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On the definition of critical heat flux margin

D.C. Groeneveld

Fuel Channel Thermalhydraulics Branch, Chalk River Laboratories, Atomic Energy of Canada Limited, Chalk River, Ontario, Canada

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Abstract

This paper reviews the current definition of critical heat flux (CHF) margins and discusses their differences.

Prediction of critical heat flux (CHF) occurrence for uniformly heated water-cooled tubes is a complex task, as the proliferation of CHF correlations demonstrates: by 1990 over 700 CHF correlations were available. This is a cause for concern, as reliable CHF prediction methods are required to predict the CHF power for a reactor channel or reactor core. Although early CHF prediction methods were frequently based on inlet conditions (i.e. $F(P, G, T_{in}$, geometry), these correlations could not satisfactorily account for separate effects, such as axial flux distributions, spacer grids. In most cases, the CHF is a local phenomenon and is relatively insensitive to conditions at the inlet of the reactor core or fuel channel. Because of this, local-conditions-type correlations, based on the local (or cross-sectional average) enthalpy or quality at the CHF location (i.e. $F(P, G, X$, local geometry)), and modified to account for separate effects, were found to be more reliable.

The normal operating power (NOP) of a nuclear reactor is well below the critical power (CP) to allow a sufficient margin to CHF occurrence. This margin is required to allow for uncertainties such as (a) the experimental database on which the CHF prediction method is based (e.g. accuracy of dryout detection plus the measurement of power and flow), (b) extrapolation to in-reactor conditions (nuclear vs. electrical heating, flux distributions, impact of element bowing etc.), and (c) calculation of the reactor flow conditions (e.g. power, flow).

Hejzlar and Todreas (1996), Inasaka and Nariai (1996), and Groeneveld et al. (1986) have described two different methods of predicting CHF and CHF margins using local-conditions-type correlations:

(1) the so-called constant dryout quality approach or the direct substitution method, and
(2) the constant inlet conditions approach or the heat balance method.

When predicting CHF for a given system, method (1) above is the easiest to apply, but it requires prior knowledge of the enthalpy or the thermodynamic quality at CHF, a dependent parameter. Since this quality is unknown, method (2) is usually used, which requires finding the CHF from the intersection of the CHF vs. X curve and satisfying the heat balance. Fig. 1 illustrates the

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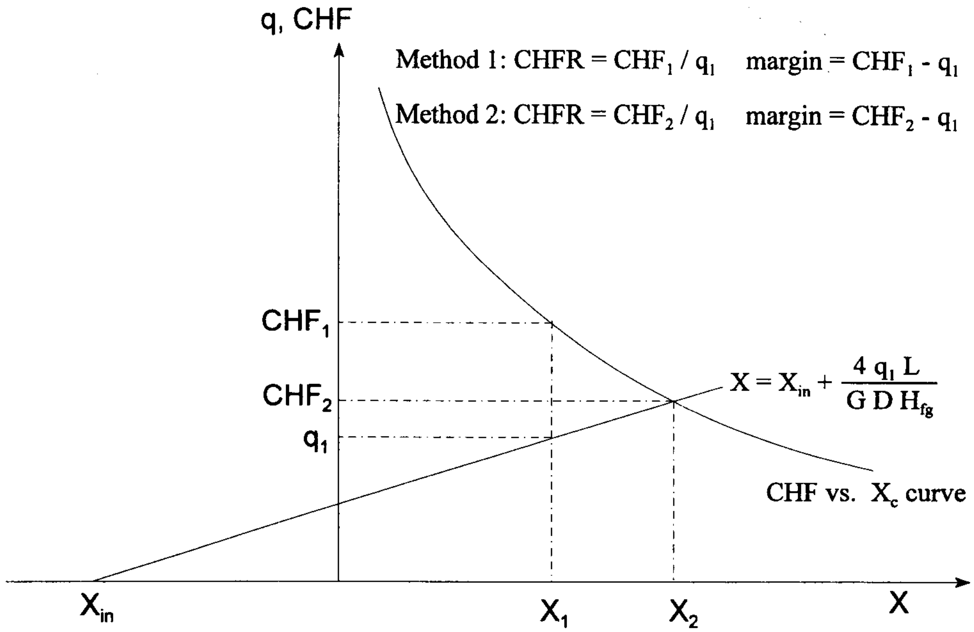

Fig. 1. CHF values and margins to CHF for a uniformly heated tube.

predicted CHF value and margin to CHF for the simple case of a uniformly heated tube having fixed inlet conditions and operating at a given heat flux for the two above methods. Note that the CHF_1 value at a constant quality ($X = X_1$) can never be obtained in this tube, as it does not satisfy the heat balance relationship. Nevertheless, the margin to CHF is frequently expressed based on a constant quality or enthalpy. As Fig. 1 shows, when evaluating the margin to CHF, method (1) tends to give a much higher CHF ratio (defined as the ratio of CHF to local heat flux) than method (2). This was also discussed by Lahey and Moody (1993). The difference in ratios depends directly on the slope of the CHF vs. X curve; it is least for a zero slope and reaches a maximum for steep negative slopes.

In a nuclear reactor system, with the fuel operating with a known heat flux distribution, pressure, inlet temperature, and mass flow, the margin to CHF occurrence can be obtained for the following ratios:

(i) minimum ratio of CHF to local heat flux (MCHFR), based on the same local enthalpy or quality as illustrated in Fig. 2(a);

(ii) CHF power ratio (CHFPR) or the ratio between the power at initial occurrence of CHF (CP_1) and the normal reactor channel or core power (NOP), based on the same inlet conditions (mass flow, inlet temperature and pressure), as illustrated in Fig. 2(b);

(iii) CP ratio (CPR), or the ratio of initial power at CHF (CP_2) to normal reactor core or reactor channel power (NOP), based on the same reactor system as illustrated in Fig. 2(c) (i.e. for a given pump and piping system).

There is a significant difference between these ratios as the following example for a pressurized heavy water reactor (PHWR) illustrates. (The ratios used in these examples are very approximate.) A MCHFR of 1.6 would represent a 60% margin to CHF if the enthalpy at the CHF location was truly an independent variable that could be kept constant during an increase in operating heat flux or power. However, for a fixed inlet temperature, an increase in surface heat flux increases the coolant enthalpy, which leads to a significant decrease in CHF. The net effect is that the true margin to CHF will be halved to about 30% (corresponding to a CHFPR of 1.3), based on the assumption of constant inlet conditions (i.e. flow, inlet temperature and pressure).

The constant flow assumption is also unrealistic

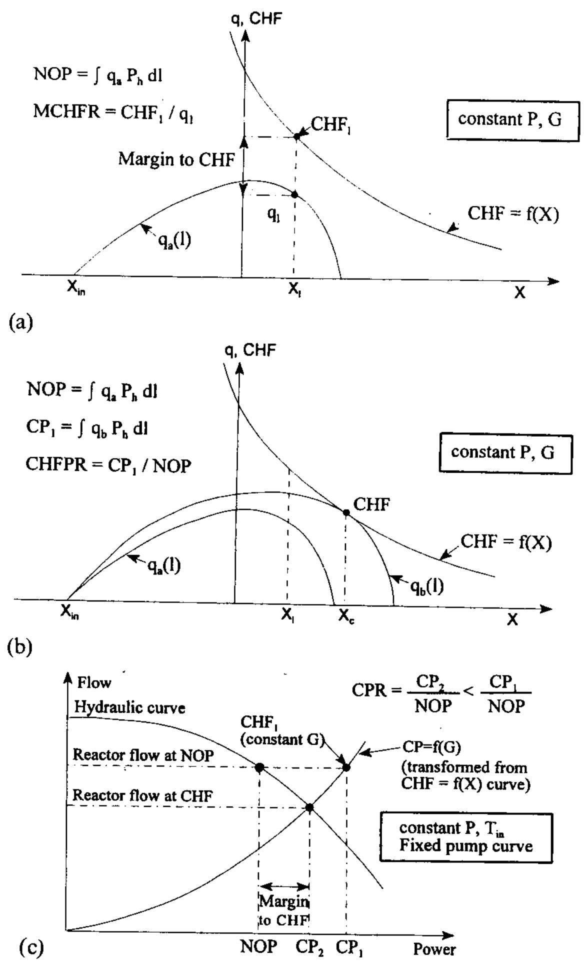

Fig. 2. Schematic representations of definitions of various CHF ratios: (a) MCHFR; (b) CHFPR; (c) CPR.

for conventional reactors that have centrifugal pumps and long piping systems between the pump and the reactor core. Here an increase in reactor power will lead to an increase in enthalpy, and eventually to two-phase flow for pressurized water reactors, which increases the effective hydraulic resistance, decreases the flow, and leads to a new operating point on the pump curve. Hence, the margin to CHF occurrence is further reduced by half to about 15% (corresponding to a value of CHFPR of 1.15). This value can vary significantly, depending on the type of reactor, the piping layout, and whether the change in effective hydraulic resistance is due to an assumed core-wide variation in neutron flux, or to a local flux perturbation. The latter case corresponds to a constant pressure drop between plenums, or constant header-to-header pressure drop for PHWRs.

Fig. 2 shows a schematic illustration of how margins to CHF erode, from large CHFR values for a constant enthalpy to much smaller CPR values for a typical PHWR reactor system. A similar observation can be made for other water-cooled reactors.

Appendix A: Nomenclature

D	tube diameter
G	mass flux
H_{fg}	latent heat of vaporization
L	heated length
P	pressure at CHF location
P_h	heated perimeter
q	surface heat flux (local)
T_{in}	inlet temperature
X	thermodynamic quality
X_{in}	thermodynamic quality at the inlet of a channel (could be negative)

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