Update on RELAP5-3D CHF Geometry Correction Factors

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2016 IRUG Meeting
Critical Heat Flux and Look up table

- Heat flux when DNB occurs
  - Local over-heating → Failure / Accident
  - Reactors designed to avoid CHF
  - CHF value from empirical correlations and look up tables

- CHF Look up table (LUT)
  - Normalized CHF value data bank for water
  - Standard table by Groeneveld et al.,
    - 1986 version: ~15000 data points (chftab.F)
    - 2006 version: ~30000 data points (chftab06.F)
  - CHF look up table is function of pressure (P), mass flux (G) and quality (X)
    - 3D interpolation needed for exact value
CHF Look up table geometry correction factor

- CHF values from LUT need correction factors
  - Factors correct given CHF value based on geometry and flow type, and range of pressure (pressure range factor in 1986 version)

- RELAP5-3D is designed to calculate appropriate correction factors for each case

- Status of correction factors in chftab06.F of RELAP5-3D v434
  - K1: Sub-channel/tube diameter, cross-section geometry (not updated)
  - K2: Bundle geometry (updated)
  - K3: Mid-plane space factor for 37 elements bundle (CANDU) (same as 1986)
  - K4: Heated length factor (same as 1986)
  - K5: Axial flux distribution factor (same as 1986)
  - K6: Radial or circumferential flux distribution factor (not updated)
  - K7: Horizontal flow orientation factor (not updated)
  - K8: Vertical low flow factor (updated)
User problem feedback

• #179: 2006 version still uses 1986 version of K1 factor
  – For 2006 version (chftab06.F), K1 factor still uses 1986 version
  – 1986 version
    • $K_1 = (0.008/D)^{0.33}$ for $D < 0.016m$, $K_1 = (0.008/0.016)^{0.33} = 0.79$ for $D > 0.016m$
  – 2006 version
    • $K_1 = (0.008/D)^{0.5}$ for $0.003 < D < 0.025m$, $K_1 = (0.008/0.025)^{0.5} = 0.57$ for $D > 0.025m$
  – Update of K1 factor is completed

• #186: Manual update needed for chftab06.F
  – Description on CHF Look up table geometry correction factors of 2006 version is insufficient
  – K6, K7 and K8 are not correctly defined in chftab06.F
  – Above factors are updated and documented (for draft manual)

• Test on updated chftab06.F was also performed
## K1 sub-channel / tube-diameter, cross section geometry factor (Updated in 2016)

<table>
<thead>
<tr>
<th>1986 version</th>
<th>2006 version</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K1 = (0.008/D)^{0.33}$ for $D &lt; 0.016m$</td>
<td>$K1 = (0.008/D)^{0.5}$ for $0.003 &lt; D &lt; 0.025m$</td>
</tr>
<tr>
<td>$K1 = (0.008/0.016)^{0.33} = 0.79$ for $D &gt; 0.016m$</td>
<td>$K1 = (0.008/0.025)^{0.5} = 0.57$ for $D &gt; 0.025m$</td>
</tr>
</tbody>
</table>

$K1(86') > K1(06')$

### K2 bundle geometry factor

- Already updated in v434

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>$K2 = \min[0.8, 0.8\exp(-0.5X_{lim}^{0.33})]$ for rod bundles</td>
<td>$K2 = \min \left[ 1, \left( \frac{1}{2} + \frac{2\delta}{D} \right) \exp \left( -\left( \frac{X_e}{D} \right)^{1/3} \right) \right]$</td>
</tr>
<tr>
<td>$X_{lim} = \min[1, \max(0,X_e)]$</td>
<td>where $\delta = \text{minimum rod spacing (}=P-D)$</td>
</tr>
<tr>
<td>$K2 = 1.0$ for other surfaces</td>
<td></td>
</tr>
</tbody>
</table>


K3, K4 and K5 factors are same in 1986 and 2006

- **K3 Grid spacer factor** (for 37 CANDU element bundle)
  
  \[
  K3 = 1 + A \cdot \exp(-B \cdot L_{SP}/D_e)
  \]
  
  where \( A = 1.5 K_{\text{loss}} 0.5(G/1000)^{0.2} \), \( B = 0.1 \)

- **K4 Heated-length factor**
  
  For \( L/D_e > 5 \)
  
  \[
  K4 = \exp\left(\left(\frac{D_e}{L}\right)\exp(2\alpha_h)\right), \text{where} \quad \alpha_h = \frac{X_e \rho_f}{X_e \rho_f + (1 - X_e) \rho_f}
  \]

- **K5 Axial flux distribution factor**
  
  For \( X_e < 0 \); \( K5 = 1.0 \) and
  
  For \( X_e > 0 \); \( K5 = q''/q''_{bla} \)
**K6 factor : new in 2006 version (added in 2016)**

- **K6 Radial or circumferential flux distribution factor**
  - Newly added in 2006 Look up table correction factor
    - For $X_e < 0$: $K6 = 1.0$ and for $X_e > 0$: $K6 = \frac{q''(z)_{max}}{q''(z)_{avg}}$
    - $K6$ could be added by multiplication with $K5$, “Local boiling factor”.
      - 1CCCG80X W8(R) → $K5 \times K6$
      - Therefore, the user can implement this factor

**K7 horizontal flow factor (updated in 2016)**

- In 1986 version, horizontal flow factor defined as $K6$

<table>
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<tr>
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</tr>
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<tbody>
<tr>
<td>K6=1 if vertical</td>
<td>$K7 = 1 - \exp(-(T_1/3.0)^{0.5})$</td>
</tr>
<tr>
<td>K6=0 if horizontal stratified</td>
<td></td>
</tr>
<tr>
<td>K6=1 if horizontal high flow</td>
<td>$T_1 = \left(\frac{1-X_e}{1-\alpha}\right)^2 \frac{f_L G^2}{g_D \rho_f (\rho_f - \rho_g) \alpha^{0.5}}$</td>
</tr>
<tr>
<td>K6=interpolate if medium flow</td>
<td>where Friction factor of the channel, $f_L$, is suggested as; $f_L = 0.046 Re^{-0.2}$</td>
</tr>
</tbody>
</table>
**K8 Vertical low flow factor**

- In 1986 version, vertical flow factor defined as $K_7$

<table>
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<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>For $G&lt;-400$ or $G&gt;100 \text{ kg/m}^2\text{s}$; $K_7 = 1.0$</td>
<td>For $G&lt;-400 \text{ kg/m}^2\text{s}$ or $X_e &lt;&lt; 0$; $K_8 = 1.0$</td>
</tr>
<tr>
<td>For $-50 &lt; G &lt; 10 \text{ kg/m}^2\text{s}$</td>
<td>For $-400 &lt; G &lt; 0 \text{ kg/m}^2\text{s}$; Linear interpolation between table value</td>
</tr>
<tr>
<td>$K_7 = (1 - \alpha_h)$ for $\alpha_h &lt; 0.8$</td>
<td>$CHF_0 = CHF_{G=0,X=0}(1-\alpha_h)C_1$</td>
</tr>
<tr>
<td>$K_7 = (1 - \alpha_h) \frac{0.8 + 0.2\rho_f/\rho_g}{\alpha_h + (1 - \alpha_h)\rho_f/\rho_g}$</td>
<td>For $\alpha_h &lt; 0.8$; $C_1 = 1.0$</td>
</tr>
<tr>
<td>CHF table value at $G=0$, $X_e=0$</td>
<td>For $\alpha_h &gt; 0.8$;</td>
</tr>
<tr>
<td>For $10 &lt; G &lt; 100 \text{ kg/m}^2\text{s}$ or</td>
<td>$C_1 = \frac{0.8 + 0.2\rho_f/\rho_g}{\alpha_h + (1 - \alpha_h)\rho_f/\rho_g}$</td>
</tr>
<tr>
<td>$-400 &lt; G &lt; -50 \text{ kg/m}^2\text{s}$ interpolate</td>
<td></td>
</tr>
</tbody>
</table>

**K9 Pressure out-range factor**

- Remain from 1986 version (added to chftab06.F)

$$K_9 = \frac{\text{prop(out)}}{\text{prop(border)}} \quad \text{where} \quad \text{prop} = \rho_g^{0.5} h_f g [\sigma (\rho_f - \rho_g)]^{0.25}$$
**Vertical low flow factor test**

- **Comparison between versions**
  - $P=1e7\, Pa$, $X=0.1$, 0.2, 0.5 and 0.8
  - 35 cases of different mass flux ($G$)

- **Vertical flow factor**
  - 1986 version factor is independent to mass flux (function of void fraction and density)
  - 2006 version factor from interpolated $CHF$

\[
K8 = \frac{f_0 CHF_0 + (1 - f_0) CHF}{CHF}
\]

\[
CHF_0 = CHF_{G=0,X=0}(1 - \alpha_h)C_1, \quad f_0 = \frac{400 - |G|}{400}
\]

- **CHF value with geometry factor**
  - Both version shows different behavior
    - 1986 CHF at $-50 < G < 10\, kg/m^2/sec$
    - 1986 CHF around 100 and 200$kg/m^2/sec$
CHF Look up table value comparison

- Different behavior shows around 100 and 200 kg/m² sec
- 2006 LUT seems smoother
Updated chftab06.F test

- Comparison with existing RELAP5-3D CHF test samples
  - Bennett heat tube
Updated chftab06.F test

- Comparison with existing RELAP5-3D CHF test samples
  - ORNL THTF test
  - RIT tube test
Conclusions

• Update completed for chftab06.F
  – K1: Sub-channel/tube diameter, cross-section geometry (updated)
  – K2: Bundle geometry (updated)
  – K3: Mid-plane space factor for 37 elements bundle (CANDU) (same as 1986)
  – K4: Heated length factor (same as 1986)
  – K5: Axial flux distribution factor (same as 1986)
  – K6: Radial or circumferential flux distribution factor (updated via guideline)
  – K7: Horizontal flow orientation factor (updated)
  – K8: Vertical low flow factor (clarify mass flux range coding)
  – K9: Pressure out-range factor (remain from 1986 version)

• Test of updated chftab06.F is also performed
  – 2006 CHF LUT is more conservative

• Updates submitted for next code version

• Manual will be updated