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Development of the Heated Length to Diameter Correction Factor on Critical Heat Flux Using the Artificial Neural Networks

Yong Ho Lee, *Tae-Hyun Chun, Won-Pil Baek and Soon Heung Chang

Korea Advanced Institute of Science and Technology
*Korea Atomic Energy Research Institute

ABSTRACT

With using artificial neural networks (ANNs), an analytical study related to the heated length effect on critical heat flux(CHF) has been carried out to make an improvement of the CHF prediction accuracy based on local condition correlations or table. It has been carried out to suggest a feasible criterion of the threshold length-to-diameter (L/D) value in which heated length could affect CHF. And within the criterion, a L/D correction factor has been developed through conventional regression. In order to validate the developed L/D correction factor, CHF experiments for various heated lengths have been carried out under low and intermediate pressure conditions. The developed threshold L/D correlation provides a new feasible criterion of L/D threshold value. The developed correction factor gives a reasonable accuracy for the original database, showing the error of -2.18% for average and 27.75% for RMS, and promising results for new experimental data.

1. Introduction

To guarantee the safe operation of Nuclear Power Plant (NPP), it is necessary to acquire a full knowledge of the upper limit of such a technique, represented by the onset of the critical heat flux (CHF). In these regards, many researchers have conducted experimental studies on the CHF. As a result of those extensive studies, many aspects of the CHF have been understood to some extent and many CHF prediction methods have been developed based on experimental data. However, contrary to other parameter related to the CHF, little work has been done to identify the appropriate definitions for characteristic lengths that should be associated with CHF. Although many researchers have consented that there exist values of L/D beyond which it does not affect CHF, it is not clear what this threshold value is. The threshold value couldn't be a constant (e.g. L/D = 80 for the case of AECL look-up tables [1]), but could be varied according to other system parameters. In fact, the length effect is less severe at shorter tube for subcooled and low-quality condition and still exists at longer tube for two-phase and high-quality condition. To find the threshold value as a function of other operating conditions is prerequisite to quantify the length effect. In above reasons, the main objectives of this study are to a suggest feasible criterion where the heated length can affect on CHF, to develop a reliable L/D correction factor within the criterion, and to verify it with new experimental data. In order to quantify and analyze the heated length effect for fixed exit conditions, an advanced information processing technique such as artificial neural networks (ANNs) was introduced. It would be very reasonable because artificial neural networks could provide a valuable alternative to current techniques for estimating the CHF as verified Moon et al. [2].

2. The heated length (or L/D) effect

For the constant exit conditions, there are a few opinions about the effect of heated length on CHF. These are classified into two categories by CHF mechanism: DNB and LFD. For DNB mechanism or subcooled condition, the heated length has small contributions to CHF. For example, Collier [3] and Nariai [4] asserted that the effect of tube length on the critical heat flux for fixed exit quality is small, so it can be negligible for subcooled and low-qualuty conditions. In case of high-quality condition where liquid film dryout mechanisms are dominant, the heated length effects are more obvious and the limiting value is higher than that of subcooled condition [5]. Groeneveld [6] explained that for simple geometries this limit is 30.0 for subcooled inlet conditions and 200.0 for two-phase inlet conditions.

In another aspect, there are some different opinions contrary to above mentions. That is, the effect depends on flow or geometric parameters. There is also an indication that the limiting value does not exist and CHF is always a decreasing function of L/D [7]. Despite this disagreement, there is substantial evidence to show that the CHF is inversely related to L/D. It is clear that, since the L/D limit is related directly to the flow development, this limit is not a constant, but is related to the flow parameters and flow properties. Consequently, the threshold length is a function of other system parameters and it can be larger than usually expected.

3. L/D-correction Factor

3.1 Strategy

When required the different heated length at same local condition, the local condition correlations cannot give any information because they use average values in regions where no length effect exists according to their judgements. In this study, an analytical study related the heated length effect has been carried out to make an improvement of the prediction accuracy based on local condition correlation or table. In order to analyze the heated length effect for fixed exit conditions, various experimental CHF data with different heated lengths are needed. However, not only those data are insufficient but it is also difficult to evaluate their complex behavior because of their different parametric ranges. In this study, an advanced information processing technique, artificial neural networks (ANNs), is introduced to overcome this problem. Backpropagation neural network (BPN), one of the numerous ANNs, has been used in this study to obtain the CHF data whose heated length are different except other parameters being kept constant. Trained by using a large number of experimental CHF data for water flow in uniformly heated vertical round tubes compiled from worldwide sources, the BPN predict the CHF which are required for development of L/D correction factor at various flow and geometric conditions. The network makes good performances for both the training data and the simulation data, giving -0.99% for average error and 13.35% for RMS error.

3.2 The L/D correction Factor

There was a general agreement that there exists the limiting (threshold) value of L/D under which heated length could not affect on CHF. The limiting value is not a constant but it depends on system parameters such as diameter (D), exit quality (x), mass flux (G) and pressure (P). Evaluation of the threshold value in view of a function of system parameters is prerequisite for the development of L/D correction factor. First of all, to prepare the feasible and meaningful data set, the analysis of CHF data used in the BPN was performed in detail. Then, typical values for each parameter were established covering broad ranges (e.g., P = 1000, 3000, 5000, 10000 and 15000kPa; G = 100, 500, 1000, 2000, 4000 and 6000kg/m^{2}s; x= -0.3, -0.1, 0.0, 0.1, 0.3, 0.5 and 0.8). In this step, the important thing is that the data set must have an even distribution and meet the heat-balance criteria. Totally 179 data set were determined as mentioned above. For the determined data set; the trained BPN evaluated CHF according to various heated length; L/D = 5~600. The calculated CHF systematically decreases with L/D, but at a certain values of L/D, their decreasing rates are rapidly decreased. This may be considered as threshold value of L/D. It varies from 15 to 400 depending on mainly exit qualities. For high quality and low flow conditions, there still exist the decreasing trends at higher value of L/D than the threshold of that. It implies that the heated length effect still exists at very long tubes. For every data set, graphical analysis has been carried out to determine the threshold value. In the step of determining threshold L/D value, some errors could be anticipated due to decision making by human beings. However it doesn't matter since the some errors of threshold values cannot take an important role for development of correction factor. It just suggests a criterion of L/D whether the heated length effect exists or not. The threshold values evaluated in this way would have a functional relation with other system parameters. Finally with a statistical analysis system (SAS), the threshold L/D correlation was determined through a conventional regression. The developed threshold L/D correlation $(L/D)_{th}$) is

$$L/D)th = 252.86\left(\frac{\sigma\rho f}{G^2 D}\right)^{0.135}\left(x + 0.25\left(\frac{\rho g}{\rho f}\right)^{-0.189}\right) + 10 \qquad (3.1)$$

Using dimensionless parameters, the threshold L/D is related to system parameters (e.g., diameter, pressure, mass flux and exit quality). As exit quality increases, Eq. (3.1) gives a large value of L/D. Pressure has a similar trend but minor effect. On the other hand, mass flux and diameter are inversely proportional to the threshold L/D. As seen in Figs. 1 ~ 2, it gives a feasible value of the threshold L/D according to each parameter. Moreover, the assessment of Eq. (3.1) based on 1995 AECL look-up table shows a promising result (Table 1). It can be easily founded that the present criterion is more reasonable than that of the table. According to the result of the table's prediction based on DSM, average errors for the CHF data of $L/D < L/D)_{th}$ are negatives whether L/D of the data is higher than 80 or not. This implies that those data still have length effect. In the case of $L/D > LD)_{th}$, the data of $L/D < 80$ shows a good prediction accuracy (e.g., -2.11% and 10.95% , average and RMS error, respectively). And the data of $L/D > 80$ give average error small positive value. This means that the length effect still works even if $L/D > L/D)_{th}$

With the above criterion, the CHF data of $L/D < L/D)_{th}$ are selected from the KAIST database for the purpose of the development of correction factor. In those data, extreme conditions (e.g. $L/D < 5$) are excluded since it could give a large error for regression. Totally 1935 data are selected from KAIST database. For the selected data, the threshold L/D was calculated with using Eq. (3.1). And then, the L/D of experimental data were replaced with the calculated threshold L/D. For those transformed data, the BPN predicts CHF at threshold L/D. Using the ratio of selected experimental CHF (q_{exp}) and calculated CHF ($q_{bpn)th}$) at threshold L/D, finally, the L/D correction factor was developed. The L/D correction factor (*C.F.*) for the case of $L/D < L/D)_{th}$ is

$$C.F. = -0.2945\left[(1+x)^{1.237}\left(\frac{\sigma\rho f}{G^2 D}\right)^{0.01155} + 0.312\left(\frac{\rho f}{\rho g}\right)^{-0.0617}\right]\cdot \ln\left(\frac{L/D}{L/D)th}\right) + 1 \qquad (3.2)$$

and for the case of $L/D \geq L/D)_{th}$, the factor becomes unit; $C.F. = 1$ .The L/D correction factor can be applied in following ranges of variables: D = 0.005 ~ 0.012m, L = 0.1 ~ 6.0m, P = 101 ~ 20,000kPa, G = 12.5 ~ 7447.5kg/m^{2}s and x = -0.35 ~ 0.98.

The developed L/D correction factor depends on L/D, exit quality and mass flux. Especially, L/D is the more dominant than any other parameter. Although system pressure has an effect, it is not much. Figs. 3 ~ 6 show parametric trend of the developed correction factor. The parametric trends correspond with general acceptance. The prediction errors of Eq. (3.2) to original data are -2.18% for average and 27.75% for RMS (Fig. 7).

Table 1 Assessment result of the threshold L/D correlation based on 1995 AECL look-up table prediction (DSM)

Ranges of parameters		$L/D < L/D)_{th}$			$L/D \geq L/D)_{th}$		
D = 0.005 ~ 0.012m L/D = 5 ~ 1025 P = 101 ~ 20000kPa G = 100 ~ 7499kg/m^{2}s X = -0.35 ~ 0.99	Table's standard	No. data	Avg. err (%)	RMS err (%)	No. data	Avg. err (%)	RMS err (%)
	$L/D < 80$	845	-21.06	31.54	495	-2.11	10.95
	$L/D > 80$	1090	-18.17	30.92	8012	5.10	26.58

4. Experiments.

The developed L/D correction factor (Eq. 3.2) based on analytical method (i.e. artificial neural network) should be validated by experimental work. In these regards, experimental study has been performed under low and intermediate pressure conditions. All the experiments were intended to obtain the same exit quality for each case. However, the exit quality is not an independent variable during the test, so it was almost impossible to get exactly same exit qualities. Thus the data have a narrow range of exit qualities. Figs. 8~12 show the effect of L/D on CHF. CHF gradually decreases with increasing L/D for all cases but the trends are changed according to other parameters.

The heated length effect according to tube inner diameter

Generally, small tube diameter gives a large heated length effect. Comparison of Figs. 8 and 9 represents the heated length effects with diameter of 0.006m and 0.008m for P = 101kPa, G = 400kg/m^{2}s and x = 0.4~0.45, the heated length effect more apparent for small diameter especially for L/D < 60. However, it seems to be coupled with effect of exit quality.

The heated length effect according to system pressure

For low and intermediate pressure conditions, the heated length effect increases with pressure. Fig. 8 and 10 show the heated length effect for 101kPa and 1000kPa at low flow (G = 400kg/m^{2}s). And Figs. 4.10 and 4.11 also indicate the pressure dependency of L/D effect for 1000kPa and 2000kPa at middle flow (G = 1000kg/m^{2}s). As seen in Figs., the decreasing trends are not affected by pressure. This implies that pressure have a small contribution of L/D effect.

The heated length effect according to exit quality

As the exit quality increase, the heated length effect becomes more obvious because the deposition rate of droplets to film flow decreases due to decrease of a droplet density with increasing exit quality; *upstream effect*. It can be easily founded through Figs. 8~12.

For the purpose of validation of the developed L/D correction factor, it was applied to the experimental data. In case of low-pressure condition (101kPa), the developed L/D correction factor provided relatively small values. However, the developed L/D correction factor well reflects general trends for intermediate pressure conditions and shows a reasonable accuracy for all cases (Fig. 10~12). This fact implies that the heated length effect is severe at low-pressure and low-flow conditions (e.g. P = 101kPa and G = 400kg/m^{2}s). Comparison with the length correction factor of 1995 AECL look-up table (DSM) are also indicated at same figures. At higher flow and higher pressure, the developed L/D correction factor is more accurate than that of the table. Consequently, the developed L/D correction factor shows a good performance at new experimental data. But it is recommendable that the developed L/D correction factor should be improved at low-pressure and low-flow conditions.

5. Conclusions and Recommendations

In this study, an analytical and experimental investigation has been preformed on the heated length to diameter effect on CHF. By applying an advanced information processing technique such as artificial neural networks (ANNs), a new criterion in which the heated length could affect on CHF has been developed. And within the criterion, a L/D correction factor has been developed. A series of CHF experiments have been carried out to validate the developed L/D correction factor. Important findings of this study are summarized as follows:

(a) A new criterion of L/D threshold value as a function of other operating conditions has been developed. It gives a feasible value of threshold L/D under which the heated length could affect CHF.

(b) Within above criterion, a L/D correction factor has been developed using KAIST CHF database. The parametric trends of the developed L/D correction factor correspond with general acceptance. And it shows a good accuracy for the original data (e.g., Avg. error = -2.18% and RMS error = 27.75%).

(c) The developed L/D correction factor shows the reasonable results for new experimental data at low and intermediate pressure conditions. Compared with the length correction factor of 1995 AECL look-up table, the developed L/D correction factor provides more accurate CHF values.

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 and validation with more experimental data are recommended as future works. And more apprehensive study for the heated length effect on CHF should have to be carried out especially in view of physical and mechanical aspects.

References

1. D.C. Groeneveld et al., 1986 AECL-UO Critical Heat Flux Look-up Table, Heat Transfer Eng. 7, pp. 46-72 (1986).
2. S.K. Moon, Parametric Trands Analysis of the Critical Heat Flux Based on Artificial Neural Networks, *Nucl Eng and Design* **163** pp.29-49 (1996).
3. J.G Collier, Convective Boiling and Condensation, Oxford press (1994).
4. H. Nariai et al., Effect of Tube Length on the CHF of Subcooled Flow Boiling, *2nd Symp. on Multi-Phase Flow*, Tokyo, pp. 211-221 (1997)
5. A. Inoue and S. Lee, Influence of Two-phase Flow Characteristic on Critical Heat Flux in Low Pressure, *Proc. 4th Int. Conf. on Nucl. Eng.* 1 pp. 657-667 (1996)
6. D.C. Groeneveld et al, Heat Transfer Phenomena Related to Boiling Crisis, AECL-7239 (1981).
7. W. P. Baek et al, An Independent Assessment of Groeneveld et al.'s 1995 CHF Look-up Table, To Appear in *Nucl. Eng. Des.* (1997).

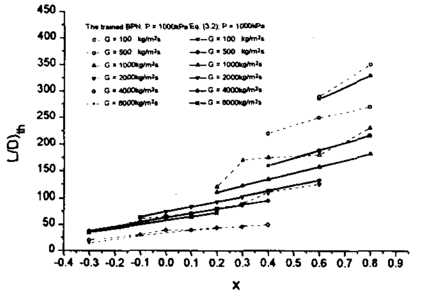

Fig. 1 Parametric trend analysis of threshold L/D correlation (Eq. (3.1)) at 1Mpa

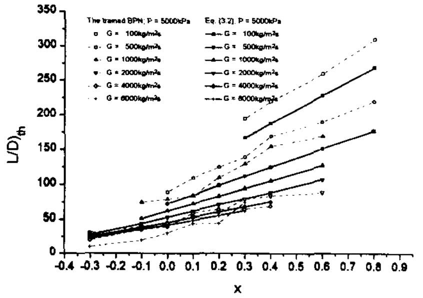

Fig. 2 Parametric trend analysis of threshold L/D correlation (Eq (3.1)) at 5Mpa

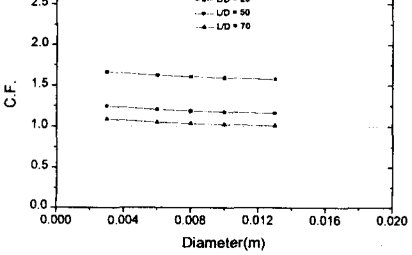

Fig. 3 Trend of the L/D correction factor according to diameter

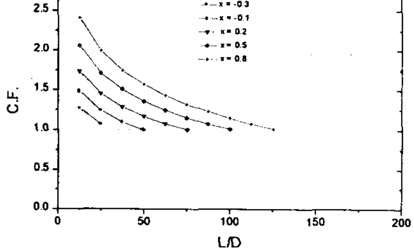

Fig. 4 Trend of the L/D correction factor according to exit quality

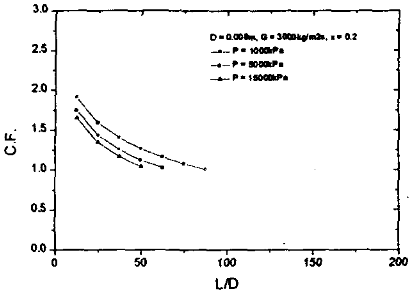

Fig. 5 Trend of the L/D correction factor according to system pressure

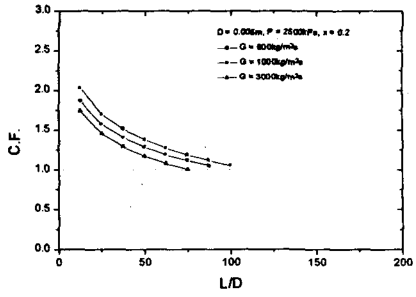

Fig. 6 Trend of the L/D correction factor according to mass flux

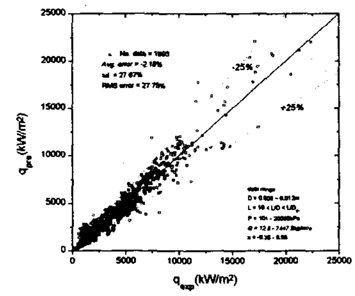

Fig. 7 Prediction accuracy of the L/D correction factor

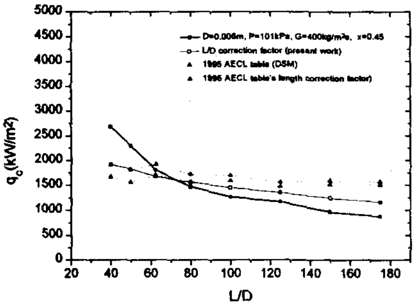

Fig. 8 Application of the L/D correction factor to experimental data for D = 0.006m, P = 101kPa, G = 400kg/m^{2}s and x = 0.45

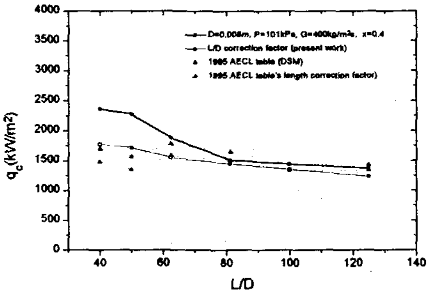

Fig. 9 Application of the L/D correction factor to experimental data for D = 0.008m, P = 101kPa, G = 400kg/m^{2}s and x = 0.4

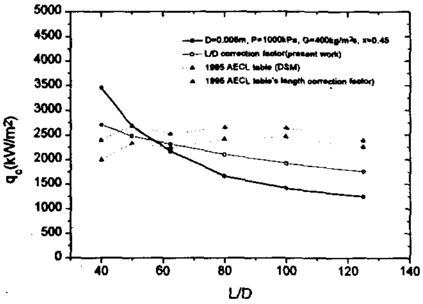

Fig. 10 Application of the L/D correction factor to experimental data for D = 0.006m, P = 1000kPa, G = 400kg/m^{2}s and x = 0.45

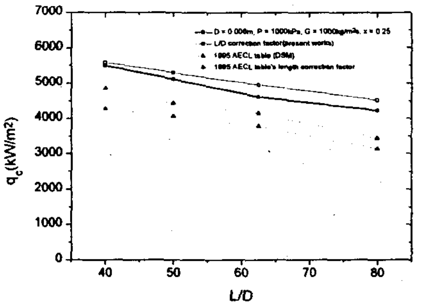

Fig. 11 Application of the L/D correction factor to experimental data for D = 0.006m, P = 1000kPa, G = 1000kg/m^{2}s and x = 0.2

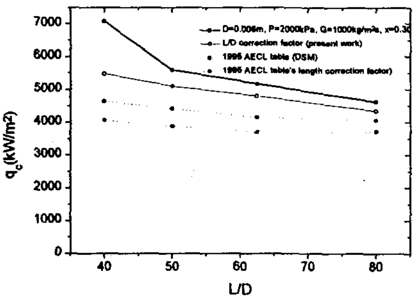

Fig. 12 Application of the L/D correction factor to experimental data for D = 0.006m, P = 2000kPa, G = 1000kg/m^{2}s and x = 0.3