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Development of Critical Heat Flux Correction Factor for Water under Flow Oscillation Conditions

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Abstract

Flow oscillations in boiling channels induces a drastic reduction of the (critical heat flux) CHF or premature burnout. However, most of CHF works and correlations have been focused on stable flow conditions without considering flow oscillation. Therefore to improve the understanding on flow oscillation CHF, in this paper a new CHF correction factor to predict the CHF values under flow oscillation conditions has been developed from 126 experimental data. Also to investigate the dominant factor on flow oscillation CHF parametric trends are analyzed by using the developed correction factor. The overall mean accuracy ratio of the developed correction factor is 1.033 with a standard deviation of 0.195. The RMS errors 0.198. Its assessment shows that the predictions agree well with the experimental data within 25% error bounds.

1. Introduction

The CHF is a major parameter which determines the cooling performance and therefore limits the power level of nuclear reactor. In a boiling system, various flow oscillations are encountered particularly at low pressures. In nuclear reactor, also, the flow oscillation can be occurred for nuclear reactors in accident conditions, such as a loss of coolant accident (LOCA) and for various natural circulation systems to remove decay heat [1]. However, most of the existing CHF works have been performed for conditions without flow oscillation (i.e. stable flow conditions) and most of the CHF correlations have been developed for stable flow condition without considering flow oscillation [2-5]. Flow oscillation in boiling channels induces a drastic reduction of the CHF from the value under stable operating conditions [6-9].

The existing CHF correlations based on stable flow conditions may overestimate or cannot well predict the CHF value under the flow oscillation conditions, because the flow behavior under flow oscillation conditions is quite different from that of stable conditions and the existing correlations have been developed without considering the amplitude and period of flow oscillation. The CHF problems under flow oscillations should be analyzed taking into account of the effects of these two factors. The increase in the amplitude of the flow oscillation may enhance the initiation of the premature dryout, and the decrease in the period of the oscillation may enhance the rapid cooling and/or rewetting after the premature dryout. The period and the amplitude of the flow oscillation are closely related to each other and are strong functions of the operating conditions, such as mass flux, heat flux, inlet conditions and system geometries.

Therefore this study aims to understand the influence of the amplitude and period of flow oscillation on CHF, to extend experimental CHF data base under oscillatory flow conditions, and to develop the CHF correction factor applicable at the conditions where the flow is fluctuant or oscillatory. Finally parametric trends analysis have performed to know what parameters are dominant to affect on the CHF under flow oscillation conditions.

2. Development of correction factor

Under the flow oscillation conditions, if the inlet mass flux of the test section has a function of sinusoidal form with time, the function of mass flux can be described as follows

$$G = G_{avg} + \varDelta G \sin(2\pi t/\tau) \tag{1}$$

where G_{avg} is the average mass flux of flow oscillation, $\varDelta G$ is the flow amplitude of flow oscillation and τ is a oscillation period.

To develop the CHF correction factor under flow oscillation conditions, The CHF correction factor (C.F.) is defined as follows

$$C.F. = \frac{q_{CHF,FO}}{q_{CHF,NFO}} \tag{2}$$

where $q_{CHF,FO}$ is CHF with flow oscillation and $q_{CHF,NFO}$ is CHF without flow oscillation.

This is the most interesting form to apply and to compare with the existing CHF data which are obtained at the conditions without flow oscillation. It is proposed in this study the correction factor (C.F.) is a function of following parameters

$$C.F. = f\{P,\ G_{avg},\ \varDelta G,\ \tau,\ T_i,\ Geometries(L_h,\ D)\} \tag{3}$$

where T_i is the inlet temperature of test section and L_h and D are the heated length and diameter of test section respectively.

To simplify the development of CHF correction factor under flow oscillation conditions, the following parameters have been taken considered:

(a) system pressure; P, ρ_g/ρ_f, (b) inlet conditions; T_i, $\varDelta h_i$, ρ_{fi} (c) mass flux; $\varDelta G$, G_{avg}, (d) transit time; $T_{tr} = \frac{L_h}{u_{fi}} = \frac{L_h}{(G_{avg}/\rho_{fi})}$ (e) period of flow oscillation; τ

where the transit time(T_{tr}) which takes to pass through from the inlet to the outlet of test section is adopted to apply the period of flow oscillation in the type of dimensionless. And in the present state of things, the effect of test section geometries and inlet temperature did not include from the parameters of the correction factor because the collected data is not enough.

The above parameters can be changed as follows:

(a) average mass flux; G_{avg}, (b) ratio of amplitude to average mass flux; $(\varDelta G/G_{avg})$, (c) ratio of density; (ρ_g/ρ_f), and non-dimensional time; (τ/T_{tr}).

The total number of the flow oscillation CHF data for water have collected about 126 as shown in Table 1. To develop the correction factor, the first form is as follows

$$C.F. = \exp\left(C_1 \frac{\varDelta G}{G_{avg}} \frac{\tau}{T_{tr}}\right) \left(1 + \frac{\tau}{T_{tr}}\right)^{C_2} \left(\frac{\rho_g}{\rho_f}\right)^{C_3 \varDelta G/G_{avg}} G_{avg}{}^{C_4 \rho_g/\rho_f} \tag{4}$$

where $T_{tr} = L_h / G_{avg} / \rho_{fi}$.

The coefficients were found by using the statistical analysis system (SAS) computer program which uses the non-linear least square method as a regression technique. The results of SAS regression are shown in Table 2 and the final form is as follows

$$C.F. = \frac{\exp(-0.3409\frac{\Delta G}{G_{avg}}\frac{\tau}{T_{tr}})}{(1+\frac{\tau}{T_{tr}})^{0.0187}(\frac{\rho_g}{\rho_f})^{0.024\Delta G/G_{avg}}{G_{avg}}^{0.023\rho_g/\rho_f}} \quad . \tag{5}$$

Table 1. Parameter ranges of experimental CHF data for water under flow oscillation

Parameters	Range
Working fluid	Water
Pressure (P), kPa	101, 300, 400
Heated length (L_h), m	0.9
Inlet subcooling (Δh_i), kJ/kg	83.7, 226.3, 269.7
Tube diameter (D), mm	3.0, 4.0, 5.0
Average mass flux (G_{avg}), kg/m^{2}s	100, 200, 300, 380, 400
Ratio of mass flux ($\Delta G/G_{avg}$), -	0.215 ~ 3.77
Period of flow oscillation (τ), sec	2.0, 4.0, 6.0
Number of data	126

Table 2. Results of SAS regression

Parameter	Estimate	Asymptotic std. error	Asymptotic 95% Confidence Interval	
			Lower	Upper
C_1	0.3409	0.03876	0.2642	0.4177
C_2	-0.0187	0.03406	-0.0861	0.0487
C_3	-0.0240	0.01047	-0.0447	-0.0033
C_4	-0.0230	0.01645	-0.0555	0.0096

3. Results and discussion

3.1 CHF prediction results

The comparison of the predicted and experimental CHF values with correction factor is presented as shown in Fig. 1. Also, Figs. 2-4 show the dependence of the prediction accuracy on ratio of mass flux, ratio of period and ratio of density. As shown in Table 3, the overall mean accuracy ratio of the developed correction factor is 1.033 with a standard deviation of 0.195. The RMS errors 0.198. Its assessment shows that the predictions agree well with the experimental data within 25%.

3.2 Parametric trends of the CHF

The parametric trends are shown in Fig. 5 and are discussed as follows.

(a) (ratio of mass flux, $\Delta G/G_{avg}$) This is a effect of the mass flux amplitude of flow oscillation on CHF. The ratio of flow oscillation CHF to non-flow oscillation CHF decreases as the ratio of mass flux increases as shown Fig. 5(a)-(c).

(b) (ratio of period to transit time, τ / T_{tr}) As shown in Fig. 5(a), the ratio of CHF decreases as the ratio of period to transit time increases. The reduction rate of CHF at the long period is larger than that of short period.

(c) (ratio of density, ρ_g / ρ_f) This is a effect of pressure on CHF. The ratio of CHF decreases slightly as the ratio of density increases as shown in Fig. 5(b).

(d) (average mass flux, G_{avg}) The ratio of CHF also decreases slightly as average mass flux increases as shown in Fig. 5(c).

From the above results, we can know that the flow amplitude and teer period of flow oscillation are more dominant factors than ratio of density and average mass flux on flow oscillation CHF. The above simulation results show good agreements with the existing experimental results.

Table 3. Prediction results for flow oscillatory CHF with the developed correction factor

Errors	Values
Mean accuracy	1.033
Mean error	0.033
RMS error	0.198
Standard deviation	0.195

1) Mean accuracy = $\frac{(q_{FO}/q_{NFO})_{pred}}{(q_{FO}/q_{NFO})_{\exp}}$, where $(q_{FO}/q_{NFO})_{pred}$ is the ratio of CHF predicted from the correction factor and $(q_{FO}/q_{NFO})_{\exp}$ is the ratio of CHF from the experimental data.

2) Error : $\varepsilon = \frac{(q_{FO}/q_{NFO})_{pred} - (q_{FO}/q_{NFO})_{\exp}}{(q_{FO}/q_{NFO})_{\exp}}$, 3) Mean error : $\bar{\varepsilon} = \sum_{i=1}^{i=N} \varepsilon_i / N$,

4) RMS error : $\varepsilon_{RMS} = \left[\sum_{i=1}^{i=N} \varepsilon_i^2 / N \right]^{1/2}$, 5) Standard deviation : $\sigma = \left[\sum_{i=1}^{i=N} (\varepsilon_i - \bar{\varepsilon})^2 / N \right]^{1/2} = [\varepsilon_{RMS}^2 - \bar{\varepsilon}^2]^{1/2}$.

4. Conclusions

The following conclusions can be drawn from this study

(a) The CHF data bank have been collected under flow oscillation conditions.

(b) Finally, the CHF correction factor for water under flow oscillation conditions has developed as follows;

$$C.F. = \frac{\exp(-0.3409 \frac{\Delta G}{G_{avg}} \frac{\tau}{T_{tr}})}{(1 + \frac{\tau}{T_{tr}})^{0.0187} (\frac{\rho_g}{\rho_f})^{0.024 \Delta G / G_{avg}} G_{avg}^{0.023 \rho_g / \rho_f}}$$

where

$$T_{tr} = \frac{L_h}{G_{avg} / \rho_{fi}}$$

(c) The overall mean accuracy ratio of the developed correction factor is 1.033 with a standard deviation of 0.195. The RMS errors 0.198. Its assessment shows that the predictions agree well with the experimental data within 25% error bounds.

(d) Based on the developed correction factor, parametric trends analysis is verified that the amplitude and the period of flow oscillation is are dominant variables on the flow oscillation CHF.

Nomenclature

D : tube diameter, (m)
G_{avg} : average mass flux, (kg/m^{2}s)
ΔG : amplitude of mass flux, (kg/m^{2}s)
L_h : heated length, (m)
P : pressure, (kPa)
u_{fi} : inelt flow velocity, (m/s)
ρ : density, (kg/m^3)
T_{tr} : transit time, (sec)
$q_{CHF,FO}$: flow oscillation CHF, (kW/m^2)
$q_{CHF,NFO}$: non-flow oscillation CHF, (kW/m^2)
T_i : inlet temperature, (℃)

Subscripts

avg : average
f : liquid
g : vapor
tr : transit

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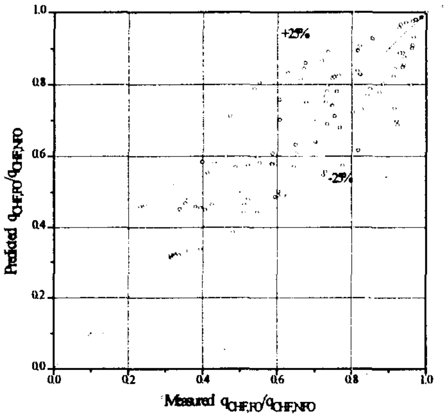


Fig. 1. Comparison of predicted CHF with correction factor and measured CHF

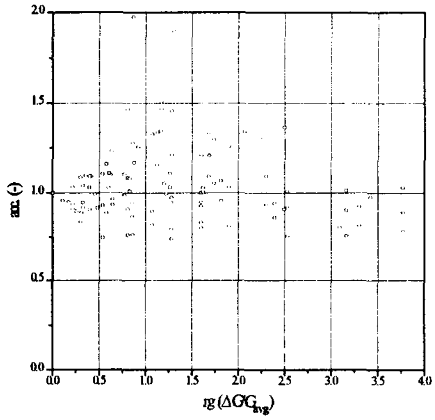


Fig. 2 Prediction accuracy on the ratio of mass flux

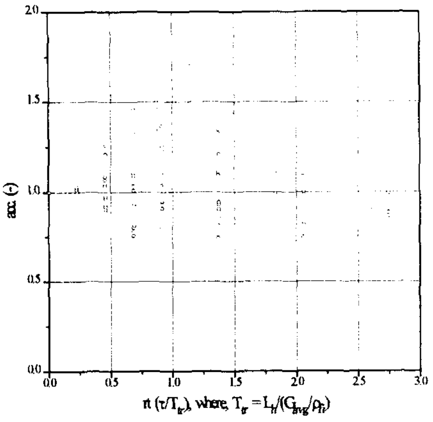
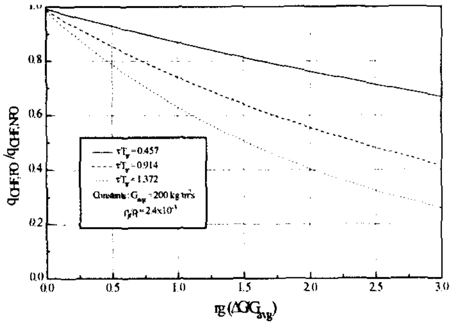
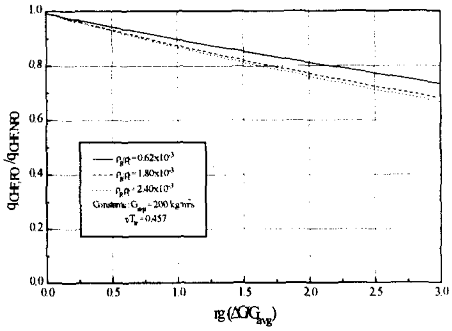


Fig. 3. Prediction accuracy on the ratio of time



(a) period of flow oscillation



(b) ratio of density

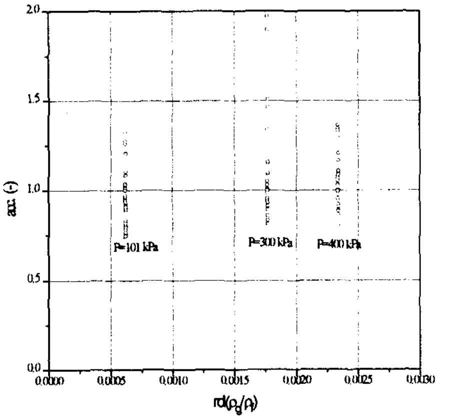
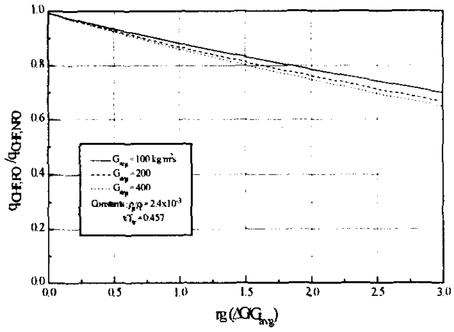


Fig. 4. Prediction accuracy on ratio of density (i.e., pressure)



(c) average mass flux

Fig. 5. Parametric trends of flow oscillatory CHF by using the correction factor