Forced convective boiling:
Relation between wall temperature and regimes

Forced convective boiling:
Heat transfer regimes as function of heat flux and quality

Forced convective boiling:
Models used in codes: The "boiling surface".

- Assumes unique surface for given , p. to geometry.
- Shape of surface will vary with pressure and mass flux, reflecting changes of flow regime.
Forced convective boiling:
Nucleate boiling heat transfer correlations

For correlation not taking account of surface effects, Foster & Zuber AIChEJ vol.1 p.532 (1955):

\[ \alpha_{FZ} = \frac{q}{\Delta T_{sat}} = 0.00122 \frac{\text{Re}^{0.24} \text{Pr}^{0.79}}{\text{Pr}^{0.34}} \]

For correlation taking account of surface effects (Rohsenow Trans. ASME vol.74 p.96, 1952):

\[ C_S = \frac{\text{cp} \frac{\Delta T_{sat}}{\Delta T}}{C_f} = \frac{\text{q}}{\Delta T_{sat}} \left[ \frac{\alpha}{\rho_L \Delta T} \right]^{0.33} \frac{\text{cp} \frac{\Delta T}{\Delta T_f}}{\Delta T_f} \]

\( C_P \) depends on surface finish and fluid e.g. water/platinum: 0.013,
water/stainless: 0.020, \( N = 1.0 \) for water, \( n = 1.7 \) for other fluids.

Forced convective boiling:
Chen superposition correlation

\[ \alpha = \alpha_{NB} + \alpha_{FC} \]

\[ \alpha_{NB} = S \alpha_{FZ} \]

\[ \frac{\alpha_{FZ}}{\alpha_L} = F = f_N \left( \frac{1}{X_B} \right) \]

Saturation region:

\[ \dot{q} = \alpha_{FZ} \left( T_B - T_{sat} \right) + \alpha_{RB} \left( T_B - T_{sat} \right) \]

Subcooled region:

(For this region take \( \text{Re} = \text{Re}_L \)

In calculation of \( S \)

\[ T_B = \text{Bulk liquid temperature} \]

Critical heat flux: Definition


Definitions:

1. For heat flux controlled system, CHF corresponds to INORDINATE INCREASE in surface temperature following small change in system parameter (e.g. Heat flux, mass flux, inlet subcooling).
2. For surface temperature controlled system, CHF corresponds to condition where there is an INORDINATE DECREASE in surface heat flux following a change in system parameter.
Parametric effects on CHF:
Fixed length and diameter

\[ \dot{q}_{\text{crit}} = \Delta T_{\text{sub}} = 0 \]

\[ \dot{m} \text{ fixed} \]

\[ \Delta T_{\text{sub}} = T_{\text{sat}} - T_{\text{in}} \]

\[ \Delta h_{\text{sub}} = c_p \Delta T_{\text{sub}} \]

Parametric effects on CHF:
Fixed mass flux and \( \Delta h_{\text{sub}} = 0 \)

\[ \dot{q}_{\text{crit}} \]

\[ \dot{q} = \text{power input to achieve CHF} \]

Note: Horizontal channels have lower CHF due to segregation

Critical heat flux mechanisms:
Sub-cooled and low quality

(A) Hot spot under single bubble

(B) Dryout under slug or vapour clot

(C) Vapour bubble crowding – bubble boundary layer

Link between CHF (dryout) and liquid film flow

Steam + drops

Film Extract

Heated length

Water

Tentative diagram of regions of operation of CHF mechanisms

Basic correlation types:
Flux/quality and quality/boiling length

Burnout at end of tube - same data
If \( \dot{q}_i = f(x) \) for fixed \( D, \dot{m} \)
\[ L_B = \frac{Dh_i}{\dot{q}_i} = f(n(x)) \]
\[ x = f(n(L_B)) \]

Effect of non-uniform heat flux:
Flux/quality relationship

Results of Shiralkar (1972)
(Shiralkar NEDM – 13279, 1972)
Very poor representation of non-uniform flux data

Critical heat flux correlations:
Effect of non-uniform heat flux on quality/boiling length relationship

\( \frac{x}{L_B} \) much better representation of data. Recommended For \( x > 10\% \)
Failure of both flux/quality and quality/boiling length correlations. 1: Cold patch experiments

CHF (burnout) power increases if part of tube is unheated!

Water evaporating in a 12.6 mm vertical tube at 6.89 MPa

Bennet et al (1967)

Phenomenological methods for predicting CHF: Annular flow

\[ m_{LF} = \frac{M_{LF}}{\pi d^2 / 4} \]

\[ \frac{dh_{LF}}{dz} = 4 \left( D - E - \frac{\dot{q}}{h_{LG}} \right) \]

D and E – deposition and entrainment rates per unit area of tube surface.

Whalley et al., 5th Int. H. T. C., Tokyo, 1974, Paper B6.11

Phenomenological methods for predicting CHF: Prediction of entrainment curves

Critical heat flux prediction in annular flow: Application of model to rod bundle CHF
Transients: Extension of film dryout methodology  
(James and Whalley, 1978)

Equations for core and film:

- **Film mass balance**
  \[
  \begin{align*}
  \frac{1}{\rho_f} \left( \frac{\partial}{\partial t} (E - \varepsilon_f) \right) &= \frac{1}{\rho_f} \left( \frac{\partial}{\partial z} \right) \left( \delta \varepsilon_f \right) + \frac{1}{\rho_f} \left( \frac{\partial}{\partial z} \right) \left( \delta q_m \right) \\
  \alpha_f \frac{\partial}{\partial t} (E - \varepsilon_f) &= \frac{1}{\rho_f} \left( \frac{\partial}{\partial z} \right) \left( \delta q_m \right) + \frac{1}{\rho_f} \left( \frac{\partial}{\partial z} \right) \left( \delta q_m \right)
  \end{align*}
  \]

- **Core mass balance**
  \[
  \begin{align*}
  \frac{1}{\rho_c} \left( \frac{\partial}{\partial t} (E - \varepsilon_c) \right) &= \frac{1}{\rho_c} \left( \frac{\partial}{\partial z} \right) \left( \delta \varepsilon_c \right) + \frac{1}{\rho_c} \left( \frac{\partial}{\partial z} \right) \left( \delta q_m \right) \\
  \alpha_c \frac{\partial}{\partial t} (E - \varepsilon_c) &= \frac{1}{\rho_c} \left( \frac{\partial}{\partial z} \right) \left( \delta q_m \right) + \frac{1}{\rho_c} \left( \frac{\partial}{\partial z} \right) \left( \delta q_m \right)
  \end{align*}
  \]

- **Vapour mass balance**
  \[
  \begin{align*}
  \frac{1}{\rho_v} \left( \frac{\partial}{\partial t} (E - \varepsilon_v) \right) &= \frac{1}{\rho_v} \left( \frac{\partial}{\partial z} \right) \left( \delta \varepsilon_v \right) + \frac{1}{\rho_v} \left( \frac{\partial}{\partial z} \right) \left( \delta q_m \right) \\
  \alpha_v \frac{\partial}{\partial t} (E - \varepsilon_v) &= \frac{1}{\rho_v} \left( \frac{\partial}{\partial z} \right) \left( \delta q_m \right) + \frac{1}{\rho_v} \left( \frac{\partial}{\partial z} \right) \left( \delta q_m \right)
  \end{align*}
  \]

- **Overall energy balance**
  \[
  \begin{align*}
  \frac{1}{\rho} \left( \frac{\partial}{\partial t} (E - \varepsilon) \right) &= \left( \frac{1}{\rho_f} + \frac{1}{\rho_c} + \frac{1}{\rho_v} \right) \left( \frac{\partial}{\partial z} \right) \left( \delta q_m \right) + \frac{1}{\rho} \left( \frac{\partial}{\partial z} \right) \left( \delta q_m \right)
  \end{align*}
  \]

\(F_{FLF}\) and \(F_{LFL}\) are the rates of flashing of the film and drops per unit interface area.
\(\varepsilon_f\) and \(\varepsilon_c\) are the internal energies of the liquid and vapour phases.

Critical heat flux prediction in annular flow:
Application of model to CHF in flow transient

\[
\dot{m}(t) = 785 + 1926 \exp\left(-t/0.275\right) \text{ (kg/m}^2\text{ s)}
\]  

Comparison with Moxon and Edwards data:

<table>
<thead>
<tr>
<th>Run No</th>
<th>Heat flux (kW/m²)</th>
<th>Subcooling (kJ/kg)</th>
<th>Experiment</th>
<th>Old Model (PW31)</th>
<th>New Model (PW31A)</th>
<th>New model Predicted (s)</th>
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</tr>
</tbody>
</table>

Dryout and rewetting I:  
Hewitt and Govan (1990)

Transitions occur when film flow rate at wet/dry boundary is zero as calculated from transient film flow model.

Dryout and rewetting II:  
Hewitt and Govan (1990)

(a) Fast transient  
(b) Slow transient

CHF condition corresponds to situation where:

\[ q_b = \dot{m}_{out}(x_2 - x_1)h_{LG} \]

Where \( q_b \) is that part of the heat flux which goes into generating bubbles. Critical condition corresponds to void fraction in the wall layer of 0.82.

Phenomenological methods for predicting CHF: CHF modelling methods: Comparison with data

International data tables for CHF for water in uniformly heated tubes at 70 bar

Lowest value applies. Higher value from Weisman and Pei model may apply to hot spots in annular flow region.

Post-CHF (post dryout) heat transfer: Nil evaporation case

Post-CHF (post dryout) heat transfer: Equilibrium case

Droplets do not evaporate in post-dryout region. All heat goes into heating Steam. (Low \( m \), low \( p \))

Droplets evaporate at rate sufficient to maintain vapour at \( T_{SAT} \). Vapour velocity increases and \( T_w \) decreases along channel.