A Technical Basis for the Flux Corrected Local Conditions Critical Heat Flux Correlation

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Abstract

The so-called "flux-corrected" local conditions CHF correlation was developed at Ontario Hydro in the 1980's and was demonstrated to successfully correlate the Onset of Intermittent Dryout (OID) CHF data for 37-element fuel with a downstream-skewed axial heat flux distribution. However, because the heat flux correction factor appeared to be an ad-hoc, albeit a successful modifying factor in the correlation, there was reluctance to accept the correlation more generally. This paper presents a thermalhydraulic basis, derived from two-phase flow considerations, that supports the appropriateness of the heat flux correction as a local effects modifying factor.

1. Introduction

Derivation of a reliable and robust mechanistic model for critical heat flux in a fuel bundle remains an elusive goal. Such a model would greatly facilitate nuclear safety analysis where one of the objectives is to establish the two-phase fluid conditions, either transient or steady-state, at which fuel dryout occurs. Without a mechanistic model there is continued reliance on correlations of full-scale water critical heat flux (CHF) test data.

Early CHF tests were conducted with heated section bundle simulators that had constant axial power distribution (referred to as uniform axial heat flux distribution). In these tests the highest coolant quality occurred at the exit of the test section and, because of the constant heat flux distribution, this was also the location of the onset of dryout. In later tests on 28-element bundle simulators performed at Columbia University and 37-element bundle simulators at Chalk River and, subsequently at Stern Laboratories, downstream-skewed non-uniform axial heat flux distributions were employed. Under these conditions the onset of first CHF no longer occurred at the test section outlet but was dependent upon the axial heat flux distribution.

CHF correlations that had been developed for the uniform heat flux distribution test data using cross-sectional average local thermalhydraulic fluid properties were found to provide unreliable predictions of the location of dryout in the fuel string with non-uniform heat flux distribution. However, an alternate correlation concept that employed "boiling length average" fluid properties was found to be reliable. The boiling length average approach requires knowledge of the steady-state length of the fuel string in boiling and is therefore not applicable to transient conditions. The local conditions approach is, in principle, applicable to both steady-state and transient conditions.

In the mid-1980's a modified local conditions correlation using a flux distribution form factor term was developed at Ontario Hydro [Ref. 1]. This correlation, referred to as the "flux-corrected local conditions" correlation exhibited similar characteristics to the boiling length average correlation and was successful in predicting both the location of initial dryout and subsequent dryouts in the non-uniform heat flux distribution simulated fuel string test sections. However, because of the apparent ad-hoc nature of the correlating flux form factor there has been some reluctance to continue using the correlation and, instead, to revert to a boiling length average correlation, despite the difficulties associated with application to transient thermalhydraulic conditions.

The features of the various CHF correlations are reviewed in this paper and a technical basis is established for the flux corrected local conditions CHF correlation based upon the concept of local vapor velocity in a two-phase mixture. Utilizing this technical basis a modified local conditions correlation is proposed which has the potential to provide improved margin.

2. Review of CHF Correlations

The local conditions hypothesis for correlating experimental CHF data points is based upon the assumption that there is a consistent relationship between the critical heat flux, q_{CHF} , and selected cross-section averaged local fluid properties at a location in the fuel string, namely:

$$q_{CHF} = f(P_{DO}, G, \chi_{DO}) \tag{1}$$

Where P_{DO} and χ_{DO} are the local pressure and quality at the dryout plane (DO), respectively, and G is the average mass flux through the fuel channel. The local conditions hypothesis applied to an arbitrary axial heat flux distribution states that the limiting critical heat flux occurs at an axial position along the fuel string where the locus of CHF is tangential to the actual cross-section averaged heat flux, as depicted in Figure 1.

Based on the water CHF tests that employed a uniform heat flux distribution along the axial length, the critical heat flux was well represented by a correlation of the form [Ref. 2]:

$$q_{CHF} = C_1 P_{DO}^a G^b + C_2 P_{DO}^c G^d \chi_{DO} \tag{2}$$

where C_1, C_2 ,a, b,c and d are constants obtained from non-linear regression of the experimental OID data points.

However, since by definition the location of CHF occurs at the exit of the test section there is no assurance that this form of correlation will correctly represent the magnitude and location of CHF in a non-uniform heat flux distribution.

In fact, it was found that the uniform heat flux distribution local conditions correlation was not capable of adequately representing CHF magnitude and location in the non-uniform axial flux distribution (AFD) tests. When the correlation was applied to the first onset of intermittent dryout (OID) data points from these tests it yielded correct predictions at the data points that were being correlated, but significantly under-predicted the value of CHF at locations where subsequent OID occured. More importantly, the value of CHF at other locations obtained from the correlation indicated that the subsequent locations would be well into dryout before the first instance of OID – obviously an unrepresentative non-physical situation. This is depicted in Figure 2 which illustrates the fundamental problem with the basic local conditions correlation. This fundamental problem relates to the fact that the correlation can not simultaneously satisfy the two necessary conditions associated with the local conditions hypothesis. These conditions are: i) that the magnitudes of CHF and the heat flux distribution must be equal, and ii) the slopes of the two functions must be equal in order to satisfy the tangency condition at the dryout point, namely;

$$\begin{aligned} q_{CHF}(z_{DO}) &= q(z_{DO}) \\ \left.\frac{q_{CHF}(z)}{dz}\right|_{DO} &= \left.\frac{q(z)}{dz}\right|_{DO} \end{aligned} \tag{3}$$

Using the boiling length hypothesis a correlation similar in general form to the local conditions correlation was found to represent well the CHF data at first OID and subsequent OID locations. The correlation is of the form:

$$q_{CHF\_BLA} = C_3 P_{DO}^{a1} G^{b1} + C_4 P_{DO}^{c1} G^{d1} \chi_{DO} \tag{4}$$

where , q_{CHF_BLA} = boiling length average heat flux from the onset of boiling to the location of CHF, and
C_3, C_4 ,*a1, b1,c1* and *d1* are constants.

However, an appropriate value of q_{CHF_BLA} is extremely difficult to define and calculate under transient conditions. Therefore, the boiling length average correlation is applicable under either steady-state conditions or very slow, quasi-steady transient conditions; for example, very slow loss of regulation events that are used to define neutron overpower (NOP) system setpoints. The improved behaviour of this correlation is depicted in Figure 2 [Ref. 1].

Based upon the observation of the deficiency in the local conditions correlation a modified correlation was developed which incorporated a heat flux distribution form factor, ψ , which was applied to the general form of a local conditions correlation to yield the "flux corrected" local conditions correlation [Ref. 1]:

$$q_{CHF\_FC} = \left(C_5 P_{DO}^{a2} G^{b2} + C_6 P_{DO}^{c2} G^{d2} \chi_{DO}\right)\Psi^{e} \tag{5}$$

Where, ψ = ratio of the radially averaged heat flux at the CHF location to the channel averaged heat flux, that is;
$\psi = \phi / \phi_{av}$, and
C_5, C_6 ,*a2, b2,c2, d2* and *e* are constants.

The heat flux correction form factor resolved the problem with tangency of the CHF locus and the heat flux distribution. This is depicted in Figure 2, where it is apparent that the flux corrected local conditions correlation exhibits similar behaviour to the boiling length average correlation.

The fact that the form factor correction yields a higher critical heat flux in upstream locations where the axial heat flux is higher seemed, to some, to be somewhat counter-intuitive. However, the correlation was robust and predicted well both 37-element and 28-element test data, thereby supporting its use.

In the next section a technical basis for the flux correction factor is derived and shown to be consistent with underlying thermalhydraulic two-phase flow processes.

3. A Technical Basis for the Heat Flux Corrected Local Conditions CHF Correlation

It well established that increased local turbulence in two-phase coolant flow can increase the local critical heat flux. This is evident from the variation of critical heat flux along a heated bundle downstream of endplates and bundle appendages, which act as generators of local turbulence. It is also the basis upon which enhancement of critical heat flux in new bundles has been achieved by the addition of small turbulence-promoting “button appendages”. Additionally, it has been established from transient CHF tests that flow variations, both decreasing and increasing, can also transiently increase critical heat flux. Based upon these observations, it is postulated that the turbulence level in a bundle is proportional to the bulk velocity of the fastest moving fluid – the vapor phase in a two-phase mixture. Also, local heat transfer in turbulent flow is related to the local average velocity through the dependency of the Nusselt number on the Reynolds number to the power of 0.8, i.e.

$$\mathrm{Nu} \propto \mathrm{Re}^{0.8} \tag{6}$$

Consider now the well known relationship between cross-section averaged coolant quality and the heat transferred to the coolant:

$$\begin{aligned} \chi(z) &= \frac{Q(z) + h_{in} - h_f(P)}{h_{fg}(P)} \\ Q(z) &= \int_o^z q(x)dx \end{aligned} \tag{7}$$

Where, *q(z)* = linear heat rating at location z
= $K\phi(z)$,
$\phi(z)$ = average heat flux at location z,
h_{in} = inlet enthalpy to the heated section,
h_f, h_{fg} = saturated liquid enthalpy and latent heat of vaporization at local pressure *P*.

Now the local linear vapor velocity at location *z*, $V_v(z)$, is given by:

$$V_v(z) = \frac{\chi(z)W}{A\rho_g} \tag{8}$$

Where W is the mass flow rate through the channel, A is the flow cross-sectional area and ρ_g is the saturated steam density.

Using the above equations the variation of vapor velocity along the boiling length of the channel is obtained simply from differentiation as:

$$\begin{aligned}
&\frac{dV_v(z)}{dz} = \frac{q(z)\,W}{Ah_{fg}\rho_g} \\
&q(z) = K\phi(z) \\
&\text{and} \\
&\frac{dV_v(z)}{dz} = \frac{K\,W}{Ah_{fg}\rho_g}\phi(z)
\end{aligned} \tag{9}$$

Now for a uniform heat flux distribution, $\phi(z) = \phi_o$, the variation in vapor velocity with distance along the boiling length is approximately constant and is given by:

$$\frac{dV_v(z)}{dz} = \frac{K\,W}{Ah_{fg}\rho_g}\phi_o \approx \quad \text{constant} \tag{10}$$

It has also been established that the CHF data for a uniform heat flux distribution is well represented by a correlation of the form (see Eq.2):

$$q_{CHF} = C_1 P_{DO}^a G^b + C_2 P_{DO}^c G^d \chi_{DO} \tag{11}$$

As shown in Eq. 9 the non-uniform axial heat flux distribution introduces a variation in vapor velocity along the boiling length. This, in turn, introduces variations in the level of flow turbulence along the channel relative to a uniform heat flux distribution which has constant flow variation with boiling length, as indicated by Eq. 10. The relative variation in vapor velocity (and hence turbulence level) for the same mass flow rate is given by the ratio of the two derivatives, i.e.:

$$\frac{\left.\dfrac{dV_v(z)}{dz}\right|_{non\_uniform}}{\left.\dfrac{dV_v(z)}{dz}\right|_{uniform}} = \frac{\phi}{\phi_o} \tag{12}$$

Finally the relationship between Nusselt number and Reynolds number for turbulent flow is given by Eq.6. Therefore, a correction factor, FC, that accounts for the effect of variation in local turbulence can be defined as:

$$FC = \left(\frac{\phi}{\phi_o} \right)^{0.8} \tag{13}$$

Applying this correction factor to the uniform heat flux correlation yields the non-uniform heat flux distribution CHF correlation as:

$$q_{CHF\_FC} = \left(C_5 P_{DO}^{a2} G^{b2} + C_6 P_{DO}^{c2} G^{d2} \chi_{DO} \right) \left(\frac{\phi}{\phi_o} \right)^{0.8} \tag{14}$$

Interestingly, the value of the exponent constant, e , in the flux corrected local conditions CHF correlation was found to be approximately equal to 0.8 [Ref. 1].

4. A Modified Flux Corrected Local Conditions CHF Correlation

The above development addresses the effect of variations in the level of turbulence induced by the variation in the vapor phase velocity (the higher velocity phase in the two-phase mixture). It is possible to also consider variations in the liquid phase in the boiling length. Dryout in CANDU fuel bundles is due to a process of disruption of the liquid film on the heated wall (that is, OID) and the subsequent spread of the drypatch area. The disruption of the liquid film is expected to be dependent upon the mass fraction of liquid, FL , in the two phase mixture at any location, which in turn is related to the local quality by:

$$FL = (1 - \chi) \tag{15}$$

Therefore, a modified local conditions correlation is suggested of the form:

$$q_{CHF\_FC} = \left(C_5 P_{DO}^{a2} G^{b2} + C_6 P_{DO}^{c2} G^{d2} \chi_{DO} \right) \left(\frac{\phi}{\phi_o} \right)^{0.8} \left(\frac{(1 - \chi_{DO})}{(1 - \chi_{DO1})} \right)^{k} \tag{16}$$

Where, k is a constant, which should be approximately unity,
χ_{DO} = local dryout quality,
χ_{DO1} = is the dryout quality for the first OID point.

The effect of this modification will be to increase CHF slightly at upstream locations where the quality is lower and should therefore achieve even better agreement between a local conditions and boiling length averaged correlation. Further work is planned to investigate this form of correlation.

5. Conclusions

An assessment of the effect of variations in vapor velocity on the local turbulence in a fuel bundle has been performed. This assessment indicates that the effect of non-uniform heat flux distribution relative to a uniform heat flux distribution will give rise to a relative variation in heat transfer that is proportional to the ratio of non-uniform heat flux to uniform heat flux raised to the power 0.8. This is consistent with the term introduced in the flux corrected local conditions CHF correlation where the regression fit of the OID CHF data yielded a power value for the correction factor which was approximately equal to 0.8.

This assessment establishes a plausible technical basis for the form of the flux corrected local conditions correlation based upon basic properties of two-phase flow.

A modification to the flux corrected local conditions CHF correlation is suggested which provides an additional small correction to account for the variation in liquid phase content along the boiling length.

6. Acknowledgments

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7. References

1. J.A. Lorenc, M.T. Kwee, N.N Wahba and B. Lautsch, " Critical heat Flux in 37-Element Fuel", Ontario Hydro Design and Development Division, Report No. 85099, March 1985.
2. A.G. McDonald, "Critical heat Flux in a 37-Element 6 m Long Segmented Rod Bundle Geometry", AECL CRNL-2065, May 1980.

FIGURE 1
THE LOCAL CONDITIONS CHF CONCEPT
(From Ref. 1)

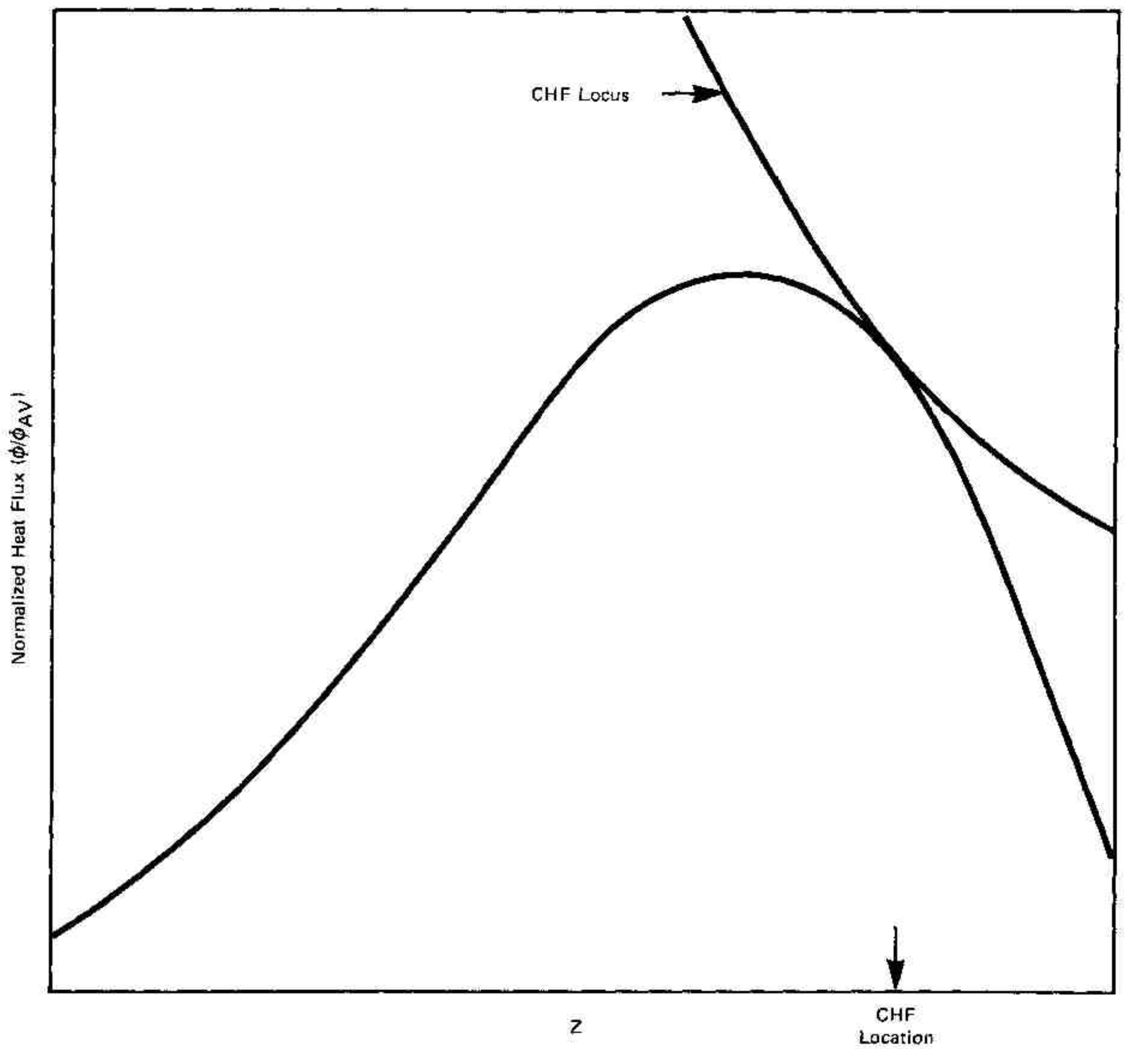

FIGURE 2
COMPARISON OF LOCAL CONDITIONS AND BOILING LENGTH AVERAGE CHF CORRELATIONS
(From Ref. 1)