Figs. 3~6). The developed correction factor is

$$R = C_1 \exp[-C_2 L / D] + C_3 \tag{4}$$

where the coefficients C1, C2 and C3 are dependent on system parameters as follows:

for the case of L/D < 125

$$C_1 = \frac{6.14185}{\log[(1-x)\,G^{0.95}]}$$

$$C_2 = (0.009267 + 0.0012(1-\exp(x-1))\log G)$$

$$C_3 = 0.95$$

and for the case of L/D>125

$$C_1 = 0.3427\,(1-x)^{0.5253}\,G^{0.1541}$$

$$C_2 = 0.00276147\,\frac{\log(L/D)}{\log G}$$

$$C_3 = 0.205$$

4. EXPERIMENTAL VALIDATION

To verify the developed length correction factor, experiments was carried out in the following ranges of variables:

Diameter,	d = 0.006 and 0.008 m
Heated length,	L = 0.32~1.05m
Pressure,	p = 101kPa (at atmospheric pressure)
Mass flux,	G = 400kg/m^{2}s
Quality,	X = 0.42~0.51

The schematic diagram of experimental loop is shown in Fig.2. Heat is produced directly in the test section by the Joule effect using a direct current (DC). The experimental data presented in this paper has been obtained on INCONEL 600 tubes (test section) having 0.006 and 0.008 m inner diameter. The electric potential from the power controller is applied to the test section by means of two copper clamps; by moving the upstream clamp different heated length can be obtained. The test section is instrumented with thermocouples to detect the incipient dryout and to trip the power controller. Three chromel-alumel (K type) ungrounded thermocouples are spot welded on the external surface of the tube. The signals produced by the thermocouples and other flow parameters are recorded in real time and collected by data acquisition system for later analysis. Once the flow parameters were established and controlled, the power applied to the test section was gradually increased until the wall temperature spike was detected (for uniformly heated tubes dryout usually occurs at the end of the heated length). For the different heated length, it is very difficult to get same exit quality because it is dependent variable during the test. Therefore, with the degree of subcooling at inlet of the test section controlled by preheater, the test was repeatedly carried out until the data could be reached to a same local condition in different heated length.

The test results of the verification of the developed heated length correction factor are shown in Figs. 7~8. The comparison with the correction factor of 1995 AECL lookup table was also indicated. Though a small number of experimental data have been tested, it can be easily found that the developed heated length correction factor is more accurate than Eq. (1).

5. CONCLUSIONS AND RECOMMENDATIONS

In this work, a L/D correction factor for CHF is developed from the KAIST CHF data base and validated by independent new data. The developed correction factor shows reasonable accuracy for both the original data base and new experimental data. It is expected to be useful to convert the short tube data into a standard data for longer tubes and to predict the CHF for short tubes by local condition correlations. Further improvement of the correction factor with including the pressure influence and validation with more experimental data are recommended as future work.

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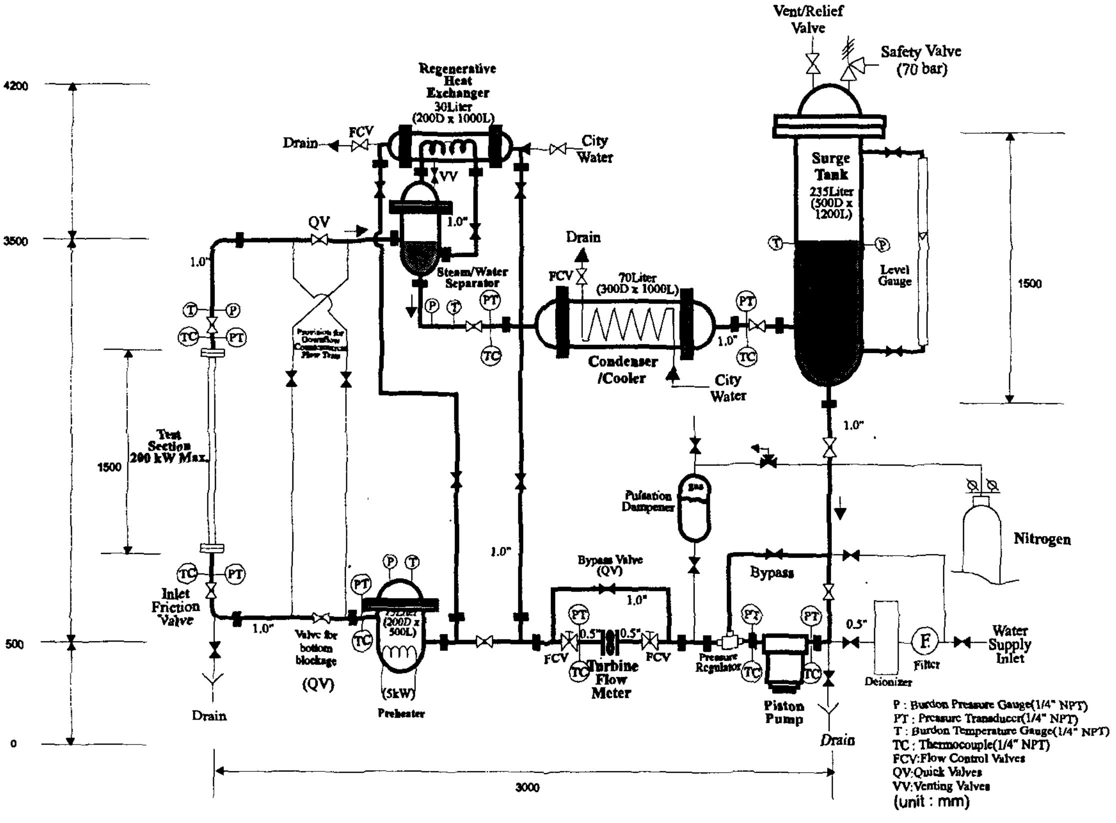

Fig. 2. Schematic Diagram of CHF Experimental Facility for Middle Pressure Conditions

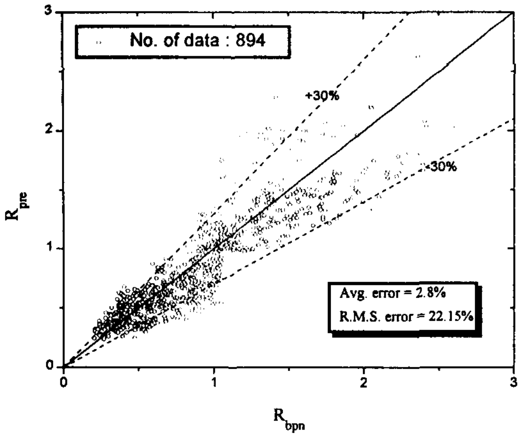

Fig. 3 Overall prediction accuracy of the developed L/D correction factor

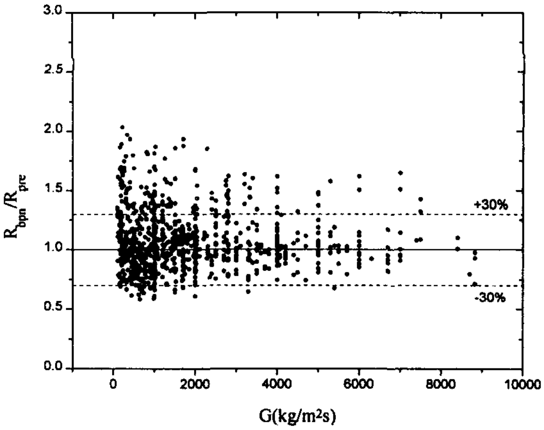

Fig. 4 Prediction result according to Mass Flux

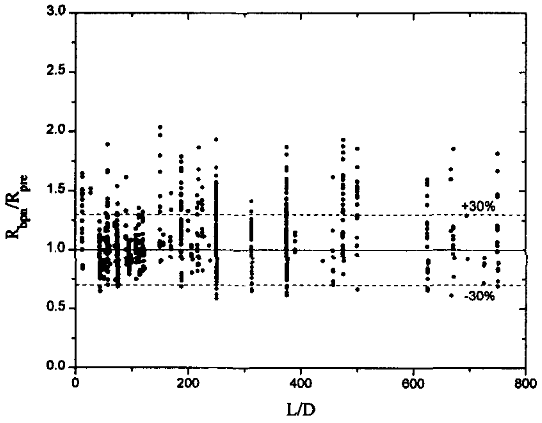

Fig. 5 Prediction result according to Length to Diameter

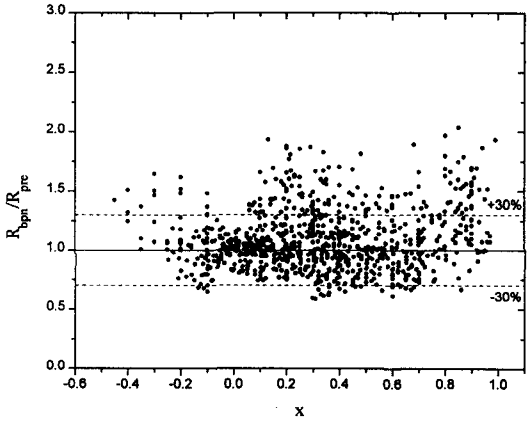

Fig. 6 Prediction result according to Exit quality.

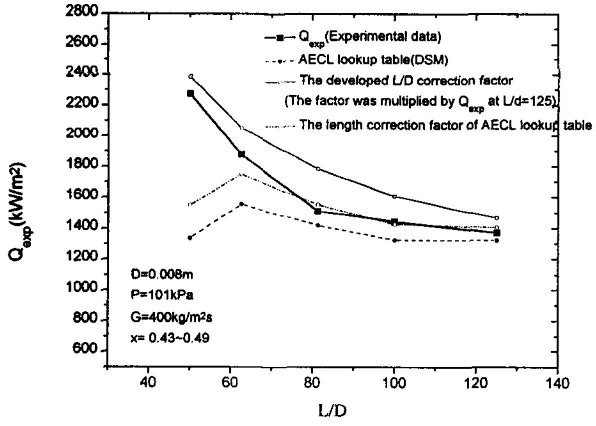

Fig.7 The comparision of AECL-lookup table(DSM)
and the developed L/D-correction factor(applied to experiment data)

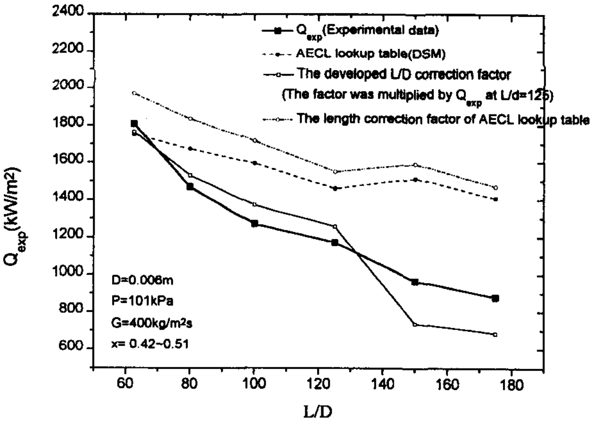

Fig.8 The comparision of length AECL-lookup table(DSM)
and the developed L/D-correction factor(applied to experiment data)