Assessment of 12 CHF prediction methods, for an axially non-uniform heat flux distribution, with the RELAP5 computer code

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ABSTRACT

The present article covers the evaluation of the performance of twelve critical heat flux methods/correlations published in the open literature. The study concerns the simulation of an axially non-uniform heat flux distribution with the RELAP5 computer code in a single boiling water reactor channel benchmark problem. The nodalization scheme employed for the considered particular geometry, as modelled in RELAP5 code, is described. For this purpose a review of critical heat flux models/correlations applicable to non-uniform axial heat profile is provided. Simulation results using the RELAP5 code and those obtained from our computer program, based on three type predictions methods such as local conditions, F-factor and boiling length average approaches were compared.

1. Introduction

Systems utilizing boiling phenomenon dissipate large heat fluxes at small temperature differences. But under some conditions called “critical conditions” the steam produced forms an insulating layer over the surface and leads to large surface temperature. In the heat flux controlled systems, such as nuclear reactors, fossil-fueled boilers, etc., the critical heat flux (CHF) condition causes a drastic reduction of heat transfer coefficient and sometimes involves a physical failure of the heated surface. So, the critical heat flux forms a very important limit in the safety analysis of nuclear reactors. The critical heat flux called also boiling crisis depends on flow conditions and can be classified as departure from nucleate boiling (DNB) under subcooled boiling or low quality conditions. This later occurs at relatively high heat flux while dryout occurs under high quality and low heat flux.

The technical importance of the heat CHF conditions has led to the development of variety of empirical correlations. It is estimated that several hundred thousand CHF data points have been obtained in different laboratories around the world. More than 400 correlations have been developed in order to correlate the data. However, they are mainly limited to the same geometry and at the same working conditions as used in experiments. The present proliferation of correlations illustrates the complexity of the state-of-the-art in predicting the CHF phenomenon even for simple geometry at steady-state flow conditions.

In this study, we propose to evaluate the performance of twelve CHF correlations/methods published in the open literature for an axially non-uniform heat flux distribution in a single boiling water reactor channel, with the RELAP5/MOD3.3 computer code. This code has a robust thermal hydraulic model and widely accepted in the nuclear field. For predicting the critical heat flux, the code uses two methods: the 1986 AECL-UO critical heat flux look-up table method developed by Groeneveld et al. (1986) and the PG-CHF correlations (Pernica and Cizek, 1994, 1995) developed by the Nuclear Research Institute Rez in Czech Republic. The twelve evaluated correlations/methods are classified in three categories: the local condition hypothesis, the F-factor and boiling length average heat flux hypothesis. In predicting the CHF phenomenon even for simple geometry at steady-state flow conditions.

2. CHF prediction

Critical heat flux correlations are classified in two categories: upstream conditions correlation (UCC) and local conditions correlation (LCC). In the first category, the CHF is a function of five
### Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A )</td>
<td>flow cross section (( m^2 ))</td>
</tr>
<tr>
<td>AECL</td>
<td>Atomic Energy of Canada Limited</td>
</tr>
<tr>
<td>CHF</td>
<td>critical heat flux (( MW \cdot m^{-2} ))</td>
</tr>
<tr>
<td>( h )</td>
<td>enthalpy (( kJ \cdot kg^{-1} ))</td>
</tr>
<tr>
<td>( h_{\text{fg}} )</td>
<td>latent heat (( kJ \cdot kg^{-1} ))</td>
</tr>
<tr>
<td>( \Delta h_{\text{in}} )</td>
<td>inlet subcooling (( kJ \cdot kg^{-1} ))</td>
</tr>
<tr>
<td>LUT</td>
<td>look-up table</td>
</tr>
<tr>
<td>86LUT</td>
<td>the 1986 look-up table</td>
</tr>
<tr>
<td>95LUT</td>
<td>the 1995 look-up table</td>
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<tr>
<td>MF</td>
<td>mixed flow</td>
</tr>
<tr>
<td>( p )</td>
<td>pressure (Pa)</td>
</tr>
<tr>
<td>RS</td>
<td>RELAP5</td>
</tr>
<tr>
<td>SF</td>
<td>subchannel flow</td>
</tr>
<tr>
<td>UO</td>
<td>University of Ontario</td>
</tr>
<tr>
<td>( x )</td>
<td>local quality</td>
</tr>
<tr>
<td>( \text{z} )</td>
<td>heated length</td>
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</table>

### Greek Letter

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \phi )</td>
<td>heat flux (( MW \cdot m^{-2} ))</td>
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### Subscripts

<table>
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<th>Subscript</th>
<th>Description</th>
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<tr>
<td>crit</td>
<td>critical conditions</td>
</tr>
<tr>
<td>in</td>
<td>inlet conditions</td>
</tr>
<tr>
<td>nu</td>
<td>non-uniform</td>
</tr>
<tr>
<td>onb</td>
<td>onset of nucleate boiling</td>
</tr>
<tr>
<td>sat</td>
<td>saturation conditions</td>
</tr>
<tr>
<td>sub</td>
<td>subchannel flow</td>
</tr>
<tr>
<td>u</td>
<td>uniform</td>
</tr>
</tbody>
</table>

### Independent Variables

\[
\phi_{\text{CRIT}} = f_n(G, D, \rho, L, x_m). 
\]  

(1)

In the second category, the CHF is an explicit function of local quality, the length, \( L \), is eliminated by using the heat balance equation.

\[
\phi_{\text{CRIT}} = f_n(G, D, \rho, x_{\text{CRIT}}). 
\]  

(2)

With the first type, the evaluation is straightforward since the quantities on the right of Eq. (1) are known. While in the second type, the local conditions correlation can be evaluated with two methods: the direct substitution method (DSM) and the heat balance method (HBM).

In DSM, the local quality at each axial position of interest is calculated using the heat balance equation. This local quality is then directly substituted into the local condition correlation to obtain the CHF. In HBM, CHF at axial position of interest is predicted by an iterative method which satisfies simultaneously Eq. (2) and the energy balance by varying the heat flux. According to Inasaka and Nariai (1996), Celata (1996) and Groeneveld (1996), the HBM gives better results than DSM with the experimental data. Siman-Tov (1996) has the opposite view and argues that only DSM is correct for comparison of correlation with experimental data. In this paper, we have compared the correlations at the same thermal hydraulic conditions, so the used method of evaluating is only the DSM.

The first experiments with non-uniform heat flux distribution, have been conducted on vertical up-flow round tube. In order to know the limitation in the safe operation of nuclear power rectors, the form of the heat flux axial profile looks like a sine wave:

\[
\phi(z) = \phi_{\text{MAX}} \sin \left( \frac{\pi z}{L} \right) = \phi_{\text{MAX}} f(z) 
\]  

(3)

In rod bundles conditions, the rods diameter are small and are spaced one from another by grid spacers. Then, the CHF phenomenon is different from that in round tubes or annuli due to the cross flow between subchannels, effects of grid spacers, effects of cold walls, etc.

The effect of non-uniform heating on CHF can be predicted based on one of the following hypothesis: local conditions hypothesis, the \( F \)-factor method and the boiling length average heat flux hypothesis.

#### 2.1 Local-conditions type prediction methods

In this approach, it is assumed that the CHF is controlled only by the local heat flux and local quality and the upstream history is not important and there is a unique relationship (Eq. (2)), between critical heat flux and the local quality with all other parameters (\( D, L, G \) and \( p \)) fixed. The linear critical heat flux/quality relationship has a negative slope and formulated as

\[
\phi_{\text{CRIT}}(z) = A - Bx(z) = A - \frac{B}{h_{\text{fg}}} (h(z) - h_l). 
\]  

(4)

The energy balance equation, when the entire channel of rod bundle is assumed to behave in one-dimensional as if it were a single channel, is given by

\[
h(z_{\text{CRIT}}) - h_l = \frac{N \pi D_{\text{cl-out}}}{G A} \int_0^{z_{\text{CRIT}}} \phi(z) \, dz - \Delta h_{\text{in}}, 
\]  

(5)

where \( N \) is the number of heated rods, \( D_{\text{cl-out}} \) the diameter of heated rod, \( \phi(z) \) the heat flux, and \( G \) is the mass flux. The average quality is given by

\[
x(z_{\text{CRIT}}) = x_{\text{in}} + \frac{N \pi D_{\text{cl-out}}}{G h_{\text{fg}}} \int_0^{z_{\text{CRIT}}} \phi(z) \, dz. 
\]  

(6)

When we consider a square sub-channel and we assume that neither transport nor flux occurs along the straight boundaries marked by double lines (see Fig. 1), the energy balance is

\[
h(z_{\text{CRIT}}) - h_l = \frac{\pi D_{\text{cl-out}}}{G A_{\text{sub}} h_{\text{fg}}} \int_0^{z_{\text{CRIT}}} \phi(z) \, dz - \Delta h_{\text{in}}, 
\]  

(7)

and the quality is given by

\[
x(z_{\text{CRIT}}) = x_{\text{in}} + \frac{\pi D_{\text{cl-out}}}{G h_{\text{fg}}} \int_0^{z_{\text{CRIT}}} \phi(z) \, dz. 
\]  

(8)
2.1.1. Peak heat flux method

In this section, we have applied the same method described by Collier and Thome (1994) for single tube to the fuel assembly for which the characteristics are given in Section 3.

When the heat flux, \( \phi(z) \) and the enthalpy \( h(z) \) related by Eqs. (5) or (7) satisfy Eq. (4), the critical heat flux is then reached at this axial distance, \( z \), from the inlet. And the peak heat flux at this condition can be derived from Eqs. (4) and (5) or (7) and is given by
\[
(\phi_{\text{MAX}})_{\text{CRIT}}(z) = \frac{A + B \Delta h_{\text{in}}/h_{\text{lg}}}{f(z) + (8 \pi D_{\text{cl-out}} C/\text{h}_{\text{lg}}) \int_0^z f(z) \text{d}z},
\]
where \( C \) is expressed as
\[
C = \frac{1}{\frac{G_{\text{sub}}}{\text{sub}} N G_{\text{A}}},
\]
and
\[
The minimum value of \( (\phi_{\text{MAX}})_{\text{CRIT}}(z) \) is given when the derivative of Eq. (9) is equal to zero. Its derivative is given by
\[
\frac{d}{dz} \left( f(z) + \frac{8 \pi D_{\text{cl-out}} C}{h_{\text{lg}} G_{\text{A}}} \int_0^z f(z) \text{d}z \right)
\]

The constants \( A \) and \( B \) are taken from an adequate CHF correlation of a tube heated uniformly. In this study, the constants \( A \) and \( B \) are obtained from two different correlations developed respectively by Biasi et al. (1967), Bowring (1972) and numerically from the 1995 look-up table (Groeneveld et al., 1996).

2.1.2. Kirby correlation

Using only the non-uniform heating tube data, Kirby (1966) has re-optimized the constants of Eq. (4) and the obtained correlation is presented as
\[
\phi_{\text{CRIT}} = Y_1 G^2 D^{Y_3} - Y_4 G^2 D^{Y_6} X(z),
\]
where the constants \( Y_1, Y_2, Y_3, Y_4, Y_5 \) and \( Y_6 \) are functions of system pressure.

2.1.3. Macbeth correlation

By assuming that a channel behaves in one dimensional with average properties, Macbeth (1964) has proposed, for 69 bar only, a correlation as
\[
\phi_{\text{CRIT}} \times 10^{-6} = \frac{A + B \Delta h_{\text{in}}}{C + z},
\]
where the constant \( A, B \) and \( C \) are functions of heated equivalent diameter and mass flux.

2.1.4. Barnett correlation

Barnett (1968) showed that his annulus correlation with some correction, predicts a wide range of rod bundle data with remarkable accuracy. The Barnett correlation has the same form as Eq. (13) and may be used for pressures other than 69 bar with a slight modification as indicated below:
\[
\phi_{\text{CRIT}} \times 10^{-6} = \frac{A(h_{\text{lg}}/649) + B \Delta h_{\text{in}}}{C + z}
\]

2.1.5. Hench–Levy correlation

For design purpose of BWR, limit lines (Janssen and Levy, 1962), known as Janssen–Levy limit lines, have been developed to provide the CHF value as a simple linear functions of mass flux and critical quality. These limit lines were subsequently replaced by Hench–Levy limit lines (Healzer et al., 1966):

For 1000 psia
\[
\phi_{\text{CRIT}} = \begin{cases} 
1.0, & x(z) < x_{\text{lim}1} \\
1.9 - 3.3 x(z) - 0.7 \tanh^2(3G), & x_{\text{lim}1} < x(z) < x_{\text{lim}2} \\
0.6 - 0.7 x(z) - 0.09 \tanh^2(2G), & x(z) > x_{\text{lim}2}
\end{cases}
\]

where \( x_{\text{lim}1} = 0.273 - 0.212 \tanh^2(3G): \ x_{\text{lim}2} = 0.5 - 0.269 \tanh^2(3G) + 0.0346 \tanh^2(2G) \).

For pressures other than 1000 psia, the critical heat flux is given by
\[
\phi_{\text{CRIT}} = \frac{1 - 0.1 \left( \frac{e^{0.9} - 0.212 \tan^2(3G)}{e^{0.25} - 0.0346 \tan^2(2G)} \right)}{0.5356 \ln(1 + x_{\text{lim}2})}
\]

where \( p \) is the pressure in psia, \( G \) in Mlb/h ft\(^2\) and \( \phi_{\text{CRIT}} \) in MBtu/h ft\(^2\).

2.1.6. Condie and Bengston correlation

Based on 5200 bundle CHF data, an empirical correlation has been proposed by Condie and Bengston (1978):
\[
\phi_{\text{CRIT}} = \frac{25,487 (G/1356)^{0.1775 \ln(x_{\text{lim}2})}}{(x + 1)^{1.3900} - 0.5356 \ln(1 + x_{\text{lim}2})} \times 0.3234 \text{RPF}^{0.053}
\]

where RPF is the maximum radial power factor for the bundle.

2.1.7. Bowring correlation

Bowring (1977) has proposed a mixed flow correlation applied to all types of nuclear fuel as follows:
\[
\phi_{\text{CRIT}} = \frac{A + B \Delta h_{\text{in}}}{C + 2Y}
\]

where the constants \( A, B \) and \( C \) depend on pressure, mass flux, hydraulic diameter, equivalent heated diameter and shape profile of heat flux. \( Y \) is the ratio of average heat flux from entry to \( z \) to the local heat flux at \( z \), which is determined as follows:
\[
Y = \frac{1}{\epsilon_{\text{CRIT}}} \int_0^\epsilon_{\text{CRIT}} \frac{\phi(z)}{\phi_{\text{CRIT}}} \text{d}z
\]

2.1.8. EPRI correlation

A widely used general correlation applicable to both PWR and BWR conditions is that developed by EPRI (Reddy and Fighetti, 1983) and has the form:
\[
\phi_{\text{CRIT}} = \frac{A_0 - x_{\text{in}}}{C_0 F_{\text{nu}} ((\epsilon(z) - x_{\text{in}}) / \phi(z))}
\]

where the constants \( A_0 \) and \( C_0 \) are functions of pressure and mass flux, and \( F_{\text{nu}} \) is a grid spacer factor given by
\[
F_s = 1.3 - 0.3 K_p,
\]

where \( K_p \) is a grid pressure loss coefficient. \( F_{\text{nu}} \) is a non-uniform axial flux factor expressed as
\[
F_{\text{nu}} = 1 + \frac{Y - 1}{1 + G}
\]

2.2. F-factor type prediction methods

2.2.1. Tong method

A consequence of the non-consistence of the local conditions hypothesis for non-uniform heat flux distributions is that the local critical heat flux must depend, to some degree, on the heat flux profile upstream of the point considered. To take account of the effect of the upstream flux profile on the local critical heat flux,
Tong (1972) has proposed a semi-empirical method. A factor, $F$, is defined as fellow:

$$F = \frac{[\phi(z)]_{u}}{[\phi(z)]_{nu}}$$

where $[\phi(z)]_{u}$ is the critical heat flux with uniform heat flux profile case and $[\phi(z)]_{nu}$ is the critical heat flux with non-uniform axial heat flux distribution. By assuming that CHF occurs at a limiting value of superheat in the liquid sublayer, Tong (1972) has developed a correlation for the factor $F$ as fellow:

$$F = \frac{1}{1 - \exp(-Cz_{CRIT})} \int_{0}^{z_{CRIT}} \phi(z) \exp[-C(z_{CRIT} - z)]dz,$$  

where $C$ is a function of both local steam quality $x(z_{CRIT})$ and mass velocity $G$, given by

$$C = 17.323 \left(1 - x(z_{CRIT})\right)^{7.9} \left(G/1356\right)^{1.72}.$$  

2.2.2. Smolin method

Based on Tong shape factor equation (Eq. (21)), several researchers have proposed slightly revised forms of the F-factor. The form used by Smolin and Polyakov (1978) is

$$F = \frac{C}{1 - \exp(-Cz_{CRIT})} \int_{0}^{z_{CRIT}} \frac{\phi(z)}{\phi(z_{CRIT})} \exp[-C(z_{CRIT} - z)]dz,$$

where $C$ is a function of both local steam quality $x(z_{CRIT})$ and mass velocity $G$, given by

$$C = 5.906 \left(1 - x(z_{CRIT})\right)^{4.31} \left(G/1356\right)^{0.478}.$$  

2.3. Boiling length average heat flux hypothesis

The boiling length average (BLA) heat flux hypothesis is a tentative modification of the local condition hypothesis to take the history effect into account. It assumes that the CHF occurs when the BLA heat flux reaches a certain critical value.

2.3.1. Groeneveld method

In the Groeneveld et al. (1986) method, which is used in RELAP5 code, the predicted CHF values, at uniform heat flux for a tube diameter of 8 mm, are obtained by linear interpolation between data provided in a look-up table as function of discrete values of pressure, mass flux and quality. In other flow situations including flow in rod bundles, the CHF is calculated as fellows:

$$[\phi(z)]_{bundle} = [\phi(z)]_{BLA} K_{hy} K_{bf} K_{sp} K_{hl} K_{nu} K_{hor} K_{ver}$$

where $K_{hy}$, $K_{bf}$, $K_{sp}$, $K_{hl}$, $K_{nu}$, $K_{hor}$, and $K_{ver}$ are respectively the hydraulic diameter factor, the bundle factor, the grid spacer factor, the heated length factor, the axial flux distribution factor, horizontal flow factor and the vertical flow factor. In comparison with the others models, the $F$-factor adopted by Groeneveld et al., which

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig2}
\caption{Cross section of the fuel assembly (DelNevo et al., 2006).}
\end{figure}
Table 1
The main geometrical data of the fuel assembly

<table>
<thead>
<tr>
<th>Component</th>
<th>Symbol</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core height</td>
<td>H</td>
<td>4.10654 m</td>
</tr>
<tr>
<td>Core height—active part</td>
<td>H_A</td>
<td>3.810 m</td>
</tr>
<tr>
<td>Assembly width</td>
<td>B</td>
<td>0.13406 m</td>
</tr>
<tr>
<td>Bypass width</td>
<td>L</td>
<td>0.008509 m</td>
</tr>
<tr>
<td>Number of spacer grids</td>
<td>–</td>
<td>7</td>
</tr>
<tr>
<td>Cladding outer diameter</td>
<td>D_{cl-out}</td>
<td>0.0125222 m</td>
</tr>
<tr>
<td>Control rod width</td>
<td>K</td>
<td>0.13406 m</td>
</tr>
</tbody>
</table>

is equivalent to the Bowring’s $Y$ factor over the boiling length, is expressed as

\[
F = \frac{1}{K_{nu}} = \frac{\int_{z_{\text{SAT}}}^{z_{\text{CRIT}}} \phi(z) dz}{\phi(z_{\text{CRIT}})(z_{\text{CRIT}} - z_{\text{SAT}})}.
\]  

(27)

2.3.2. Lee method

Based on the 1995 look-up table (Groeneveld, 1996) and on the measured bundle CHF data, Lee (2000) has proposed a set of correction factors in order to extend the application of the 1995 look-up table to other flow conditions. The proposed correction factors are slightly different from those proposed by Groeneveld and are defined as

\[
\phi(z_{\text{CRIT}})_{\text{bundle}} = \phi(z_{\text{CRIT}})_{\text{95LUT}}K_{hy}K_{hl}K_{bf}K_{cw}K_{rp}K_{sp}K_{nu},
\]  

(28)

where $K_{hy}$, $K_{hl}$, $K_{bf}$, $K_{cw}$, $K_{rp}$, $K_{sp}$, and $K_{nu}$ are respectively the hydraulic diameter factor, the heated length factor, the bundle factor, the cold wall factor, the radial power distribution factor, the grid spacer factor and the axial flux distribution factor. To take account of the effect of non-uniform axial heat flux, Lee (2000) has proposed a new form of correction factor given as

\[
K_{nu} = \frac{1}{F} = C_3(1 + (Y - 1)\exp(2.66x(z)));
\]  

(29)

where $C_3 = 0.728$ in direct substitution method.

3. Simulation conditions

The geometry of the simulated fuel assembly is 8 × 8: 63 fuel pins and 1 water rod (see Fig. 2). The height of the fuel channel is 4.106 m. The active part of the core is 3.810 m. The equivalent cross-sectional area and hydraulic diameter are 100.9018 × 10^{-4} m², 0.01322 m, respectively. The nodalization scheme used in the simulation is shown in Fig. 3. The heated length (modelled by the pipe component 101) is divided into 24 meshes and the fuel rods are supported by seven spacer grids. The scheme consists of two pipe components (101 and 102), two branch components (B), two time dependent volumes (TDV) and one time dependent junction (TDJ). The assembly is fed by subcooled water (12 K lower than the saturation temperature), with a mass flow inlet of 17 kg/s. The bypass (modelled by the pipe component 102) mass flow rate is about 10% of core flow rate. The pressure is 72 MPa at the core outlet. The main geometrical data are summarized in Table 1. Seven spacer grids have been taken into account with suitable energy loss coefficients ($K_p = 0.02$) located at the top of “active” nodes 5, 8, 11, 14, 17, 20 and 23 (see Fig. 3).

The power of the single assembly is 7 MW with uniform radial profile. The axial distribution is reported in Fig. 4. A detailed description of the assembly is provided by DelNevo et al. (2006).

4. Results and discussion

The prediction methods discussed previously were compared at steady state and at the same thermal hydraulic conditions using geometrical and flow characteristics provided by DelNevo et al. (2006). A demonstration of the reached stationary condition has been performed selecting four parameters trends (core collapsed level, maximum cladding temperature, core outlet temperature and core inlet mass flow rate) and verifying that each of them, after one hundred seconds “transient-steady state” calculation, is stable with an inherent drift <1%/100 s (D’Auria et al., 2004). The quantities such as critical heat flux and thermodynamic quality, predicted by RELAP5 are taken at 200 s.

On the other hand, a set of computer programs, written (in FORTRAN), were developed: one program for each method of prediction and one for predicting the thermophysical properties which are
contained in the recent revised release of the international association for the properties of water and steam (Wagner and Kruse, 1998). As stated earlier, we have compared the correlations using the direct substitution method. Fig. 5 shows the thermodynamic quality distributions predicted by RELAP5 and by Eq. (6) are very close. The small difference is due to the pressure which is considered constant and to the use of a different thermodynamic table. The quality distributions of the mixed flow (Eq. (6)) and subchannel flow (Eq. (8)) look similar so that one can confound them.

4.1. RELAP5 results

Two options of CHF prediction are available in the RELAP5/MOD3.3: the CHF look-up table method and the PG-CHF correlations. As stated in volume 4 of the RELAP5 code documentation, the first option uses the direct substitution method to obtain the CHF. While the second option has four different formulations (basic, flux, geometry, and power) which the users may activate. In the first three PG-CHF the direct substitution method is used and the last uses the heat balance method. In this study, we have activated the PG-CHF flux form, which requires the distance from the inlet and the axial power distribution. The results obtained by RELAP5 are presented in Fig. 6 using the look-up table and PG-CHF. The results of PG-CHF power form which use the HBM method are also presented for comparison. Fig. 6 shows the predicted CHF using look-up table are higher than the PG-CHF correlations. The power form and the flux form PG-CHF provide the same results when the length exceed the value 2.937 m and the quality reaches the value 0.212.

4.2. Local conditions hypothesis results

4.2.1. Peak heat flux method

Using values of A and B derived from uniformly heated tubes, the peak heat flux (Eq. (9)) when the critical heat flux is exceeded at \( z \), is calculated for both subchannel and mixed flow and represented in Fig. 6. The selected uniform critical heat flux correlations are respectively, Biasi et al. (1967), Bowring (1972) and the 1995 look-up table (Groeneveld et al., 1996). For the mixed flow, the CHF values from round tube look-up table were also adapted to rod bundles by multiplying them by a set of correction factors proposed respectively by Groeneveld et al. (1986) and Lee (2000). The uniform heat flux CHF is calculated as

\[
\phi_{\text{crit}}(z) = \phi_{\text{crit}}(2)\times\text{look-up table} \times K_y \times K_{sp} \times K_{hl} \times K_w
\]

For a selected round tube CHF uniform correlation, the peak heat flux predicted in mixed flow is higher than the subchannel flow one and both are higher than the RELAP5 predictions.

4.2.2. Correlations

In Fig. 7 the critical heat flux predicted from the local conditions approach quoted in Section 2.1 are compared against the RELAP5 ones. To predict the CHF for a given quality, some correlations such as Eqs. (13), (14) and (17), which were formulated for inlet conditions, are transferred via the heat balance. It can been seen that Bowring curve has the highest slope. The Barnett and PG-CHF flux form correlations bracket the predicted values. A common characteristic for all correlations is that the CHF decreases with quality, except for Hench–Levy correlation where calculated values are constants at low qualities. The same tendency is also obtained in the region of negative thermodynamic quality, by RELAP5 when the CHF table look-up method is activated. In the entrance region, the predicted CHF values from the RELAP5 code using the look-up method are higher than the Hench–Levy lines limits which were applied in BWR design with a margin safety corresponding to minimum critical heat flux ratio (MCHFR) of 1.9. However, we must mention that the hydraulic diameter of the studied geometric configuration is slightly superior to the limit value of the application.
domain with a value of 0.88 mm. The values from Kirby correlation, for the subchannel flow are slightly lower than the mixed flow ones and are close to but slightly above the CHF look-up table ones. With the Condie–Bengston correlation which is developed for RELAP4/MOD7, the calculated values are lower than RELAP5 ones when using the CHF table look-up method. A very good agreement may be observed for the EPRI correlation and the PG-CHF power form correlation using the heat balance method.

4.3. F-factor methods results

Fig. 8 shows the comparison of the three different F-factor models proposed respectively by Tong, Lin and Smolin. The F-factor varies quantitatively in the same manner. The Smolin’s F-factor for which the parameter C is only function of hydraulic diameter, is lower than both Tong and Lin values at low qualities (below 0.08) and higher beyond this value. According to the definition of the F-factor (Eq. (21)), the non-uniform critical heat flux depends considerably on the equivalent uniform critical heat flux. The equivalent uniform critical heat flux for both subchannel and mixed flow using Bowring’s correlation and the look-up table method are compared in Fig. 9. The calculated values for mixed flow are higher than subchannel flow ones. To take account for bundle specific effects, the tube look-up table was applied by multiplying the CHF table by a set of correction factors proposed respectively by Groeneveld et al. and by Lee. The obtained results are also shown in Fig. 10. In this study, we have used for the Groeneveld method, the correction factors derived for the 1986 AECL-UO look-up table.

In Fig. 9 the critical heat flux predicted from the F-factor approach quoted in Section 2.2 are compared against the RELAP5 ones.

4.4. Boiling length average heat flux hypothesis results

In Fig. 11 the critical heat flux predicted from the BLA approach are compared against the RELAP5 ones. The calculated CHF from the Lee correspond very closely with the PG-CHF power form correlation in the low qualities range ($x < 0.15$). Near the outlet region, the results are not good. The predictions from the Groeneveld model, using the same set of correction factor and two different look-up table (1986 AECL-UO, 1995 look-up table) are slightly different.

5. Conclusions

A literature review of critical heat flux models/correlations applicable to non-uniform axial heat flux profile has been conducted. Three types of prediction methods were considered: local conditions, F-factor and boiling length average approaches. The obtained results were compared with RELAP5 results at same thermal conditions in a single boiling water reactor channel. This comparison showed that no satisfactory model to predict critical heat flux for non-uniform heat flux exists. Correlations based on local conditions hypothesis such as EPRI, Condie–Bengston and Kirby presented more consistent results in comparison with RELAP5 ones. For subchannel flow, the predicted critical heat flux are lower than the mixed flow. When comparing the F-factor method with RELAP5 model, the Lin and Tong correlation results are in better consistency at low qualities whereas the Smolin’s models is better at high quality. At low qualities ($x < 0.20$) the results predicted from the Lee correlation based on the BLA approach correspond closely with the RELAP5 values when the PG-CHF power
form is selected but at high qualities the results is in contradiction with other correlations.

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