The shape factor for DNB heat flux calculation in non-uniform heated channels

Introduction

The W-3 is a widely used CHF correlation for PWR conditions, where DNB is the dominant CHF mechanism.

The correlation consists of the following equation:

$$q''_{CHF,u} = \{(2.022 - 0.06238p) + (0.1722 - 0.01427p)\exp[(18.177 - 0.5987p)x_e]\}$$
$$[(0.1484 - 1.596x_e + 0.1729x_e|x_e|)\cdot 2.326G + 3271]\cdot[1.157 - 0.869x_e]$$
$$[0.2664 + 0.8357\exp(-124.1D_h)]\cdot[0.8258 + 0.0003413(h_f - h_{in})]$$

$$(1)$$

where:

$q''_{CHF,u}$ is in kW/m^2

p (pressure) = 5.5 to 16 MPa
G (mass flux) = 1,356 to 6,800 kg/m^{2}s
D_h (heated diameter) = 0.015 to 0.018 m
x_e (equilibrium quality) = -0.15 to 0.15
L (tube length) = 0.254 to 3.70 m
h_{in} (inlet enthalpy) > 930 kJ/kg

Equation (1) was developed for axially uniform heated channels only, and provides the value of the CHF at any given location, once the equilibrium quality, the mass flux, the equivalent diameter, the pressure at that location, and the inlet enthalpy are known.

It is well known that for axially non-uniform heating there exists an effect of the upstream history on the local value of the CHF [1]. A method has been derived by Tong [2], which enables to account for the effect of the heat flux profile on the local CHF value. A similar approach has been proposed independently by Silvestri [3].

A shape factor F is defined as:

$$F = \frac{q''_{CHF,u}}{q''_{CHF}} \qquad (2)$$

where q"$_{CHF,u}$ is the value of the critical heat flux calculated by means of the W-3 correlation for a axially uniform heated channel, and q"$_{CHF}$ is the critical heat flux in the case of a non-uniform heated channel.

An energy balance for the bubble layer provides the analytical expression of F [1]:

$$F = \frac{C}{q''(\ell_{DNB})[1 - \exp(-C\ell_{DNB})]}\int_0^{\ell_{DNB}} q''(\xi)\exp[-C(\ell_{DNB} - \xi)]d\xi \qquad (3)$$

ℓ_{DNB} is the location of interest measured from the location of the inception of nucleate boiling, q" is the operating heat flux and $C(\ell_{DNB})$ is an experimental coefficient describing the heat and mass transfer effectiveness at the bubble-layer/subcooled-liquid-core interface:

$$C(\ell_{DNB}) = 185.6 \frac{\left[1 - x_e(\ell_{DNB})\right]^{4.31}}{G^{0.478}} \qquad (\text{m}^{-1}) \tag{4}$$

where G is in kg/m^{2}s. Note: in Eq. (3), the C factor within the integral is to be evaluated at ℓ_{DNB}, as that was the assumption made in correlating the data via Eq. (4) [4].

Tong and Tang [1] recommend calculation of ℓ_{DNB} as simply the distance from the channel entrance. This approach is adopted in the numerical example below.

Once the value of the CHF is calculated, a local Critical Heat Flux Ratio (CHFR) can be defined as:

$$\text{CHFR} = \frac{q''_{CHF}}{q''} \tag{5}$$

The CHFR is a measure of the margin to DNB. For example, most PWRs in the U.S. are designed to maintain a CHFR of at least 1.3 throughout the core during a postulated transient overpower (e.g., 112% power).

Physical interpretation of the shape factor

The shape factor accounts for the difference in the amount of energy accumulated in the bubble layer up to the location of interest, for a uniform and non-uniform heated channel. To gain some physical insight on the shape factor, consider a channel with fixed mass flux, pressure and equivalent diameter. Now consider the three heat flux profiles shown in **Figure 1**. Also, assume that in each case the inlet temperature is adjusted to obtain the same equilibrium quality at location z^*. Case 1 is the reference situation with uniform heating. In Case 2 a larger amount of energy than in Case 1 is supplied to the bubble layer before z^*, thus, it is clear that a small further heat supply at z^* (small relative to Case 1) may cause DNB. Hence, the shape factor is greater than one:

$$F = \frac{q''_{CHF,u}}{q''_{CHF}} > 1 \tag{6}$$

Analogous reasoning would suggest that F<1 in Case 3.
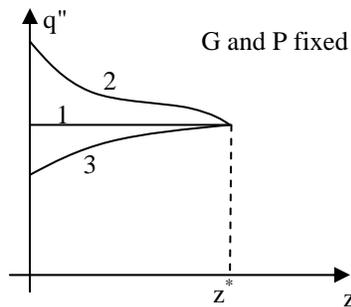
Figure 1. Non-uniform heat flux profiles.

The shape factor conveys the so-called "memory effect" of the heating axial profile on the CHF. The quantity $1/C$, which shows up in the exponential of the shape factor, can be interpreted as a characteristic "memory length": it provides an estimate of the length of the upstream region that affects the CHF at a certain location. Note that C decreases as the quality increases therefore amplifying the memory effect. In the limit of very high qualities ($x_e > 0.2$), DNB is no longer the dominant CHF mechanism, and the occurrence of CHF can be considered as a global phenomenon, with little dependence on the local value of the heat flux.

Numerical example
The fuel pin geometry for a standard Westinghouse PWR is shown in Figure 2. The heated length is 3.66 m. Consider the following operating conditions, which apply to the hot channel:

 Pressure: 15.5 MPa
 Inlet temperature: 285°C
 Mass flux: 3,500 kg/m^{2}s
 Average linear power: 30 kW/m (cosine profile)
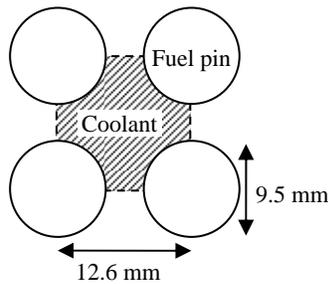
Figure 2. Cross-sectional view of the PWR channel

The axial variation of x_e, q", q"$_{CHF,u}$, q"$_{CHF}$, CHFR, C and F is shown in Figures 3 through 7. In this case the axial power profile is not flat: given the physical interpretation of the shape factor, we expect F<1 in the first half of the channel (increasing heat flux) and F>1 in the second half of the channel (decreasing heat flux). Figures 4 and 7 confirm this expectation.
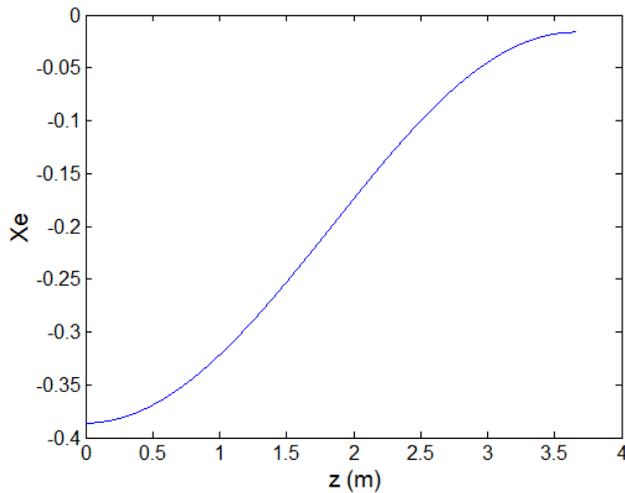
Figure 3. Equilibrium quality
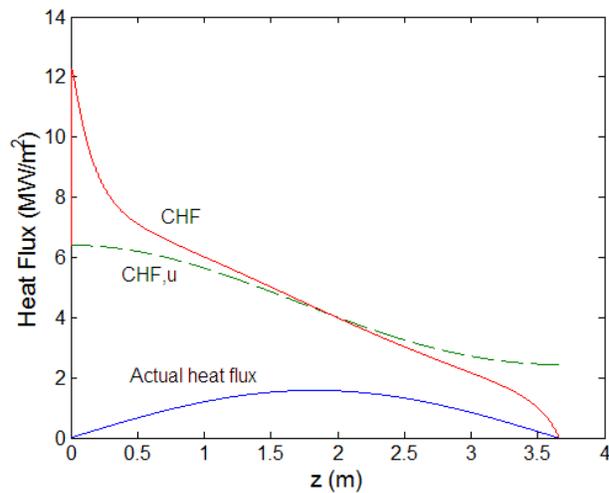
Figure 4. Actual and critical heat flux
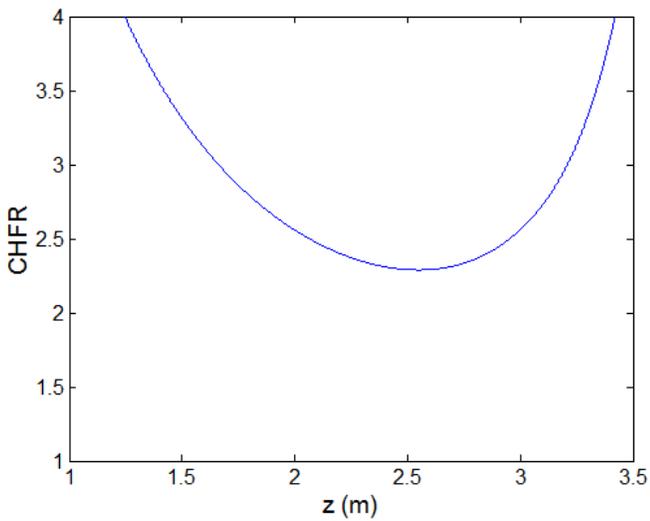
Figure 5. CHFR
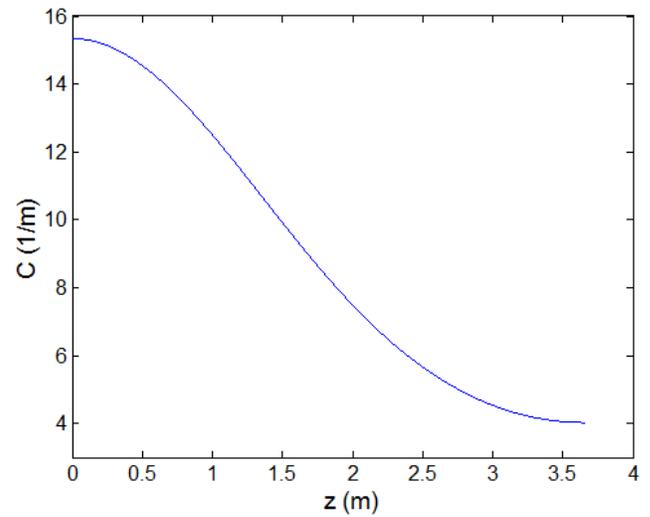
Figure 6. Coefficient C
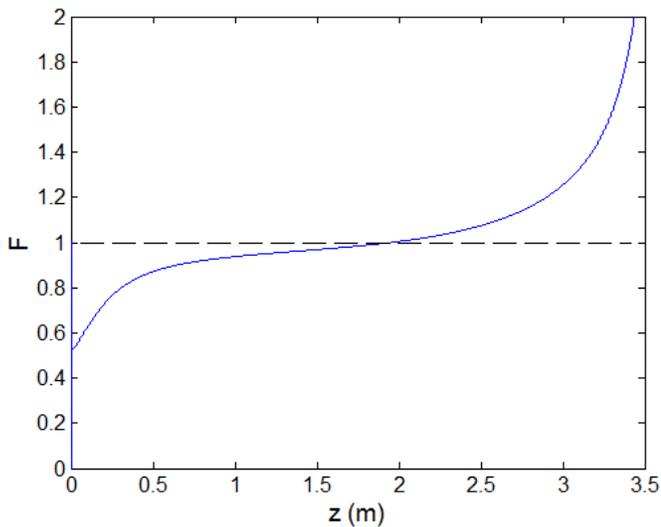
Figure 7. Shape factor F

References

[1] Tong, L. S., and Y. S. Tang, *Boiling Heat Transfer and Two-Phase Flow*, 328-336, 1997.

[2] Tong, L. S., et al., "Influence of axially non-uniform heat flux on DNB", *AIChE Chem. Eng. Prog. Symp. Ser.*, 62(64):35-40, 1966.

[3] Silvestri, M., "On the burnout equation and on location of burnout points", *Energia Nucleare*, 13(9), 469-479, 1966.

[4] Lin, W. S., et al., "Bundle critical power predictions under normal and abnormal conditions in Pressurized Water Reactors", *Nuclear Technology*, 98, 354-365, 1992.