5. Boiling and Condensation

Evaporation, \( P < P_{sat} \), no bubbles

Boiling, \( T > T_{sat} \), vapor bubbles

**Figure 1** A liquid-to-vapor phase change process is called evaporation if it occurs at a liquid–vapor interface and boiling if it occurs at a solid–liquid interface.

**Boiling Heat Flux:**

\[
\dot{q}_{boiling} = h(T_s - T_{sat}) = h \Delta T_{excess}
\]

(a) Pool Boiling

(b) Flow Boiling

**Figure 2** Classification of boiling on the basis of the presence of bulk fluid motion.

(a) Subcooled (Local) Boiling

(b) Saturated (Bulk) Boiling

**Figure 3** Classification of boiling on the basis of the presence of bulk liquid temperature.
Pool Boiling:

Natural Convection Boiling (to Point A on the Boiling Curve)

Nucleate Boiling (between Points A and C)

(b) Nucleate boiling of methanol on a horizontal 1-cm-diameter steam-heated copper tube.

Figure 4 typical boiling curves for water at 1 atm pressure.

Figure 5 Natural Convection Boiling.

Figure 6 Nucleate Boiling
**Transition Boiling** (between Points $C$ and $D$ on the Boiling Curve)

![Transition Boiling Image](image1.png)

(a) Transition boiling of methanol on a horizontal 1-cm-diameter steam-heated copper tube.

**Figure 7** Transition Boiling

**Film Boiling** (beyond Point $D$)

![Film Boiling Image](image2.png)

(b) Film boiling of methanol on a horizontal 1-cm-diameter steam-heated copper tube.

**Figure 8** Film Boiling

**Enhancement of Heat Transfer in Pool Boiling:**

![Enhancement Image](image3.png)

(a) The cavities on a rough surface

(b) a mechanically roughened surface

**Figure 10** The enhancement of boiling heat transfer.
Flow Boiling:
- Internal and external flow boiling

Figure 11 The effect of forced convection on external flow boiling for different flow velocities.

Figure 12 Different flow regimes encountered in flow boiling in a tube under forced convection.
Condensation Heat Transfer:

Figure 13 When a vapor is exposed to a surface at a temperature below $T_{\text{sat}}$, condensation in the form of a liquid film or individual droplets occurs on the surface.

Reynolds Number:

$$Re = \frac{D_h \rho_l V_l}{\mu_l} = \frac{4 A_c \rho_l V_l}{p \mu_l} = \frac{4 A_c \rho_l \delta}{p \mu_l} = \frac{4 \dot{m}}{p \mu_l}$$

where

- $D_h = 4A_c/p = 4\delta$ hydraulic diameter of the condensate flow, m
- $p$ = wetted perimeter of the condensate, m
- $A_c = p\delta$ = wetted perimeter × film thickness, m$^2$
- cross-sectional area of the condensate flow at the lowest part of the flow
- $\rho_l$ = density of the liquid, kg/m$^3$
- $\mu_l$ = viscosity of the liquid, kg/m s
- $V$ = average velocity of the condensate at the lowest part of the flow, m/s
- $\dot{m} = \rho_l V_l A_c$ = mass flow rate of the condensate at the lowest part, kg/s
Figure 15 The wetted perimeter $p$, the condensate cross-sectional area $A_c$, and the hydraulic diameter $D_h$ for some common geometries.

(a) Vertical plate

Vertical cylinder

Horizontal cylinder

(a) Vertical plate

(b) Vertical cylinder

(c) Horizontal cylinder

Figure 16 Flow regimes during film condensation on a vertical plate.

$$\begin{align*}
\text{Flow Regimes:} & \\
& \begin{cases}
\text{Re} \leq 30 & \text{laminar (wave-free)} \\
30 < \text{Re} < 1800 & \text{laminar (wavy)} \\
\text{Re} > 1800 & \text{turbulent}
\end{cases}
\end{align*}$$
Film Condensation inside Horizontal Tubes:

![Diagram of condensation in a horizontal tube](image)

**Figure 17** Condensate flow in a horizontal tube with large vapor velocities.

Dropwise Condensation:

![Image of dropwise condensation](image)

**Figure 18** Dropwise condensation of steam on a vertical surface. Dropwise condensation is achieved

**Notes:**
1. Heat transfer rates that are more than 10 times larger than those associated with film condensation can be achieved with dropwise condensation as there is no liquid film in this case to resist heat transfer.
2. Dropwise condensation is achieved by *adding* a promoting chemical into the vapor, *treating* the surface with a promoter chemical, or *coating* the surface with a polymer such as teflon or a noble metal such as gold, silver, rhodium, palladium, or platinum. The *promoters* used include various waxes and fatty acids such as oleic, stearic, and linoic acids.