A SHORT INTRODUCTION TO
TWO-PHASE FLOWS
Condensation and boiling heat transfer

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HEAT TRANSFER MECHANISMS

• Condensation heat transfer:
  – drop condensation
  – film condensation

• Boiling heat transfer:
  – Pool boiling, natural convection, *ébullition en vase*
  – Convective boiling, forced convection,

• Only for pure fluids. For mixtures see specific studies. Usually in a mixture, \( h \leq \sum x_i h_i \) and possibly \( \ll h_i \).

• Many definitions of heat transfer coefficient,

\[
h \text{[W/m}^2\text{/K]} = \frac{q}{\Delta T}, \quad \text{Nu} = \frac{hL}{k}, \quad k(T?)
\]
CONDENSATION OF PURE VAPOR

- Flow patterns
  - Liquid film flowing.
  - Drops, static, hydrophobic wall $(\theta \approx \pi)$. Clean wall, better htc.

- Fluid mixture non-condensible gases:
  - Incondensible accumulation at cold places.
  - Diffusion resistance.
  - Heat transfer deteriorates.
  - Traces may alter significantly $h$
FILM CONDENSATION

- Thermodynamic equilibrium at the interface,
  \[ T_i = T_{\text{sat}}(p_\infty) \]

- Local heat transfer coefficient,
  \[ h(z) \triangleq \frac{q}{T_i - T_p} = \frac{q}{T_{\text{sat}} - T_p} \]

- Averaged heat transfer coefficient,
  \[ \bar{h}(L) \triangleq \frac{1}{L} \int_0^L h(z) \, dz \]

- NB: Binary mixtures \( T_i(x_\alpha, p) \) and \( p_\alpha(x_\alpha, p) \). Approximate equilibrium conditions,
  - For non condensible gases in vapor, \( p_V = x P_{\text{sat}}(T_i) \), Raoult relation
  - For dissolved gases in water, \( p_G = H x_G \), Henry’s relation
CONTROLLING MECHANISMS

- Slow film, little convective effect, conduction through the film (main thermal resistance)
- Heat transfer controlled by film characteristics, thickness, waves, turbulence.
- Heat transfer regimes,

\[ \Gamma \triangleq \frac{M_L}{P}, \quad \text{Re}_F \triangleq \frac{4\Gamma}{\mu_L} \]

- Smooth, laminar, \( \text{Re}_F < 30 \),
- Wavy laminar, \( 30 < \text{Re}_F < 1600 \),
- Wavy turbulent, \( \text{Re}_F > 1600 \)
• Simplest situation, only a single heat source: interface, stagnant vapor,
• Laminar film (Nusselt, 1916, Rohsenow, 1956), correction 10 to 15%,
\[
h(z) = \left( \frac{k_L^3 \rho_L g (\rho_L - \rho_V) (h_{LV} + 0.68C_{PL}[T_{sat} - T_P])}{4\mu_L(T_{sat} - T_P) z} \right)^{\frac{1}{4}}
\]
• Averaged heat transfer coefficient \((T_W = \text{cst})\) : \(h(z) \propto z^{-\frac{1}{4}}\), \(\bar{h}(L) = \frac{4}{3}h(L)\)
• Condensate film flow rate, energy balance at the interface,
\[
\Gamma(L) = \frac{\bar{h}(L)(T_{sat} - T_P)L}{h_{LV}}
\]
• Heat transfer coefficient-flow rate relation,
\[
\frac{\bar{h}(L)}{k_L} \left( \frac{\mu_L^2}{\rho_L (\rho_L - \rho_V)} \right)^{\frac{1}{3}} = 1.47 \text{Re}_{F}^{-\frac{1}{3}}
\]
• \(h_{LV}\) and \(\rho_V\) at saturation. \(k_L, \rho_L\) at the film temperature \(T_F \triangleq \frac{1}{2}(T_W + T_i)\),
• \(\mu = \frac{1}{4}(3\mu_L(T_P) + \mu_L(T_i))\), exact when \(1/\mu_L\) linear with \(T\).
SUPERHEATED VAPOR

- Two heat sources: vapor \( T_V > T_i \) and interface.
- Increase of heat transfer wrt to saturated conditions, empirical correction,

\[
\bar{h}_S(L) = \bar{h}(L) \left( \frac{1 + C_{PV}(T_V - T_{\text{sat}})}{h_{LV}} \right)^\frac{1}{4}
\]

- Energy balance at the interface, film flow rate,

\[
\Gamma(L) = \frac{\bar{h}_S(L)(T_W - T_{\text{sat}})L}{h_{LV} + C_{PV}(T_V - T_{\text{sat}})}
\]
FILM FLOW RATE-HEAT TRANSFER COEFFICIENT

• Laminar,
\[ \frac{\bar{h}(L)}{k_L} \left( \frac{\mu_L^2}{\rho_L(\rho_L - \rho_V)} \right)^{\frac{1}{3}} = 1,47 \text{Re}_F^{-\frac{1}{3}} \]

• Wavy laminar and previous regime (Kutateladze, 1963), \( h(z) \propto \text{Re}_F^{0,22} \),
\[ \frac{\bar{h}(L)}{k_L} \left( \frac{\mu_L^2}{\rho_L(\rho_L - \rho_V)} \right)^{\frac{1}{3}} = \frac{\text{Re}_F}{1,08\text{Re}_F^{1,22} - 5,2} \]

• Turbulent and previous regimes (Labuntsov, 1975), \( h(z) \propto \text{Re}_F^{0,25} \),
\[ \frac{\bar{h}(L)}{k_L} \left( \frac{\mu_L^2}{\rho_L(\rho_L - \rho_V)} \right)^{\frac{1}{3}} = \frac{\text{Re}_F}{8750 + 58\text{Pr}_F^{-0,5}\left(\text{Re}_F^{0,75} - 253\right)} \]

• NB: Implicit relation, \( \text{Re}_F \) depends on \( \bar{h}(L) \) through \( \Gamma \).
OTHER MISCELLANEOUS EFFECTS

• Steam velocity, $v_V$, when dominant effect,
• $V_v$ descending flow, vapor shear added to gravity,
• Decreases film thickness,
• Delays transition to turbulence

$$h \propto \tau_i^{\frac{1}{2}}$$

• See for example Delhaye (2008, Ch. 9, p. 370)

• When 2 effects are comparable, $h_1$ stagnant, $h_2$ with dominant shear,

$$h = (h_1^2 + h_2^2)^{\frac{1}{2}}$$
CONDENSATION ON HORIZONTAL TUBES

- Heat transfer coefficient definition,

\[ \bar{h} = \frac{1}{\pi} \int_{0}^{\pi} h(u) du \]

- Stagnant vapor conditions, laminar film, Nusselt (1916)

\[ \bar{h} = 0.728 \left( \frac{k_L^3 \rho_L (\rho_L - \rho_V) g h_{LV}}{\mu_L (T_{sat} - T_p) D} \right)^{\frac{1}{4}} \]

- 0.728, imposed temperature, 0.70, imposed heat flux.

- \( \Gamma \), film flow rate per unit length of tube.
• Film flow rate- heat transfer coefficient, energy balance,

\[
\frac{\bar{h}}{k_L} \left( \frac{\mu_L^2}{\rho_L (\rho_L - \rho_V)} \right)^{\frac{1}{3}} = 1.51 \left( \frac{1}{\text{Re}_F} \right)^{\frac{1}{3}}
\]

(1.47)

• Vapor superheat and transport proprieties, same as vertical wall

• Effect of steam velocity (Fujii),

\[
\frac{\bar{h}}{h_0} = 1.4 \left( \frac{u_V^2 (T_{\text{sat}} - T_P) k_L}{g D h_{LV} \mu_L} \right)^{0.05} \quad 1 < \frac{\bar{h}}{h_0} < 1.7,
\]

• Tube number effect in bundles, (Kern, 1958),

\[
\frac{h(1, N)}{h_1} = N^{-1/6}
\]
DROP CONDENSATION

- Mechanisms,
  - Nucleation at the wall,
  - Drop growth,
  - Coalescence,
  - Dripping down (non wetting wall)

- Technological perspective,
  - Wall doping or coating
  - Clean walls required, fragile
  - Surface energy gradient walls. Self-draining

Condensation and boiling heat transfer
• heat transfer coefficient,

\[
\frac{1}{h} = \frac{1}{h_G} + \frac{1}{h_d} + \frac{1}{h_i} + \frac{1}{h_{co}}
\]

• \(G\): non-condensible gas, \(d\): drop, \(i\): phase change, \(co\) coating thickness.

• Non-condensible gases effect, \(\omega_i \approx 0,02 \Rightarrow h \rightarrow h/5\)

• Example, steam on copper, \(T_{\text{sat}} > 22^\circ\text{C}\), \(h\) in W/cm\(^2\)/\(^\circ\text{C}\),

\[
h_d = \min(0, 5 + 0, 2T_{\text{sat}}, 25)
\]
Nukiyama (1934)

- Only one heat sink, stagnant saturated water,
- Wire NiCr and Pt,
  - Diameter: \( \approx 50 \mu m \),
  - Length: \( l \)
  - Imposed power heating: \( P \)
**BOILING CURVE**

- Imposed heat flux,
  \[ P = q\pi Dl = UI \]

- Wall and wire temperature are equal, \( D \to 0 \)
  \[ R(T) = \frac{U}{I}, \quad \langle T \rangle _3 \approx T_W \]

- Wall super-heat: \( \Delta T = T_W - T_{\text{sat}} \)

- Heat transfer coefficient,
  \[ h \triangleq \frac{q}{T_W - T_{\text{sat}}} \]
HEAT TRANSFER REGIMES

- OA: Natural convection
- AD: Nucleate boiling
- DH: Transition boiling
- HG: Film boiling

Condensation and boiling heat transfer
• Wire energy balance,

\[ MC_v \frac{dT}{dt} = P - qS \]

• Linearize at \( \Delta T_0, q_0, T = T_0 + T_1, \)

\[ MC_v \frac{dT_1}{dt} = P - q_0S - S \frac{\partial q}{\partial \Delta T} T_1 = 0 \]

• Solution, linear ODE,

\[ T_1 = T_{10} \exp(-\alpha t), \quad \alpha = \frac{S}{MC_v} \left( \frac{\partial q}{\partial \Delta T} \right)_{T_0} \]

• 2 stable solutions, one unstable (DH),

\[ \frac{\partial q}{\partial \Delta T} < 0 \]

• Transition boiling, imposed temperature experiments (Drew et Müller, 1937).

Condensation and boiling heat transfer 17/42
NATURAL CONVECTION

- Wire diameter $D$, natural convection

\[ q = h(T_F - T_{sat}), \quad \text{Nu} = \frac{hD}{k} \]

\[ \text{Pr} = \frac{\nu_L}{\alpha_L}, \quad \text{Ra} = \frac{g\beta(T_F - T_{sat})D^3}{\nu_L\alpha_L} \]

- Nusselt number is the non-dimensional heat transfer coefficient ($h$).
- $k_L, \alpha_L, \nu_L$ at the film temperature $\frac{1}{2}(T_F + T_{sat})$, $\beta \approx T_{sat}$.
- Churchill & Chu (1975), $10^{-5} < \text{Ra} < 10^{12}$,

\[ \text{Nu} = \left( 0.60 + \frac{0.387 \text{Ra}^{1/6}}{1 + \left( \frac{0.559}{\text{Pr}} \right)^{9/16}} \right)^2 \]
NATURAL CONVECTION ON A FLAT PLATE

• Scales $A$, $P$, plate area and perimeter. Length scale, $L = \frac{A}{P}$.

\[
Nu = \frac{hL}{k} = \frac{qL}{kL(T_P - T_\infty)}, \quad Ra = \frac{g\beta(T_P - T_\infty)L^3}{\nu_L \alpha_L}
\]

• Two regimes,

\[
Nu = \begin{cases} 
0,560 Ra^{1/4} & \text{if } 1 < Ra < 10^7 \\
(1 + (0,492Pr)^{9/16})^{4/9} & \\
0,14 Ra^{1/3} \left( \frac{1 + 0,0107Pr}{1 + 0,01Pr} \right) & \text{if } 0,024 \leq Pr \leq 2000, \quad Ra < 2 \times 10^{11}
\end{cases}
\]

• Thermodynamic and transport properties Raithby & Hollands (1998). For liquids: all at $T_F = \frac{1}{2}(T_P + T_\infty)$
ONSET OF NUCLEATE BOILING

- Control parameters: $p_L$ et $T_W = T_{L\infty}$
- Super-heated wall: $T_{L\infty} = T_{\text{sat}}(p_L) + \Delta T$
- Site distribution: $r, R = R(r, \theta)$
- Mechanical balance: $p_V = p_L + \frac{2\sigma}{R}$
- Thermodynamic equilibrium:
  $$p_V = p_{\text{sat}}(T_{Li}) \Rightarrow T_{Li} = T_{\text{sat}}(p_V)$$
  $$T_{Li} = T_{\text{sat}}(p_L + \frac{2\sigma}{R}) \approx (T_{L\infty} - \Delta T) + \frac{2\sigma}{R} \frac{dT}{d p_{\text{sat}}}$$
- Heat flux to interface: $q > 0, \dot{R} > 0$

$$q = h(T_{L\infty} - T_{Li}) = h \left(\Delta T - \frac{2\sigma}{R} \frac{dT}{dp_{\text{sat}}} \right)$$

$$\Delta T > \Delta T_{\text{eq}} = \frac{2\sigma}{R} \frac{dT}{dp_{\text{sat}}}, \quad R > R_{\text{eq}} = \frac{2\sigma}{\Delta T} \frac{dT}{dp_{\text{sat}}}$$

1 bar, $\Delta T = 3^\circ C$, $R_{\text{eq}} = 5.2 \mu m$, 155 bar, $\Delta T = 3^\circ C$, $R_{\text{eq}} = 0.08 \mu m$
NUCLEATE BOILING MECHANISMS

- Super-heated liquid transport, Yagumata et al. (1955)
  \[ q \propto (T_P - T_{sat})^{1.2} n^{0.33} \]

- \( n \): active sites number density,
  \[ n \propto \Delta T_{sat}^{5/6} \Rightarrow q \propto \Delta T_{sat}^3 \]

- Very high heat transfer, precision unnecessary.

- Rohsenow (1952), analogy with convective h. t.: \( \text{Nu} = C\text{Re}^a\text{Pr}^b \),

- Scales: \( \text{Re} = \frac{\rho_L V L}{\mu_L} \),
  - Length: detachment diameter, capillary length: \( L \approx \sqrt{\frac{\sigma}{g(\rho_L - \rho_V)}} \)
  - Liquid velocity: energy balance, \( q = \dot{m}h_{LV}, V \approx \frac{q}{\rho_L h_{LV}} \)
    \[ \text{Ja} \triangleq \frac{C_p L (T_P - T_{sat})}{h_{LV}} = C_{sf} \text{Re}^{0.33} \text{Pr}_L^s \]

- \( C_{sf} \approx 0.013, s = 1 \) water, \( s = 1.7 \) other fluids.
BOILING CRISIS, CRITICAL HEAT FLUX

- Flow pattern close to CHF: critical heat flux, Rayleigh-Taylor instability,
- Stability of the vapor column: Kelvin-Helmholtz,
- Energy balance over $A$,

$$
\lambda_T = 2\pi \sqrt{3} \sqrt{\frac{\sigma}{g(\rho_L - \rho_V)}}, \quad \frac{1}{2} \rho_V U_V^2 < \pi \frac{\sigma}{\lambda_H}, \quad qA = \rho_V U_V A_j h_{LV}
$$

Condensation and boiling heat transfer
• Zuber (1958), jet radius $R_J = \frac{1}{4} \lambda_T$, $\lambda_H = 2\pi R_J$, marginal stability,

$$q_{CHF} = 0.12 \rho_v^{1/2} h_{LV} \sqrt[4]{\sigma g (\rho_v - \rho_L)}$$

• Lienhard & Dhir (1973), jet radius $R_J = \frac{1}{4} \lambda_T$, $\lambda_H = \lambda_T$,

$$q_{CHF} = 0.15 \rho_v^{1/2} h_{LV} \sqrt[4]{\sigma g (\rho_v - \rho_L)}$$

• Kutateladze (1948), dimensional analysis and experiments,

$$q_{CHF} = 0.13 \rho_v^{1/2} h_{LV} \sqrt[4]{\sigma g (\rho_v - \rho_L)}$$
Films boiling

- Analogy with condensation (Nusselt, Rohsenow), Bromley (1950), \( V \leftrightarrow L \)

\[
\text{Nu}_L = 0.62 \left( \frac{\rho_V g (\rho_L - \rho_V) h'_{LV} D^3}{\mu_V k_V (T_W - T_{\text{sat}})} \right)^{\frac{1}{4}}, \quad h'_{LV} = h_{LV} \left( 1 + 0.34 \frac{C_{PV} (T_W - T_{\text{sat}})}{h_{LV}} \right)
\]

- Transport and thermodynamical properties:
  - Liquid at saturation \( T_{\text{sat}} \),
  - Vapor at the film temperature, \( T_F = \frac{1}{2}(T_{\text{sat}} + T_W) \).

- Radiation correction: \( T_W > 300^\circ C \), \( \epsilon \): emissivity, \( \sigma = 5.67 \times 10^{-8} \text{ W/m}^2/\text{K}^4 \)

\[
h = h(T < 300^\circ C) + \frac{\epsilon \sigma (T_W^4 - T_{\text{sat}}^4)}{T_W - T_{\text{sat}}}
\]
TRANSITION BOILING

- Minimum flux,

\[ q_{\text{min}} = C h_{LV} \sqrt[4]{\frac{\sigma g (\rho_L - \rho_V)}{\left(\rho_L + \rho_V\right)^2}} \]

- Zuber (1959), \( C = 0.13 \), stability of film boiling,
- Berenson (1960), \( C = 0.09 \), rewetting, Liendenfrost temperature.

- Scarce data in transition boiling,
- Quick fix, \( \Delta T_{\text{min}} \) and \( \Delta T_{\text{max}} \), from each neighboring regime (NB and FB),
- Linear evolution in between (log-log plot!).
Liquid sub-cooling, $T_L < T_{\text{sat}}$, $\Delta T_{\text{sub}} \triangleq T_{\text{sat}} - T_L$

Ivey & Morris (1961)

$$q_{C,\text{sub}} = q_{C,\text{sat}} \left( 1 + 0,1 \left( \frac{\rho_L}{\rho_V} \right)^{3/4} \frac{C_{PL} \Delta T_{\text{sub}}}{h_{LV}} \right)$$
CONVECTIVE BOILING REGIMES

→ Increasing heat flux, constant flow rate →

1. Onset of nucleate boiling
2. Nucleate boiling suppression
3. Liquid film dry-out
4. Super-heated vapor

Condensation and boiling heat transfer
• Regime boundaries depend very much on $z$. Change of variable, $x_{eq}$

• Equilibrium quality, non dimensional mixture enthalpy,

\[
x_{eq} \triangleq \frac{h - h_{Lsat}}{h_{LV}}
\]

• Energy balance, low velocity, stationary flows,

\[
M \frac{dh}{dz} = Mh_{LV} \frac{dx_{eq}}{dz} = qP
\]

• Uniform heat flux, $x_{eq}$ linear in $z$. Close to equilibrium, $x_{eq} \approx x$

• According to the assumptions of the HEM,

\[
0 > x_{eq} \quad \text{single-phase liquid (sub-cooled)}
\]
\[
0 < x_{eq} < 1 \quad \text{two-phase, saturated}
\]
\[
1 < x_{eq} \quad \text{single-phase vapor (super-heated)}
\]
Boiling flow description

- Constant heat flux heating,
- Fluid temperature evolution, \( T_{\text{sat}} \),
- Wall temperature measurement,
- Flow regime,
- Heat transfer controlling mechanism.
From the inlet, flow and heat transfer regimes,

- Single-phase convection
- Onset of nucleate boiling, ONB
- Onset of significant void, OSV
- Important points for pressure drop calculations, flow oscillations.
- Nucleate boiling suppression,
- Liquid film dry-out, boiling crisis (I),
- Single-phase vapor convection.
DO: dry-out, DNB: departure from nucleate boiling (saturated, sub-cooled), PDO: post dry-out, sat FB: saturated film boiling, Sc Film B: sub-cooled film boiling
BOILING SURFACE

Condensation and boiling heat transfer

Condensation and boiling heat transfer 34/42
SINGLE-PHASE FORCED CONVECTION

• Forced convection (Dittus & Boelte, Colburn), $\text{Re} > 10^4$,

$$\text{Nu} \triangleq \frac{hD}{k_L} = 0.023\text{Re}^{0.8}\text{Pr}^{0.4}, \quad \text{Re} = \frac{GD}{\mu_L}, \quad \text{Pr}_L = \frac{\mu_L C_{PL}}{k_L}$$

• Fluid temperature, $T_F$, mixing cup temperature, that corresponding to the area-averaged mean enthalpy.

• Transport properties at $T_{av}$
  - Local heat transfer coefficient,

$$q \triangleq h(T_W - T_F), \quad T_{av} = \frac{1}{2}(T_W + T_F)$$

  - Averaged heat transfer coefficient (length $L$),

$$\bar{q} \triangleq \bar{h}(\bar{T}_W - \bar{T}_F), \quad \bar{T}_F = \frac{1}{2}(T_{Fin} + T_{Fout}), \quad T_{av} = \frac{1}{2}(\bar{T}_W + \bar{T}_F)$$

• Always check the original papers...
Onset and suppression of nucleate boiling, ONB, (Frost & Dzakowic, 1967),

\[ T_P - T_{\text{sat}} = \left( \frac{8\sigma q T_{\text{sat}}}{k_L \rho_V h_{LV}} \right)^{0.5} \text{Pr}_L \]

Onset of significant void, OSV, (Saha & Zuber, 1974)

\[ \text{Nu} = \frac{qD}{k_L(T_{\text{sat}} - T_L)} = 455, \quad \text{Pé} < 7 \times 10^4, \quad \text{thermal regime} \]

\[ \text{St} = \frac{q}{G C_{PL}(T_{\text{sat}} - T_L)} = 0.0065, \quad \text{Pé} > 7 \times 10^4, \quad \text{hydrodynamic regime} \]
DEVELOPPED BOILING AND CONVECTION

• Weighting of two mechanisms, \( x_{eq} > 0 \) (Chen, 1966)
  – Nucleate boiling (Forster & Zuber, 1955), \( S \), suppression factor, same model for pool boiling,
  – Forced convection, Dittus Boelter, \( F \), amplification factor,

\[
h = h_{FZ}S + h_{DB}A
\]

\[
\frac{1}{S} = 1 + 2.53 \times 10^{-6} (ReF^{1.25})^{1.17}, \quad F = \begin{cases} 
1 & 1/X \leq 0.1 \\
2.35(1/X + 0.213)^{0.736} & 1/X > 0.1
\end{cases}
\]
CHEN CORRELATION (CT’D)

• Nucleate boiling,

\[ h_{FZ} = 0.00122 \frac{k_L^{0.79} C_{pL}^{0.45} \rho_L^{0.49}}{\sigma \mu_L^{0.29} h_{LV}^{0.24} \rho_V^{0.24}} (T_W - T_{sat})^{0.24} \Delta p_{sat}^{0.75} \]

• Forced convection

\[ h_{DB} = 0.023 \frac{k_L}{D} \text{Re}^{0.8} \text{Pr}_L^{0.4} \]

• From Clapeyron relation, slope of saturation line,

\[ \Delta p_{sat} = \frac{h_{LV} (T_W - T_{sat})}{T_{sat} (\nu_V - \nu_L)} \]

• Non dimensional numbers definitions,

\[ \text{Re} = \frac{GD(1 - x_{eq})}{\mu_L}, \quad X = \left( \frac{1 - x_{eq}}{x_{eq}} \right)^{0.9} \left( \frac{\rho_V}{\rho_L} \right)^{0.5} \left( \frac{\mu_L}{\mu_V} \right)^{0.1}, \quad \text{Pr}_L = \frac{\mu_L C_{pL}}{k_L} \]

• NB: implicit in \((T_W - T_{sat})\).
CRITICAL HEAT FLUX

• No general model.
  – Dry-out, multi-field modeling
  – DNB, correlations or experiment in real bundles
• Very sensitive to geometry, mixing grids,
• Recourse to experiment is compulsory,
• In general, $q_{CHF}(p, G, L, \Delta H_i, ...)$, artificial reduction of dispersion.
• For tubes and uniform heating, no length effect, $q_{CHF}(p, G, x_{eq})$
  – Tables by Groenveld,
  – Bowring (1972) correlation, best for water in tubes
  – Correlation by Katto & Ohno (1984), non dimensional, many fluids, regime identification.
After Groeneveld & Snoek (1986), tube diameter, $D = 8$ mm.

- Generally decreases with the increase of the exit quality. $q_{CHF} \to 0$, $x_{eq} \to 1$.
- Generally increases with the increase of the mass flux,
- CHF is non monotonic with pressure.
MORE ON HEAT TRANSFER

• Boiling and condensation,
  – Delhaye (1990)
  – Delhaye (2008)
  – Roshenow et al. (1998)
  – Collier & Thome (1994)
  – Groeneveld & Snoek (1986)

• Single-phase,
  – Bird et al. (2007)
  – Bejan (1993)
REFERENCES


