Transport processes

7. Semester
Chemical Engineering
Civil Engineering
Course plan

1. Elementary Fluid Dynamics
2. Fluid Kinematics
3. Finite Control Volume Analysis
4. Differential Analysis of Fluid Flow
5. Viscous Flow and Turbulence
6. Turbulent Boundary Layer Flow
7. Principles of Heat Transfer
8. Internal Forces Convection
9. Unsteady Heat Transfer
10. Boiling and Condensation
11. Mass Transfer
12. Porous Media Flow
13. Non-Newtonian Flow
Today's lecture

- Boiling and Condensation
  - Pool boiling
  - Bubble dynamics
  - Flow boiling
  - Nucleate boiling
  - Film boiling
  - Film condensation
  - Heat pipes
Boiling and condensation

- Heat and mass transfer
- Multiphase flow
- Boiling
- Fluid dynamics
Boiling heat transfer

- **Evaporation** occurs at the *liquid–vapor* interface when the vapor pressure is less than the saturation pressure of the liquid at a given temperature.

- **Boiling** occurs at the *solid–liquid interface* when a liquid is brought into contact with a surface maintained at a temperature sufficiently above the saturation temperature of the liquid.
About saturation pressure and temperature
Terminology

$$\Delta T_{\text{excess}} = T_w - T_{\text{sat}}$$
Classification of boiling

- **Pool boiling**
  - Absence of bulk fluid flow
  - Any fluid motion due to natural convection

- **Flow boiling**
  - Boiling with bulk fluid motion
Classification of boiling

• Sub-cooled boiling
  – Boiling where the bulk fluid temperature is below the saturation temperature

• Saturated boiling
  – Boiling where the bulk fluid temperature equals the saturation temperature
Classification of boiling

- Nucleation boiling
  - Bubbles form at nucleation sites on the surface

- Film boiling
  - The surface is completely covered with a stable vapor film
Overview of boiling

Subcooled / local boiling

\[ T_{sat} < T_{bulk} \]

Saturated / bulk boiling

\[ T_{sat} = T_{bulk} \]

Pool boiling

Free convection

Nucleation boiling

(Nucleation boiling)

transition boiling, Leidenfrost effect

Film boiling

flow boiling

Forced convection

Nucleation boiling

Nucleation boiling

Convective boiling (internal)

Film boiling (external)
Experiments in (pool)boiling

• Heating element in water tank
  – Controlled heat flux
  – Visual observations
  – Temperature measurements
Pool boiling

Natural convection boiling

Nucleate boiling

Transition boiling

Film boiling

\[ \dot{q}_{\text{boiling}} = \text{W/m}^2 \]

\[ \Delta T_{\text{excess}} = T_s - T_{\text{sat}}, ^\circ C \]

A-C

Bubbles collapse in the liquid

Bubbles rise to the free surface

Maximum (critical) heat flux, \( \dot{q}_{\max} \)

Leidenfrost point, \( \dot{q}_{\min} \)

(a) Natural convection

(b) Nucleate boiling

(c) Transition boiling

(d) Film boiling
Nucleation boiling

- Liquid slightly superheated
- Bubbles form at cavitations
- Bubble growth is related to the heat supply
- Bubbles detach when buoyancy forces exceed surface tension
- Vacated space are filled with liquid again
- At higher $T_w$ bubbles form continues columns of vapor

\[ R_{\text{Bubble}} \approx 0.005 \left( \frac{\sigma}{g (\rho_L - \rho_v)} \right)^{1/2} \]
Transition boiling

- At some point the liquid has difficulties reaching the heating surface \( \rightarrow \) Critical/maximum heat flux

- Heat flux decreases as \( T_W \) is increased further

- Surface is now partly covered with vapor film

- The point of minimum heat flux is called the Leidenfrost point
Film boiling

- The heater surface is completely covered by a continuous stable vapor film

- The presence of a vapor film between the heater surface and the liquid is responsible for the low heat transfer rates in the film boiling region.

- The heat transfer rate increases with increasing excess temperature (due to radiation to the liquid at high surface temperatures)
Actual boiling

- Vapor film drastically decreases heat transfer
- Heat cannot move to the liquid and therefore heats the surface material!
- “Burnout” phenomenon
- At some point the heat transfer increases again → film boiling
Heat transfer correlations

- Empirical correlations only
- Surface condition can significantly increase heat transfer
- Peak heat flux is usually crucial

- Be aware of the accuracy, some of these correlations have an accuracy of ±100%
Heat transfer correlations – Pool boiling

- Natural convection boiling regime $\rightarrow$ use natural convection relations

- Nucleate boiling $\rightarrow$ correlation by Rohsenow independent on geometry
  - (look next page)

- Film boiling $\rightarrow$ look in appropriate literature (often not important)

- Critical heat flux:

  \[ \dot{q}_{\text{max}} = C_{\text{cr}} h_{fg} \left[ \sigma g \rho_v^2 (\rho_l - \rho_v) \right]^{1/4} \]

- Minimum Heat flux:

  \[ \dot{q}_{\text{min}} = 0.09 \rho_v h_{fg} \left[ \frac{\sigma g (\rho_l - \rho_v)}{(\rho_l + \rho_v)^2} \right]^{1/4} \]

<table>
<thead>
<tr>
<th>Heater Geometry</th>
<th>$C_{\text{cr}}$</th>
<th>Charac. Dimension of Heater, $L$</th>
<th>Range of $L^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large horizontal flat heater</td>
<td>0.149</td>
<td>Width or diameter</td>
<td>$L^* &gt; 27$</td>
</tr>
<tr>
<td>Small horizontal flat heater$^1$</td>
<td>18.9$K_1$</td>
<td>Width or diameter</td>
<td>$9 &lt; L^* &lt; 20$</td>
</tr>
<tr>
<td>Large horizontal cylinder</td>
<td>0.12</td>
<td>Radius</td>
<td>$L^* &gt; 1.2$</td>
</tr>
<tr>
<td>Small horizontal cylinder</td>
<td>0.12$L^*-0.25$</td>
<td>Radius</td>
<td>$0.15 &lt; L^* &lt; 1.2$</td>
</tr>
<tr>
<td>Large sphere</td>
<td>0.11</td>
<td>Radius</td>
<td>$L^* &gt; 4.26$</td>
</tr>
<tr>
<td>Small sphere</td>
<td>0.227$L^*-0.5$</td>
<td>Radius</td>
<td>$0.15 &lt; L^* &lt; 4.26$</td>
</tr>
</tbody>
</table>

$^1K_1 = \sigma g (\rho_l - \rho_v) A_{\text{heated}}$
\[ q_{\text{nucleate}} = \mu_l h_{fg} \left[ \frac{g (\rho_l - \rho_v)}{\sigma} \right]^{1/2} \left[ \frac{C_p (T_s - T_{\text{sat}})}{C_{sf} h_{fg} \Pr_l^n} \right] \]

**Values of the coefficient $C_{sf}$ and $n$ for various fluid–surface combinations**

<table>
<thead>
<tr>
<th>Fluid–Heating Surface Combination</th>
<th>$C_{sf}$</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water–copper (polished)</td>
<td>0.0130</td>
<td>1.0</td>
</tr>
<tr>
<td>Water–copper (scored)</td>
<td>0.0068</td>
<td>1.0</td>
</tr>
<tr>
<td>Water–stainless steel (mechanically polished)</td>
<td>0.0130</td>
<td>1.0</td>
</tr>
<tr>
<td>Water–stainless steel (ground and polished)</td>
<td>0.0060</td>
<td>1.0</td>
</tr>
<tr>
<td>Water–stainless steel (teflon pitted)</td>
<td>0.0058</td>
<td>1.0</td>
</tr>
<tr>
<td>Water–stainless steel (chemically etched)</td>
<td>0.0130</td>
<td>1.0</td>
</tr>
<tr>
<td>Water–brass</td>
<td>0.0060</td>
<td>1.0</td>
</tr>
<tr>
<td>Water–nickel</td>
<td>0.0060</td>
<td>1.0</td>
</tr>
<tr>
<td>Water–platinum</td>
<td>0.0130</td>
<td>1.0</td>
</tr>
<tr>
<td>$n$-Pentane–copper (polished)</td>
<td>0.0154</td>
<td>1.7</td>
</tr>
<tr>
<td>$n$-Pentane–chromium</td>
<td>0.0150</td>
<td>1.7</td>
</tr>
<tr>
<td>Benzene–chromium</td>
<td>0.1010</td>
<td>1.7</td>
</tr>
<tr>
<td>Ethyl alcohol–chromium</td>
<td>0.0027</td>
<td>1.7</td>
</tr>
<tr>
<td>Carbon tetrachloride–copper</td>
<td>0.0130</td>
<td>1.7</td>
</tr>
<tr>
<td>Isopropanol–copper</td>
<td>0.0025</td>
<td>1.7</td>
</tr>
</tbody>
</table>

- Look in the multiphase flow handbook for more correlations
Flow boiling

- In *flow boiling*, the fluid is forced to move by an external source such as a pump as it undergoes a phase-change process.
- Convection in addition to boiling.
- Flow boiling in tubes is of prime importance in industrial boilers.
Industrial boilers
Vertical pipe flow map

- Superficial velocity

\[ j_v = \frac{m_v}{\rho_v A_c} \quad j_l = \frac{m_l}{\rho_l A_c} \]

\[ j = j_v + j_l \]
Strong coupling with flow pattern and heat transfer

Burnout
Superposition?

- Mechanism gradually changes from forced convection to nucleate boiling
Effect of liquid velocity

- Forced convection heat transfer coefficient increases with velocity
- Nucleate boiling line remains constant
- At high velocities nucleate boiling only begins to dominate at a large value of $\Delta T_{\text{excess}}$
Temperatures in flow boiling

Temperature

\( T_{\text{sat}} \)

\( x_T = 0 \)

Liquid in centre of tube

Dryout (burnout) occurs

\( x_T = 1 \)

Vapour in centre of tube

Last liquid drops evaporate

Distance

\( T_{\text{wall}} \)

\( T_{\text{fluid}} \)
Assumed types of boiling inside tubes

- **Nucleate boiling** – bubbles formed at subcooled conditions

- **Convective boiling** – heat is transferred through a thin liquid film. Evaporation takes place at the fluid vapor interface

  - Both types can coexist
  - Convective boiling gradually supplants nucleation boiling
Heat transfer coefficients

- Single phase forced convection $h \approx \text{cst}$

- Subcooled nucleation boiling $h = f(T_{\text{bulk}})$

- Saturated nucleation $h \approx \text{cst}$

- Convective boiling $h = f(x)$
Heat transfer coefficients

• Method by Chen 1963 (saturated boiling)

\[ h_{tot} = h_{NB} + h_{FC} \]

Nucleate boiling

Forced convection

\[ h_{NB} = S \cdot h_{FZ} \]

\[ h_{FC} = F \cdot h_{L} \]

- **S** = suppression factor → decreases as quality increases

- **F** = two-phase multiplier → function of the Martinelli-parameter

- **h\textsubscript{FZ}** = heat transfer coefficient by Forster-Zuber for nucleate boiling

- **h\textsubscript{L}** = single phase heat transfer coefficient based on mass flow of liquid
• Nucleate boiling correlation

\[
h_{FZ} = \frac{0.00122 \Delta T_{\text{sat}}^{0.24} \Delta P_{\text{sat}}^{0.75} C_{P,L}^{0.45} \rho_L^{0.49} k_L^{0.79}}{\sigma^{0.5} \lambda^{0.24} \mu_L^{0.29} \rho_G^{0.24}}
\]

\[\Delta T_{\text{sat}} = T_W - T_{\text{sat}}\]

\[C_{P,L} = \text{liquid specific heat}\]

\[k_L = \text{thermal conductivity}\]

\[\lambda = \text{latent heat of evaporation, } (h_{fg})\]
Correction factors $F$ and $S$

\[
\text{Re}_{TP} = \text{Re}_L F^{1.25}, \quad \text{Re}_L = \frac{G(x-1)d}{\mu_L}
\]
Martinelli parameter

- Superficial liquid Fanning friction factor $f_{SL} = F(Re_{SL}, k/D)$ (calculated from Eqs. [2.3] and [2.4] or derived from Figure 2.2)
- Superficial gas Fanning friction factor $f_{SG} = F(Re_{SG}, k/D)$ (calculated from Eqs. [2.3] and [2.4] or derived from Figure 2.2)
- Liquid Froude number
  \[ F_L = \left( \frac{\rho_L}{\Delta \rho g D} \right)^{1/2} u_{SL} \]
  \( \Delta \rho = \rho_L - \rho_G, \ g = 9.81 \text{ m/s}^2 \)
- Gas Froude number
  \[ F_G = \left( \frac{\rho_G}{\Delta \rho g D} \right)^{1/2} u_{SG} \]
- Lockhart–Martinelli parameter
  \[ X = \left( \frac{f_{SL}}{f_{SG}} \right)^{1/2} \frac{F_L}{F_G} \]
Heat flux, $\phi$

- Saturated boiling (two-phase, $T_{\text{Bulk}} = T_{\text{sat}}$)

$$\phi = h_{\text{tot}} (T_W - T_{\text{Bulk}}) = F \cdot h_L (T_W - T_{\text{Bulk}}) + S \cdot h_{NB} (T_W - T_{\text{sat}})$$

- Subcooled boiling ("single-phase", $T_{\text{Bulk}} < T_{\text{sat}}$)

$$\phi = h_L (T_W - T_{\text{Bulk}}) + h_{NB} (T_W - T_{\text{sat}})$$
Critical heat flux in flow boiling

- Critical heat flux in flow boiling
  - Different terminology referring to the same phenomenon
  - Burnout
  - Dryout
  - CHF – critical heat flux
  - DNB – departure from nucleate boiling
  - Boiling crisis
Influences on the critical heat flux (uniformly heated tube)

1. $\phi_c$ increases with increasing inlet subcooling
2. $\phi_c$ increases with increasing mass flux and tube diameter
3. $\phi_c$ decreases with increasing tube length
4. $\phi_c$ passes through a maximum at around 70 bar pressure
Forms of $\phi_c$ correlations

1. $\phi_c$ as function of the quality at which the critical conditions occur
   - suggest a local condition

2. $\phi_c$ as function of the pipe length
   - suggest a integral condition

- Heat balance over a uniformly heated pipe gives:

$$\pi d L_B \phi_c = \frac{\pi d^2}{4} G \lambda x_c$$

- Correlations contain the same amount of information
Calculation of $\phi_c$

- General form

$$\phi_c = f(x \text{ or } L, p, G, \Delta h_s, \lambda, d)$$

- Correlations or tabular methods

- Steam/water or general expressions

- Bowring 1972 correlation

$$\phi_c = \frac{A + B\Delta h_s}{C + L}$$

A, B, C functions of p, $\lambda$, d and G
Uniform heated tubes

(a) \( \phi_c \) Correlation

(b) Heat balance

(c) Eliminate \( x \)

(d) Actual heat flux (uniform)

(e) \( \phi, \phi_c, \phi_c, \phi \)
Non-uniform heating
Boiling literature

- Other sources of information:
  - Boiling, Condensation and Gas-Liquid flow by Whalley
  - One-dimensional two-phase flow by Wallis
  - Convective boiling and condensation by Collier
  - Fluent Users Guide (the VOF model)
  - Bubbles, drops, and particles by Clift, Grace and Weber (bubble bible)
  - Multiphase flows with droplets and particles by Crowe, Tsuji and Sommerfeld (primarily for particle flows)
  - Heat and mass transfer by Mills (lots of useful equations)
  - Multiphase flow handbook (e-book)
  - Fundamentals of Multiphase flow by Brennen (e-book)
Condensation

- Film condensation
  - Continuous film on the surface
  - Heat transfer from vapor through film to surface

- Drop wise condensation
  - Drops form from nucleation sites
  - Individual drop run off surface
  - Heat conducted from steam directly to surface
  - Higher heat transfer coefficient
Condensation on a vertical plate

- Liquid forms and run down under the influence of gravity:
  \[ \text{Re} = \frac{4 \delta \rho_L V_L}{\mu_L} \]

- Heat is released due to condensation \( (h_{fg}) \) and cooling of the condensate:
  \[ h_{fg}^* = h_{fg} + 0.68 C_{p,L} (T_{sat} - T_W) \]

- Liquid properties should be evaluated at the film temperature
  \[ T_{film} = \frac{(T_{sat} - T_W)}{2} \]

- Heat transfer can be expressed as
  \[ \dot{Q}_{\text{cond}} = h A_S (T_{sat} - T_W) = \dot{m} h_{fg}^* \]
Important considerations

- Ripples on the film increase the surface area and thus heat transfer to the film
- Shear force exerted by the flowing vapor on the liquid film can either increase or decrease the film thickness and thus decrease or increase the heat transfer
- Turbulence inside the film increase the heat transfer through the film
- Incondensable gasses inside the liquid film may decrease the heat transfer coefficient
• Flow regimes
  – Laminar \( Re < 30 \)
  – Wavy \( 30 < Re < 1800 \)
  – Turbulent \( Re > 1800 \)
Correlations

\[
Re = \frac{4g\rho_1 (\rho_v - \rho_c) \delta^3}{3\mu_f^2} = \frac{4g\rho_1^2}{3\mu_f^2} \left( \frac{k_i}{h_{v-1}} \right)^3 = \frac{4g}{3v_f^2} \left( \frac{k_i}{3h_{v-1}/4} \right)^3
\]

\[
Re_{v, \text{wavy}} = \left[ 4.81 + \frac{3.70 Lk_f (T_{sat} - T_s)}{\mu_i h_f^2} \left( \frac{g}{v_f^2} \right)^{1/3} \right]^{10.20}, \rho_v \ll \rho_i
\]

\[
Re_{v, \text{turbulent}} = \left[ \frac{0.0690 Lk_f \Pr^{0.5} (T_{sat} - T_s)}{\mu_i h_f^2} \left( \frac{g}{v_f^2} \right)^{1/3} - 151 \Pr^{0.5} + 253 \right]^{4/3}
\]

\[
h_{v-1} = 0.943 \left[ \frac{g\rho_1 (\rho_v - \rho_c) h_f k_i}{\mu_i (T_{sat} - T_s) R_c} \right]^{1/4}
\]

(h/W/m²·°C), 0 < Re < 30

\[
h_{v, \text{wavy}} = \frac{Re k_i}{1.08 \text{Re}^{0.22} - 5.2 \left( \frac{g}{v_f^2} \right)^{1/3}}, \quad 30 < Re < 1800, \rho_v \ll \rho_i
\]

\[
h_{v, \text{turbulent}} = \frac{Re k_i}{8750 + 58 \Pr^{0.5} \left( \text{Re}^{0.75} - 253 \right) \left( \frac{g}{v_f^2} \right)^{1/3}}, \rho_v \ll \rho_i
\]
Heat pipes

- Specified fluid and pressure depend on *operating temperature*
- High surface tension is desired
Operation of a heat pipe

– A given liquid at a specific pressure will vaporize at the saturation temperature
– The heat absorbed from evaporation is equal to the heat rejected from condensation
– The capillary pressure inside the wick move liquid against gravity
– A fluid in a channel flow in the direction of decreasing pressure
Wick

- Material: stainless steel or ceramics
- Optimal pore size: capillary force > friction force
- Wick thickness $\rightarrow$ orientation
Excercises

Well, He Couldn’t Do Any Worse than The Last Guy
• Surface tension
  – Fundamental property of liquids
  – Behave as hypothetical “skin or a membrane”
  – Attractive force between the liquids molecules
  – Force balance on droplet in equilibrium:

\[
2\pi R \sigma = \Delta p \pi R^2 \quad \text{or} \quad \Delta p = \frac{2\sigma}{R}
\]

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Surface Tension (N/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>0.466</td>
</tr>
<tr>
<td>Water</td>
<td>0.0734</td>
</tr>
<tr>
<td>Engine oil</td>
<td>0.036</td>
</tr>
<tr>
<td>Gasoline</td>
<td>0.022</td>
</tr>
</tbody>
</table>
• **Capillary tube**
  
  – The attraction between wall and molecules can be stronger than the force between molecules
  – The liquid is said to “wet” the surface
  – The angle of contact, $\theta$, between the fluid and tube depend on both the liquid and the surface.
  
  – Force balance:
    
    $$\rho g \pi R^2 h = 2\pi R \sigma \cos \theta$$
    
    or
    
    $$h = \frac{2\sigma \cos \theta}{\rho g R}$$