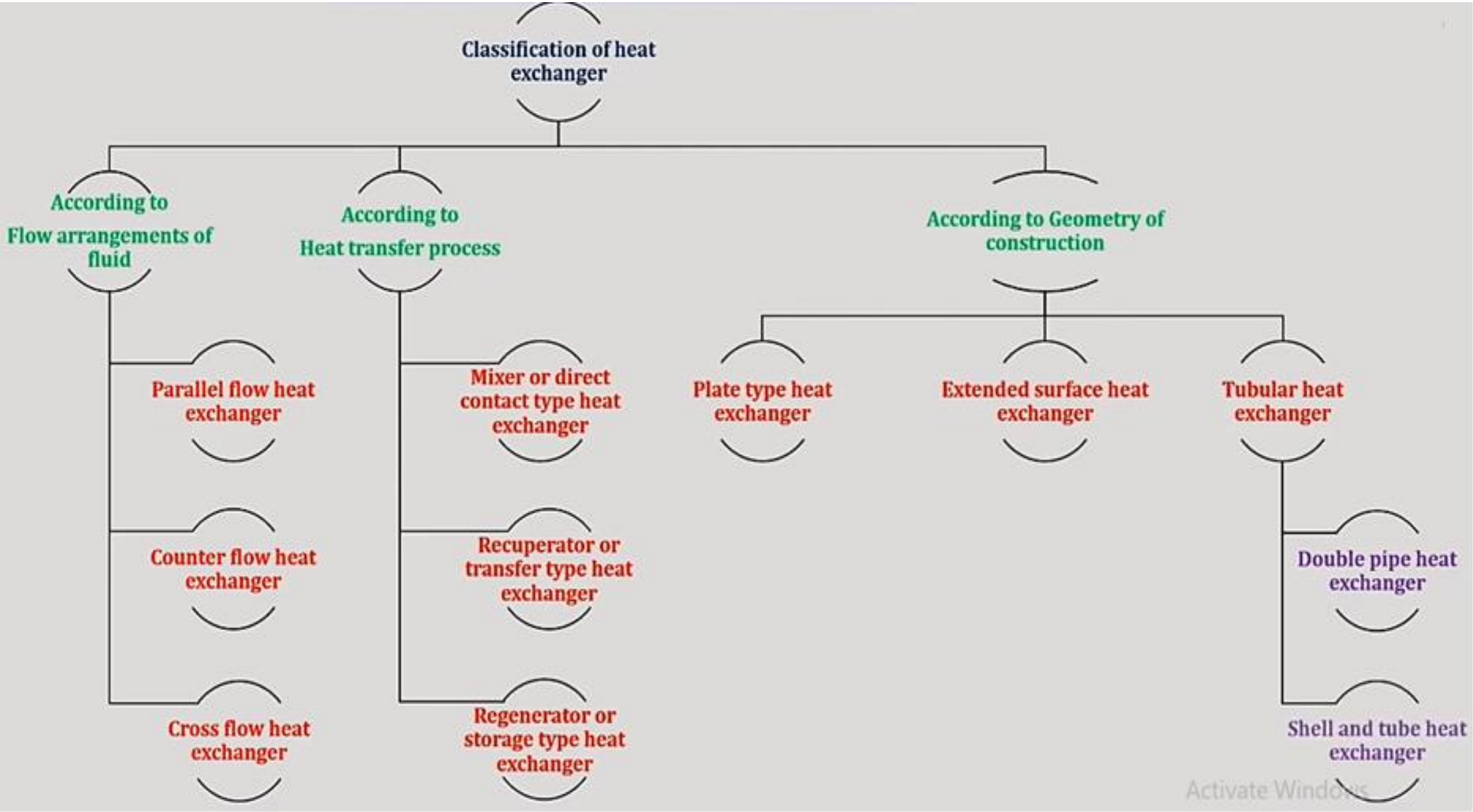
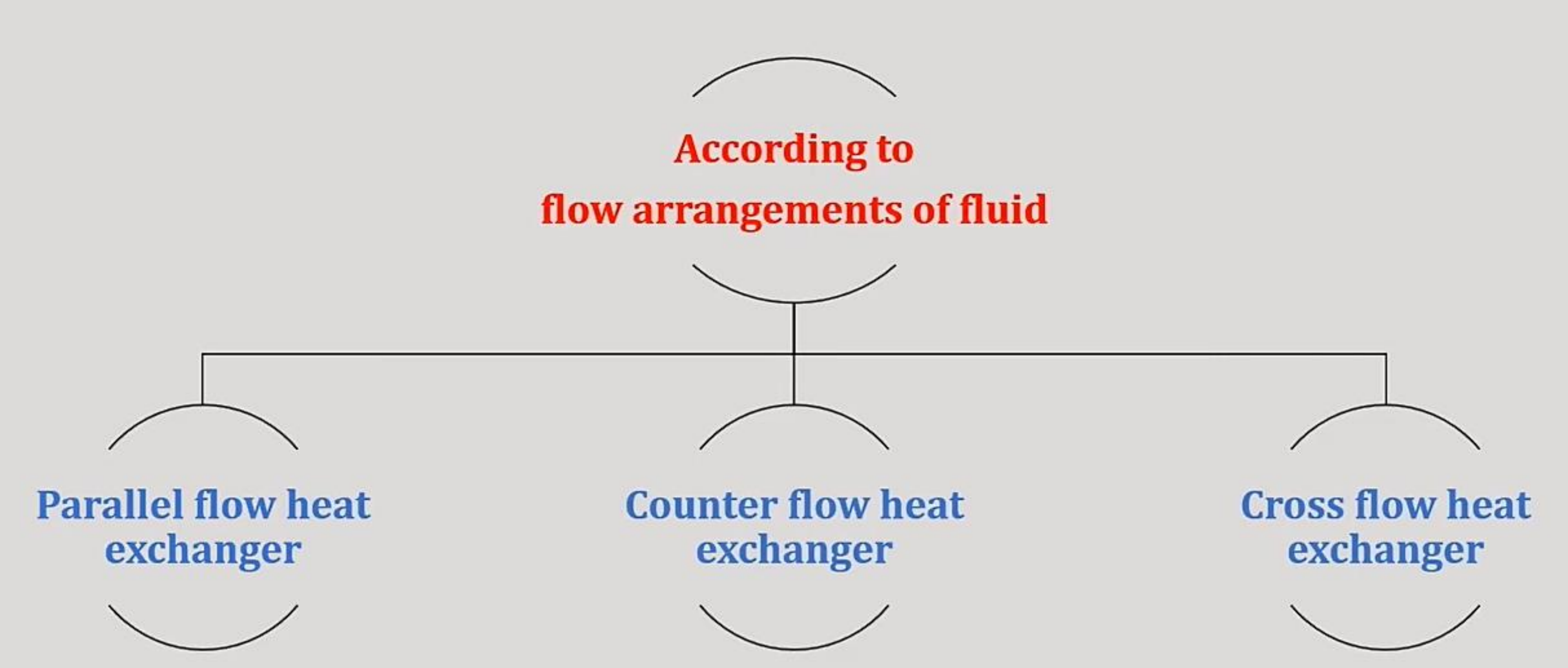
UNIT-IV Heat Exchangers

Heat exchanger is a device used for transfer to heat from a high temperature fluid to low temperature fluid, with both the fluids moving through the same device

Examples:-

1. Boilers
2. Evaporator and condenser of refrigeration system
3. Water and air coolers or heaters
4. Radiators of automobiles
5. Oil coolers of heat engine
6. Regenerator of gas turbine power plants


Classification of heat exchanger
According to Flow arrangements of fluid
According to Heat transfer process
According to Geometry of construction
Parallel flow heat exchanger
Counter flow heat exchanger
Cross flow heat exchanger
Mixer or direct contact type heat exchanger
Recuperator or transfer type heat exchanger
Regenerator or storage type heat exchanger
Plate type heat exchanger
Extended surface heat exchanger
Tubular heat exchanger
Double pipe heat exchanger
Shell and tube heat exchanger

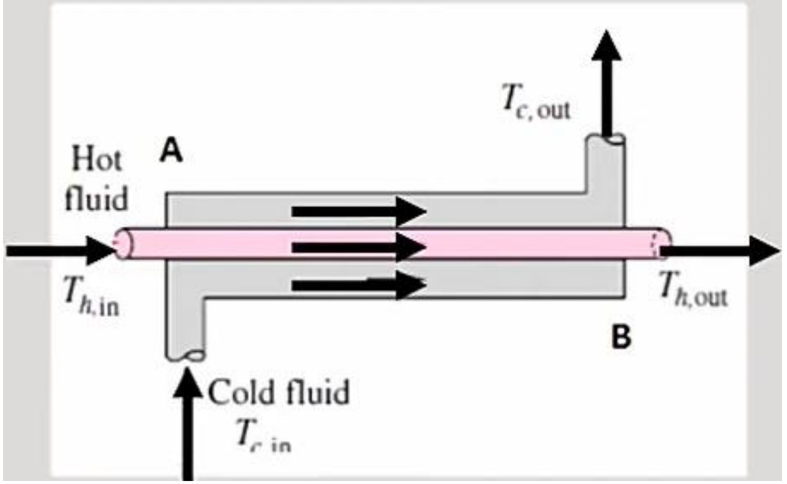


According to
flow arrangements of fluid

- Parallel flow heat exchanger
- Counter flow heat exchanger
- Cross flow heat exchanger

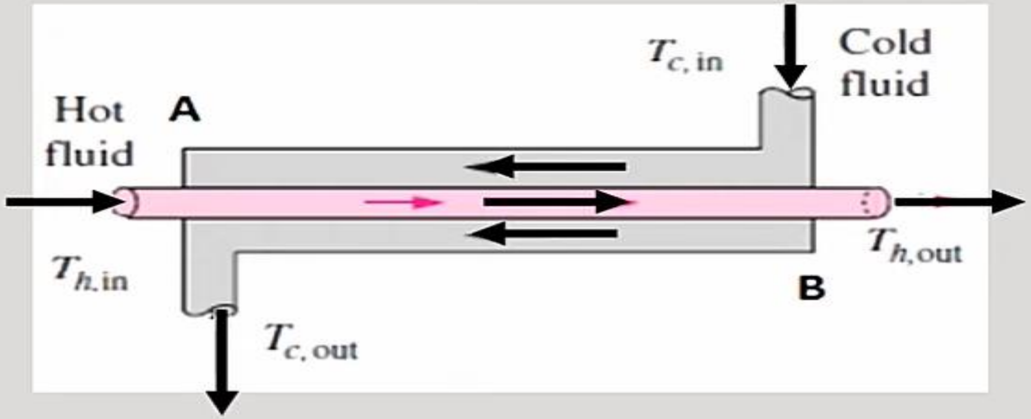
Parallel flow heat exchanger

- In parallel flow heat exchangers both hot and cold streams enter the heat exchanger at the same end and travel to the opposite end in parallel streams



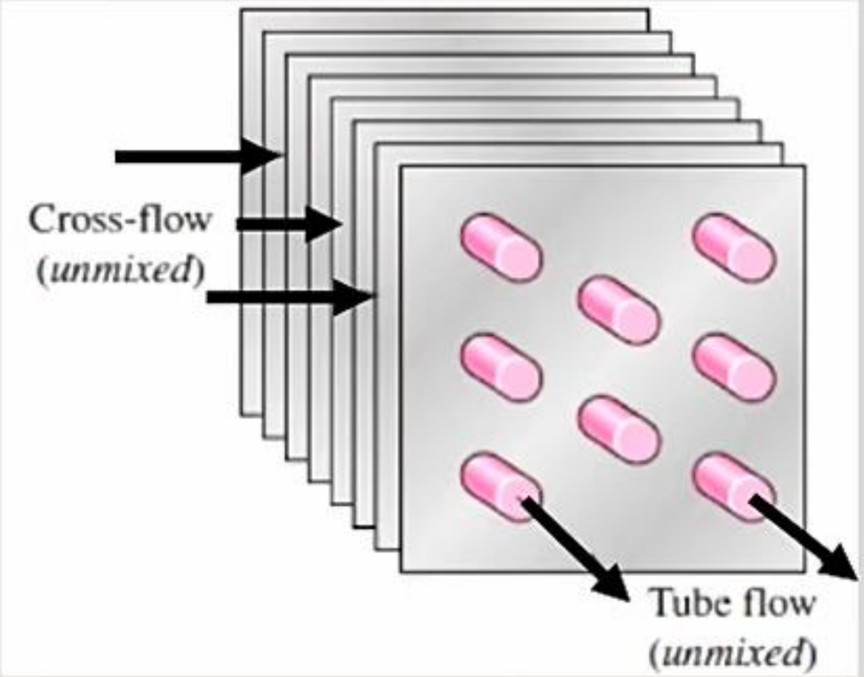
Counter flow heat exchanger

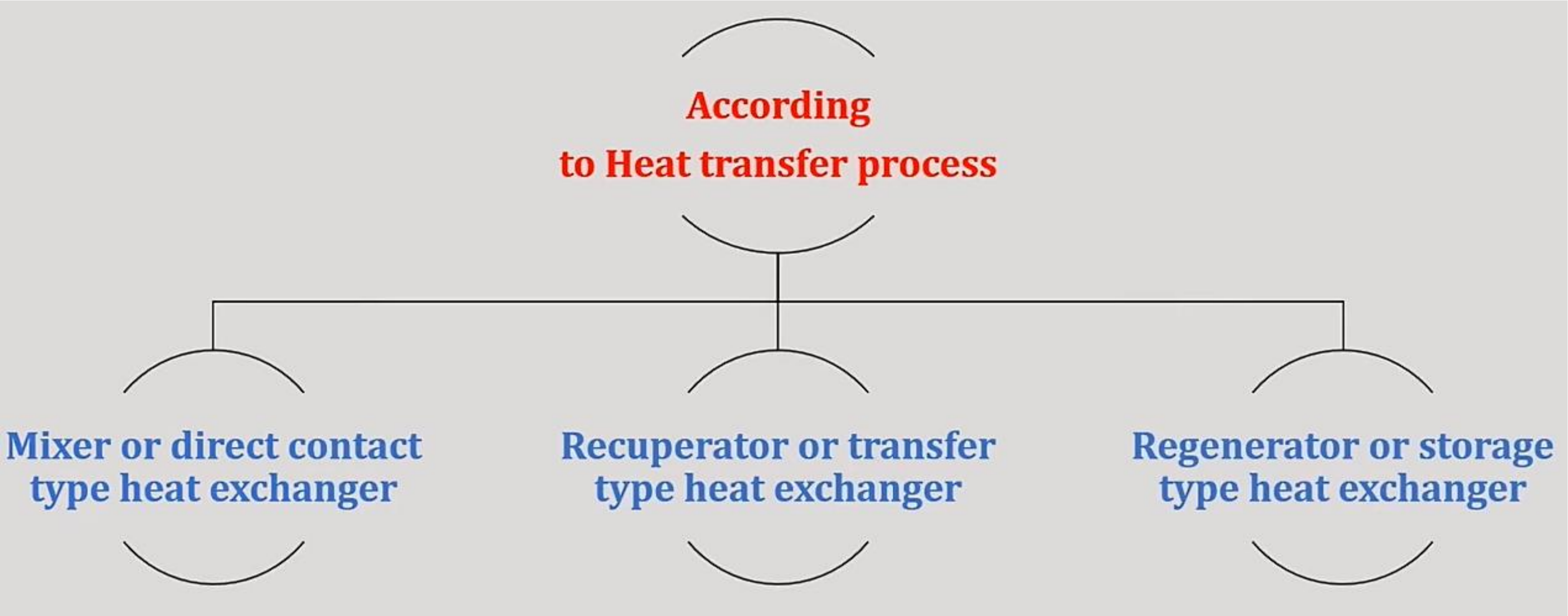
- In counter flow heat exchanger, two streams enter at opposite ends of a heat exchanger and flow in parallel but opposite directions



Cross flow heat exchanger

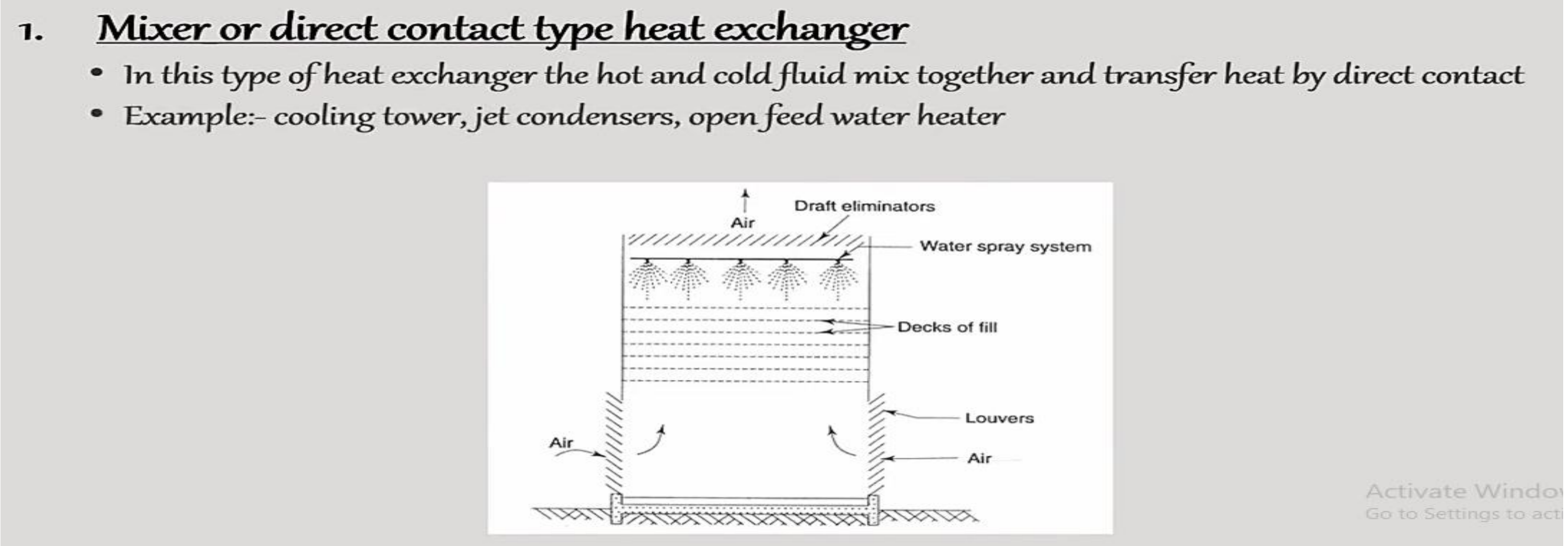
- In cross flow heat exchanger, two streams enter at right angle to each other





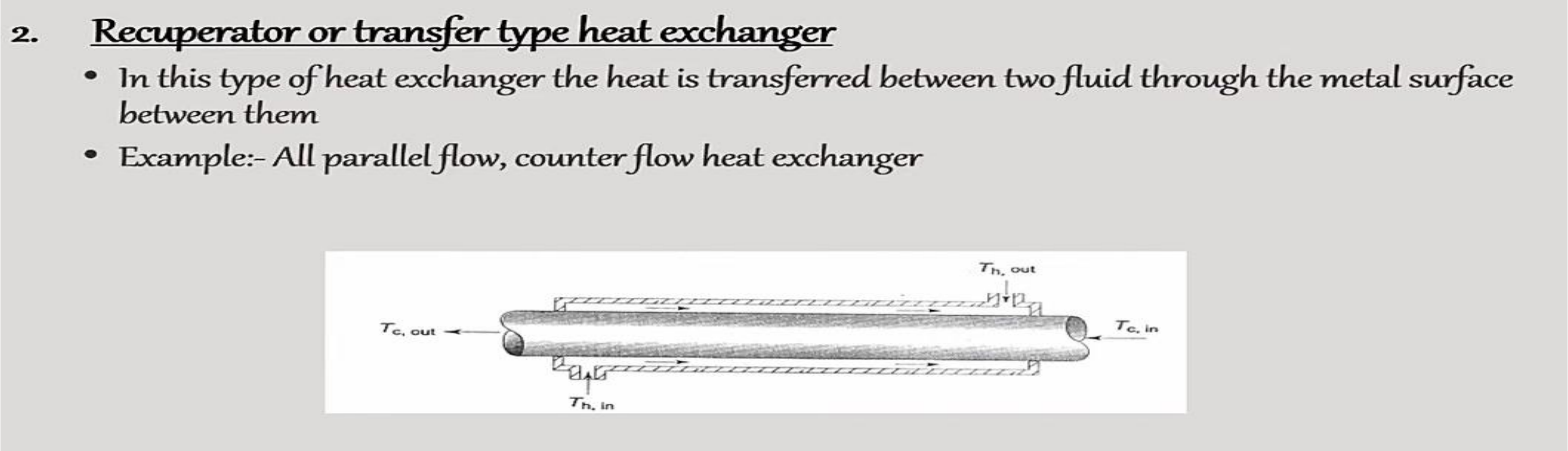
According to Heat transfer process

- Mixer or direct contact type heat exchanger
- Recuperator or transfer type heat exchanger
- Regenerator or storage type heat exchanger



1. Mixer or direct contact type heat exchanger

- In this type of heat exchanger the hot and cold fluid mix together and transfer heat by direct contact
- Example:- cooling tower, jet condensers, open feed water heater

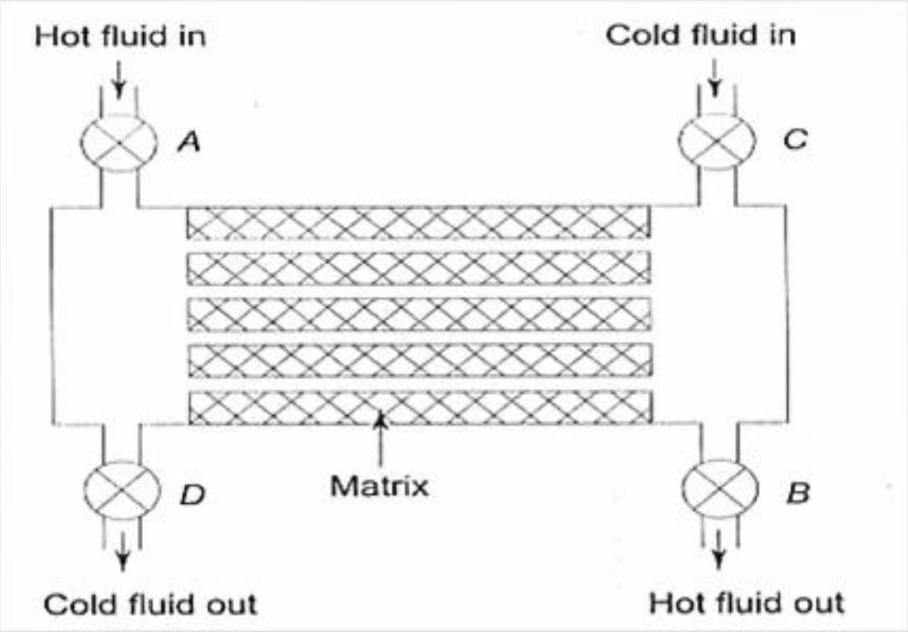


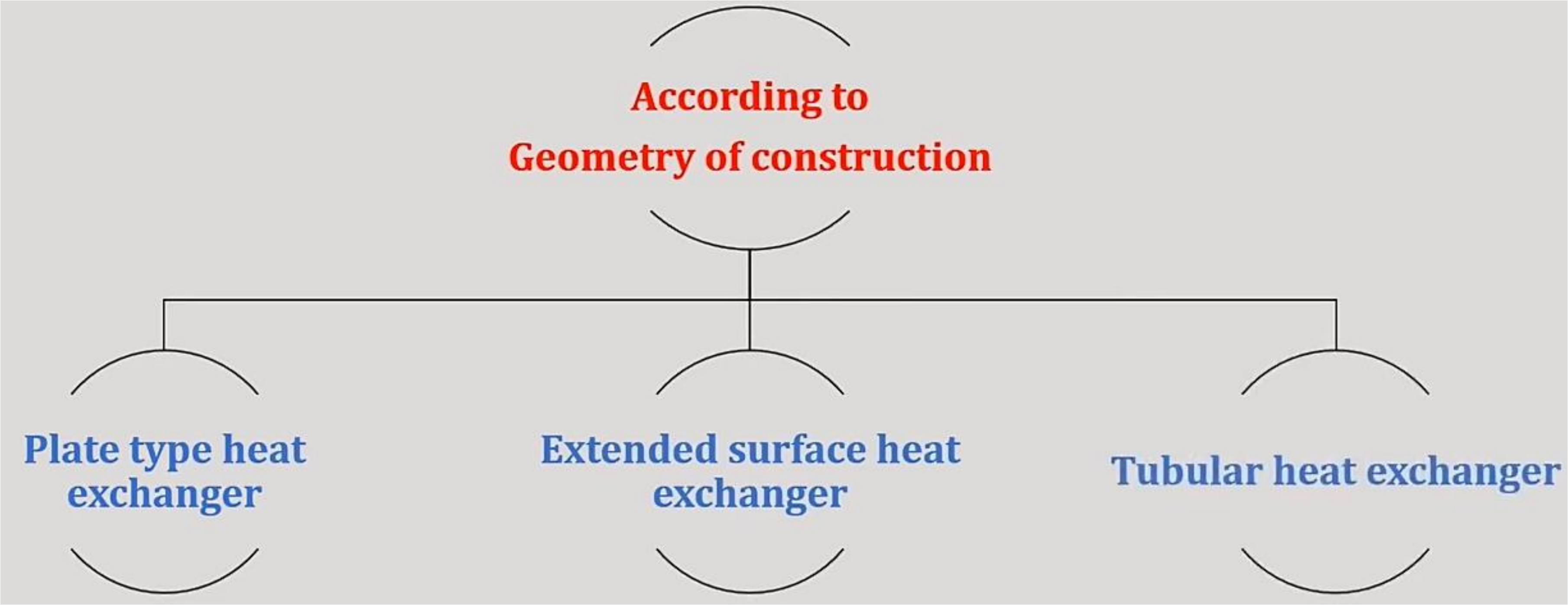
2. Recuperator or transfer type heat exchanger

- In this type of heat exchanger the heat is transferred between two fluid through the metal surface between them
- Example:- All parallel flow, counter flow heat exchanger

3. Regenerator or stogage type heat exchanger

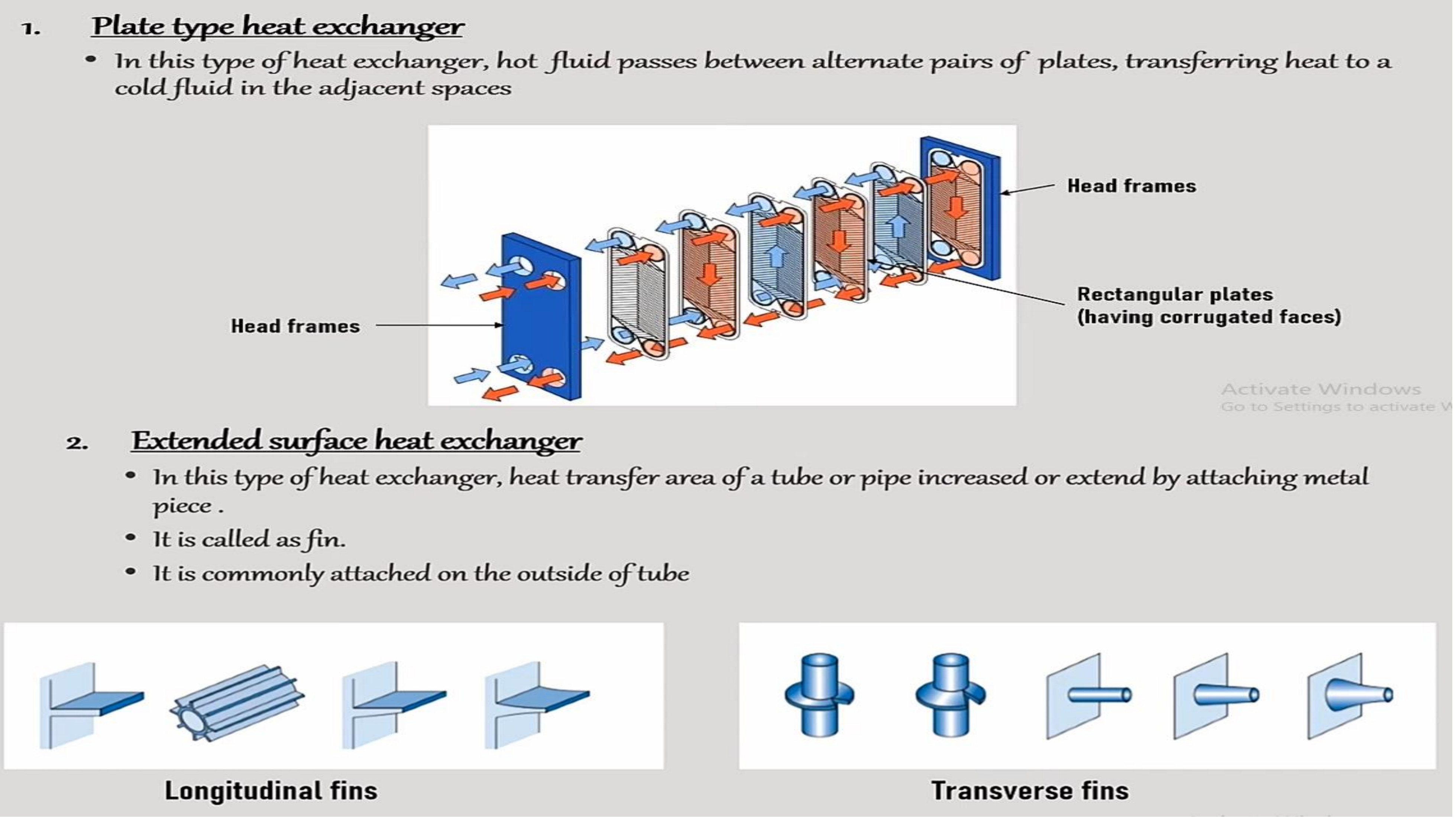
- In this type of heat exchanger, hot and cold fluid alternately flow on the same flow passage which is called as matrix





According to Geometry of construction

- Plate type heat exchanger
- Extended surface heat exchanger
- Tubular heat exchanger

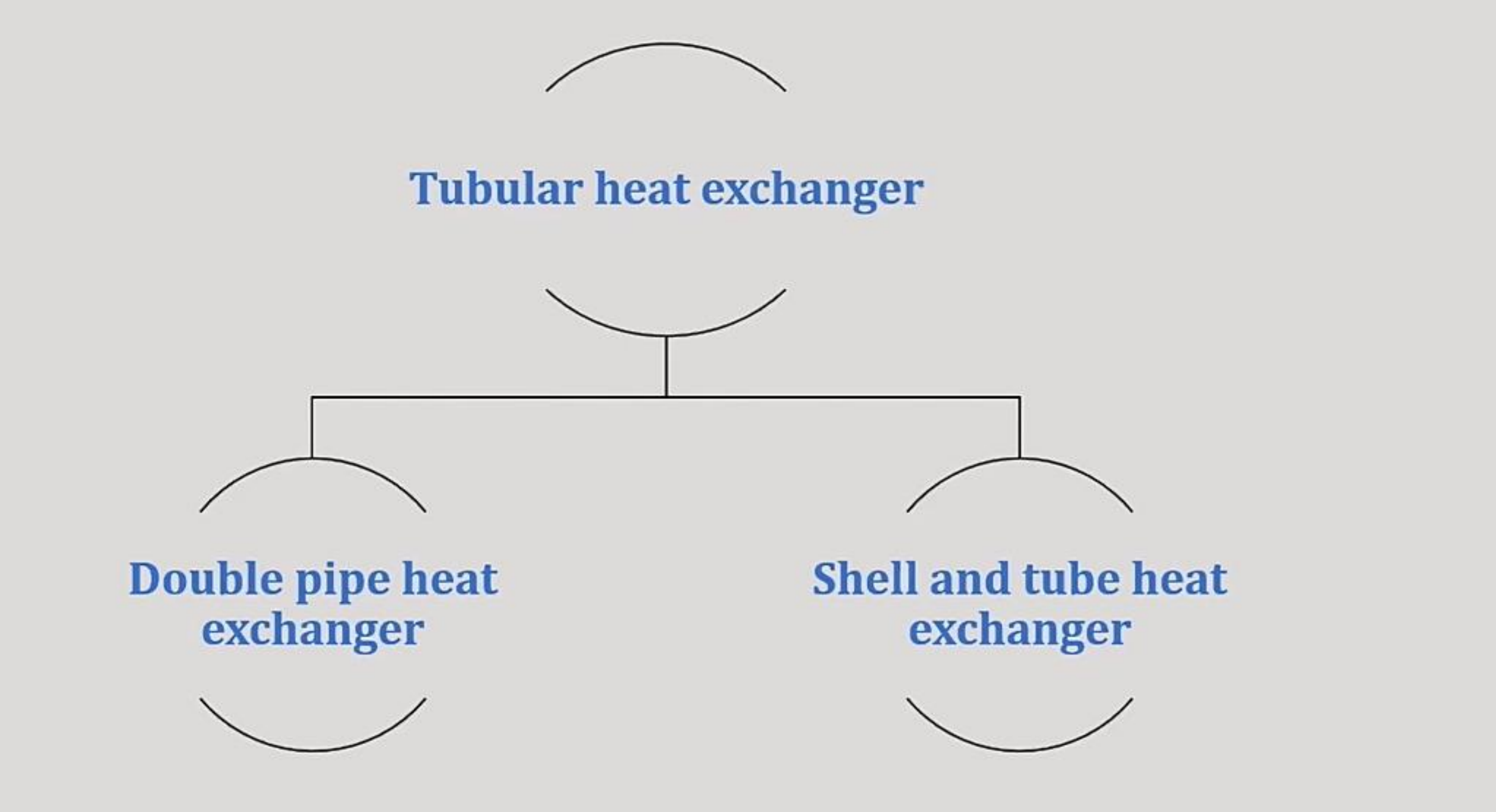


1. Plate type heat exchanger

- In this type of heat exchanger, hot fluid passes between alternate pairs of plates, transferring heat to a cold fluid in the adjacent spaces

2. Extended surface heat exchanger

- In this type of heat exchanger, heat transfer area of a tube or pipe increased or extend by attaching metal piece .
- It is called as fin.
- It is commonly attached on the outside of tube



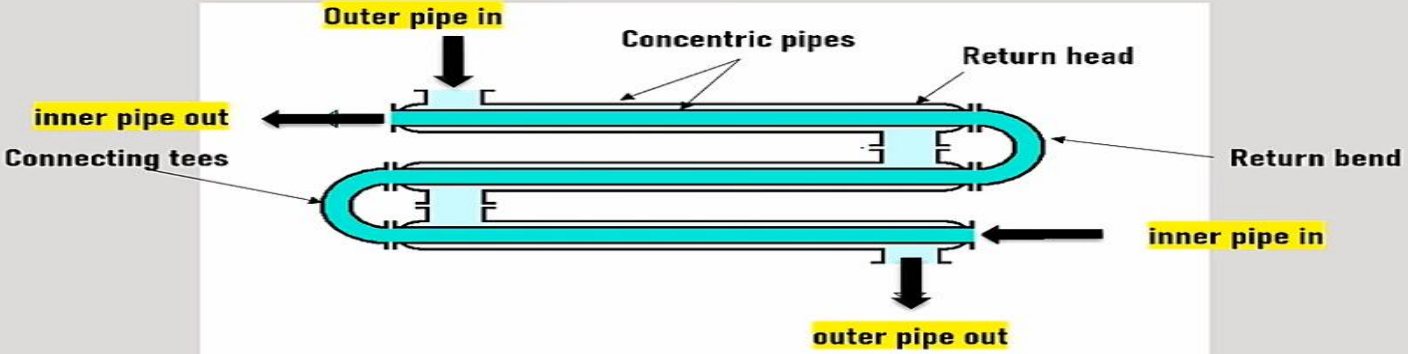
Tubular heat exchanger

Double pipe heat exchanger

Shell and tube heat exchanger

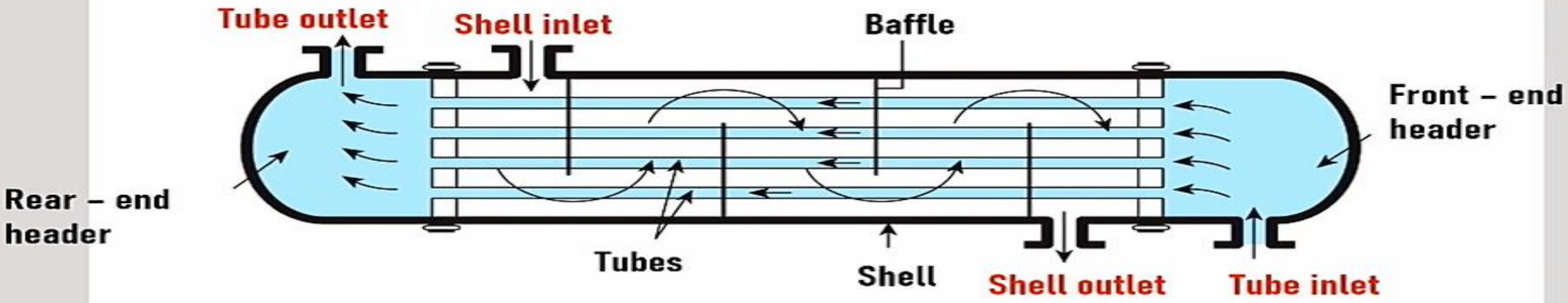
1. Double pipe heat exchanger

- In this type of heat exchanger, one of the fluid flow through inner pipe and other fluid flows the annular space created between two concentric pipes either in co-current or counter current fashion

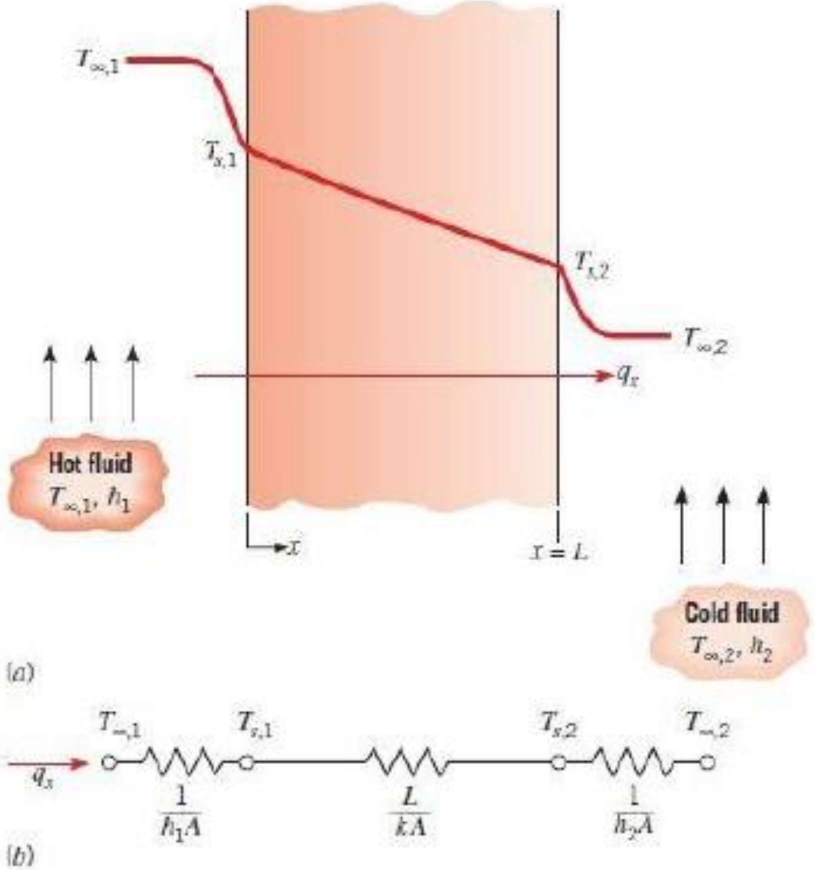


2. Shell and tube heat exchanger

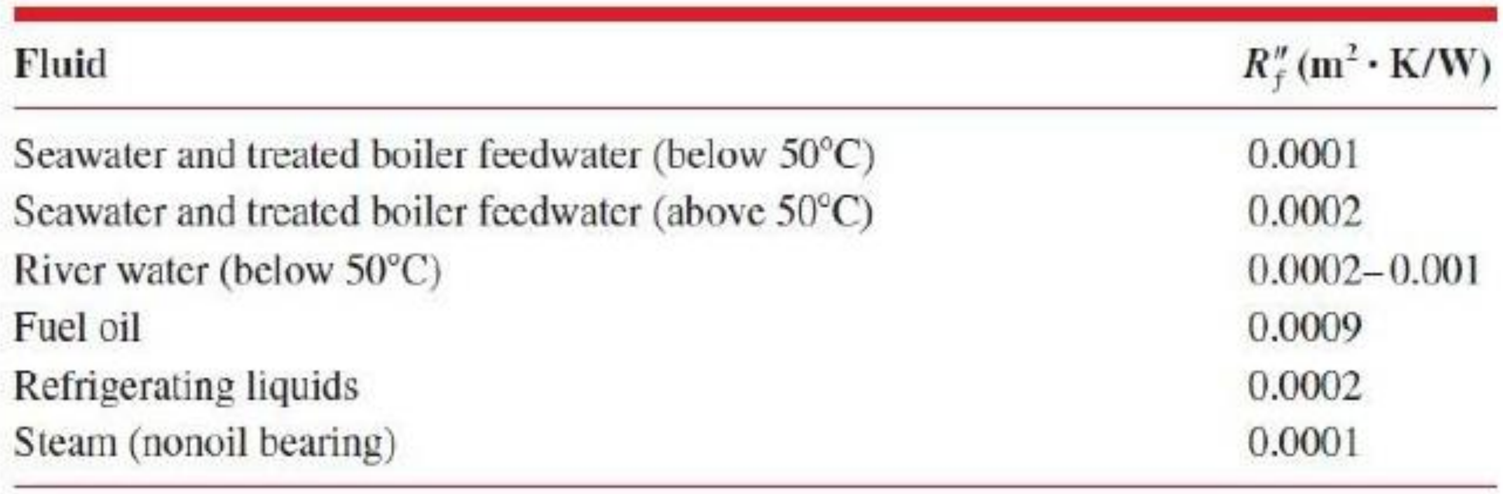
- In this type of heat exchanger, one of the fluid flow through tubes which is called as tube side fluid, while the outer fluid flows through the space created between shell and tube which is called as shell side fluid.



Overall Heat Transfer Coefficient



$$\frac{1}{UA} = \frac{1}{U_h A_h} = \frac{1}{U_c A_c} = \frac{1}{h_h A_h} + R_w + \frac{1}{h_c A_c}$$



Fluid	R''_f (m² · K/W)
Seawater and treated boiler feedwater (below 50°C)	0.0001
Seawater and treated boiler feedwater (above 50°C)	0.0002
River water (below 50°C)	0.0002–0.001
Fuel oil	0.0009
Refrigerating liquids	0.0002
Steam (nonoil bearing)	0.0001

$$\frac{1}{UA} = {}^{\cdot}\frac{1}{h_h A_h} + \frac{R^{jj}_{f,h}}{A_h}{}^{\Sigma} + R_w + {}^{\cdot}\frac{1}{h_c A_c} + \frac{R^{jj}_{f,c}}{A_c}{}^{\Sigma}$$

$$= \frac{1}{A_h}{}^{\cdot}\frac{1}{h_h} + R^{jj}_{f,h}{}^{\Sigma} + R_w + \frac{1}{A_c}{}^{\cdot}\frac{1}{h_c} + R^{jj}_{f,c}{}^{\Sigma}$$

The overall surface efficiency is expressed as:

$$q = \eta_o h A (T_b - T_\infty)$$

A is the total (fin + exposed base) surface area.

$$\eta_o = 1 - \frac{A_f}{A}(1 - \eta_f)$$

A_f is entire fin surface area, η_f is η of single fin.

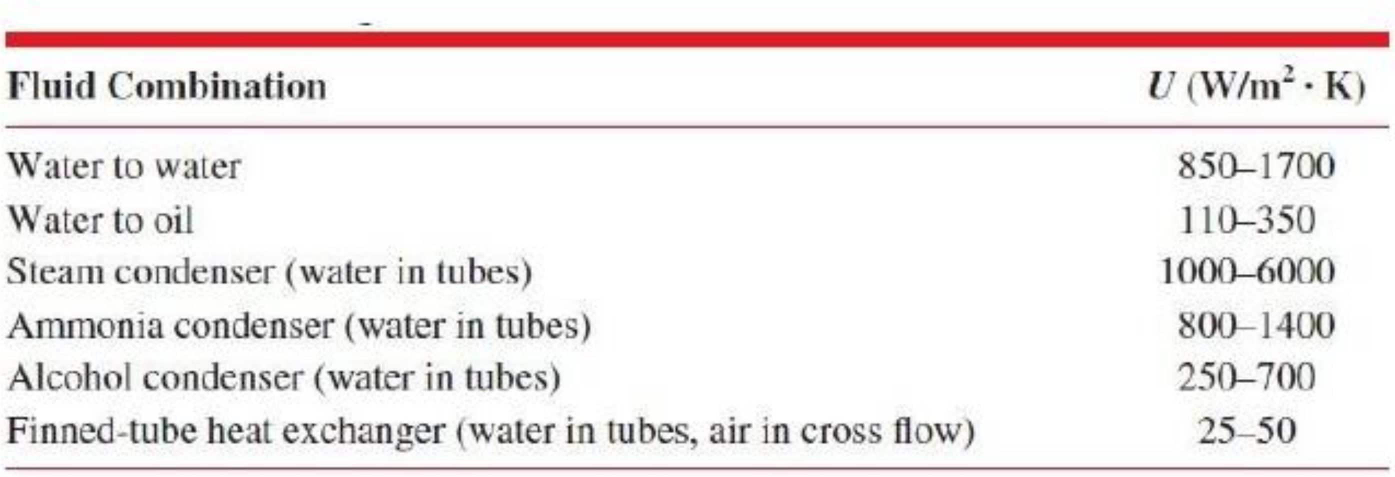
For a straight fin with an adiabatic tip:

$$\eta_f = \frac{\tanh(mL)}{mL}$$

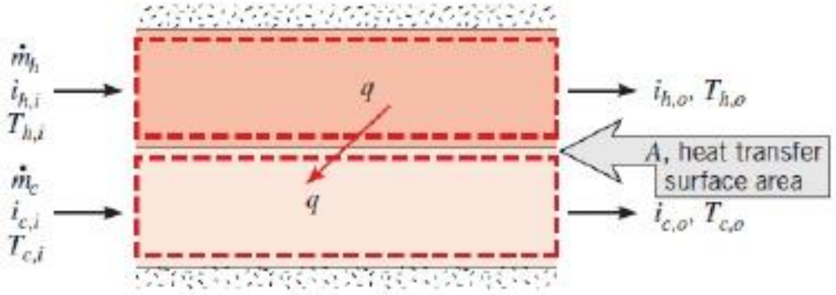
$$m = \sqrt{\frac{hP}{kA_c}}$$

$$\frac{1}{UA} = \frac{1}{\eta_{o,h}A_h}\left(\frac{1}{h_h} + R''_{f,h}\right) + R_w + \frac{1}{\eta_{o,c}A_c}\left(\frac{1}{h_c} + R''_{f,c}\right)$$
$$= \frac{1}{(\eta_o U_p A)_h} + R_w + \frac{1}{(\eta_o U_p A)_c}$$

U_p partial overall heat transfer coefficient.



Fluid Combination	U (W/m^2 · K)
Water to water	850–1700
Water to oil	110–350
Steam condenser (water in tubes)	1000–6000
Ammonia condenser (water in tubes)	800–1400
Alcohol condenser (water in tubes)	250–700
Finned-tube heat exchanger (water in tubes, air in cross flow)	25–50

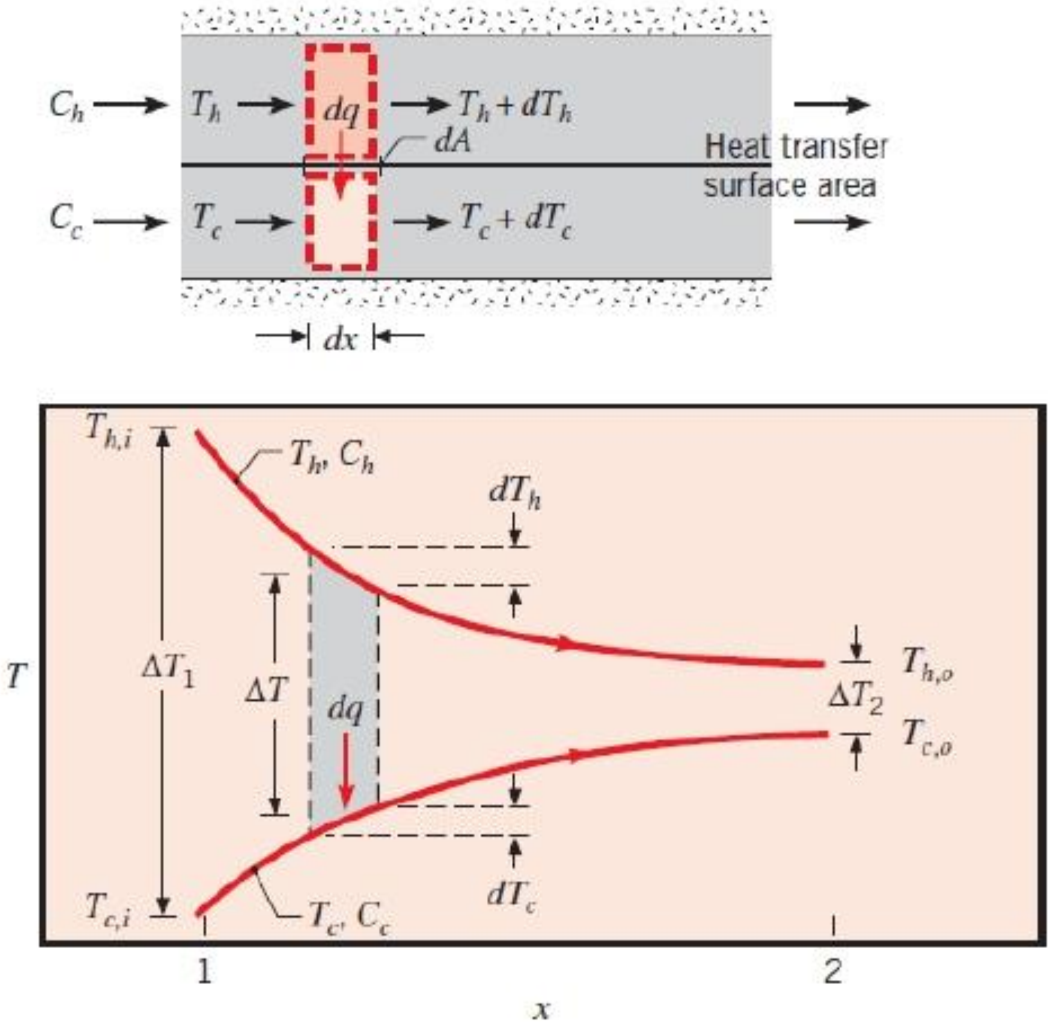


$$q = \dot{m}_h C_{p,h}(T_{h,i} - T_{h,o})$$

$$q = \dot{m}_c C_{p,c}(T_{c,o} - T_{c,i})$$

$$q = UA\Delta T_m$$

$$\Delta T \equiv T_h - T_c$$


C_h
T_h
dq
$T_h + dT_h$
dA
Heat transfer surface area
C_c
T_c
$T_c + dT_c$
dx
$T_{h,i}$
T_h, C_h
dT_h
T
ΔT_1
ΔT
dq
$T_{h,o}$
ΔT_2
$T_{c,o}$
$T_{c,i}$
T_c, C_c
dT_c
1
2
x

Effectiveness-NTU Method

The max. possible heat transfer rate, q_{max} could, in principle, be achieved in a counterflow heat exchanger of infinite length.

The max. possible temp. diff., $T_{h,i} - T_{c,i}$

$$C_c < C_h: \qquad q_{max} = C_c(T_{h,i} - T_{c,i})$$

$$C_h < C_c: \qquad q_{max} = C_h(T_{h,i} - T_{c,i})$$

$$\boxed{q_{max} = C_{min}(T_{h,i} - T_{c,i})}$$

Effectiveness,

$$\varepsilon = \frac{q}{q_{max}}$$

$$\varepsilon = \frac{C_h(T_{h,i} - T_{h,o})}{C_{min}(T_{h,i} - T_{c,i})} = \frac{C_c(T_{c,o} - T_{c,i})}{C_{min}(T_{h,i} - T_{c,i})}$$

$$q = \varepsilon C_{min}(T_{h,i} - T_{c,i})$$

Typically,

$$\varepsilon = f \;\dot{}\; \text{NTU}, \frac{C_{min}}{C_{max}} \Sigma$$

The number of transfer units (NTU) is a dimensionless parameter,

$$\text{NTU} = \frac{UA}{C_{min}}$$

NTU is defined as the ratio of the system's ability to transfer heat (UA) to the fluid's minimum ability to absorb heat(C_{min}).

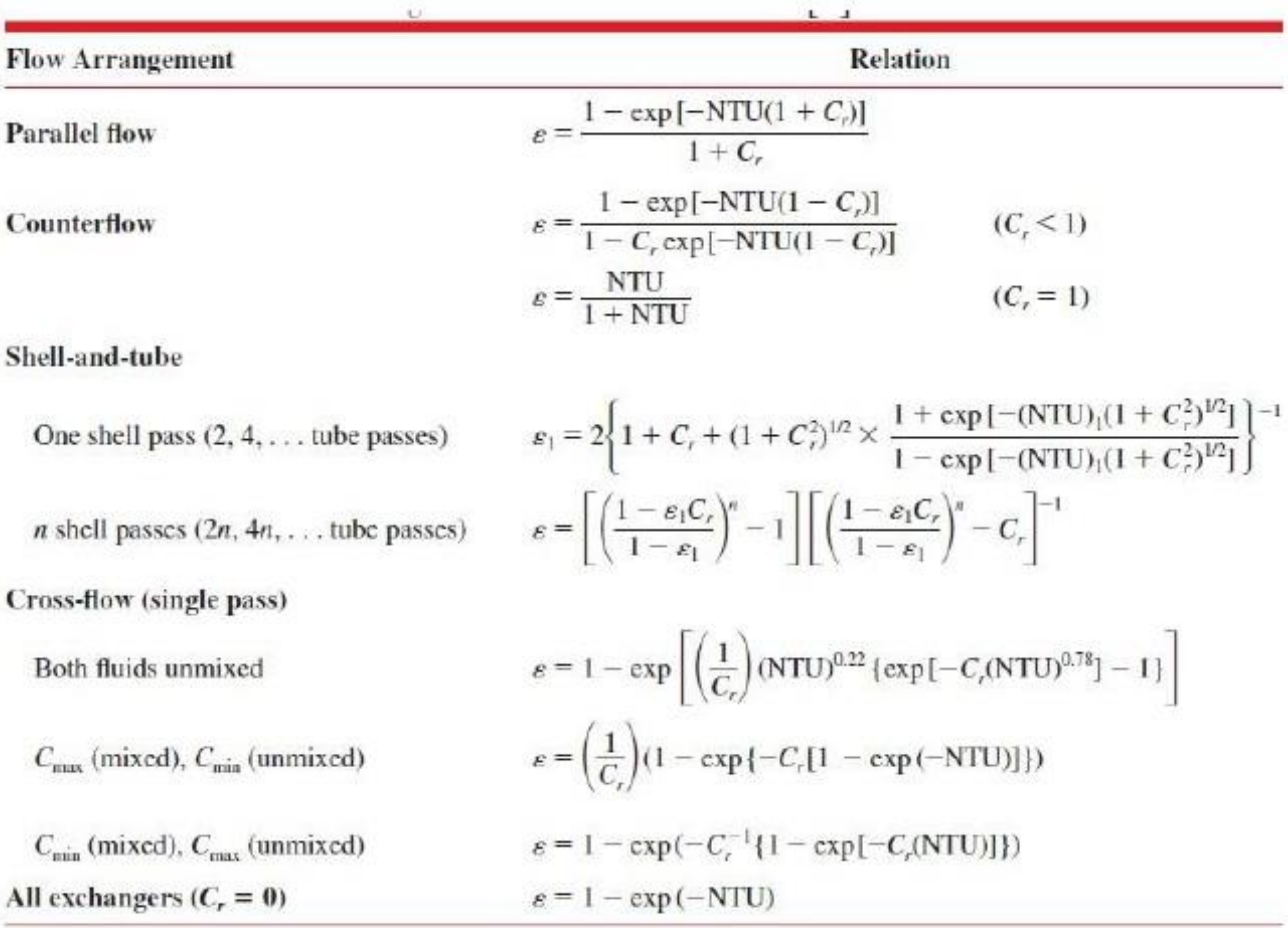
NTU indicates the size of the heat exchanger required for a given U and C_{min}.

Consider a parallel-flow with $C_{min} = C_h$.

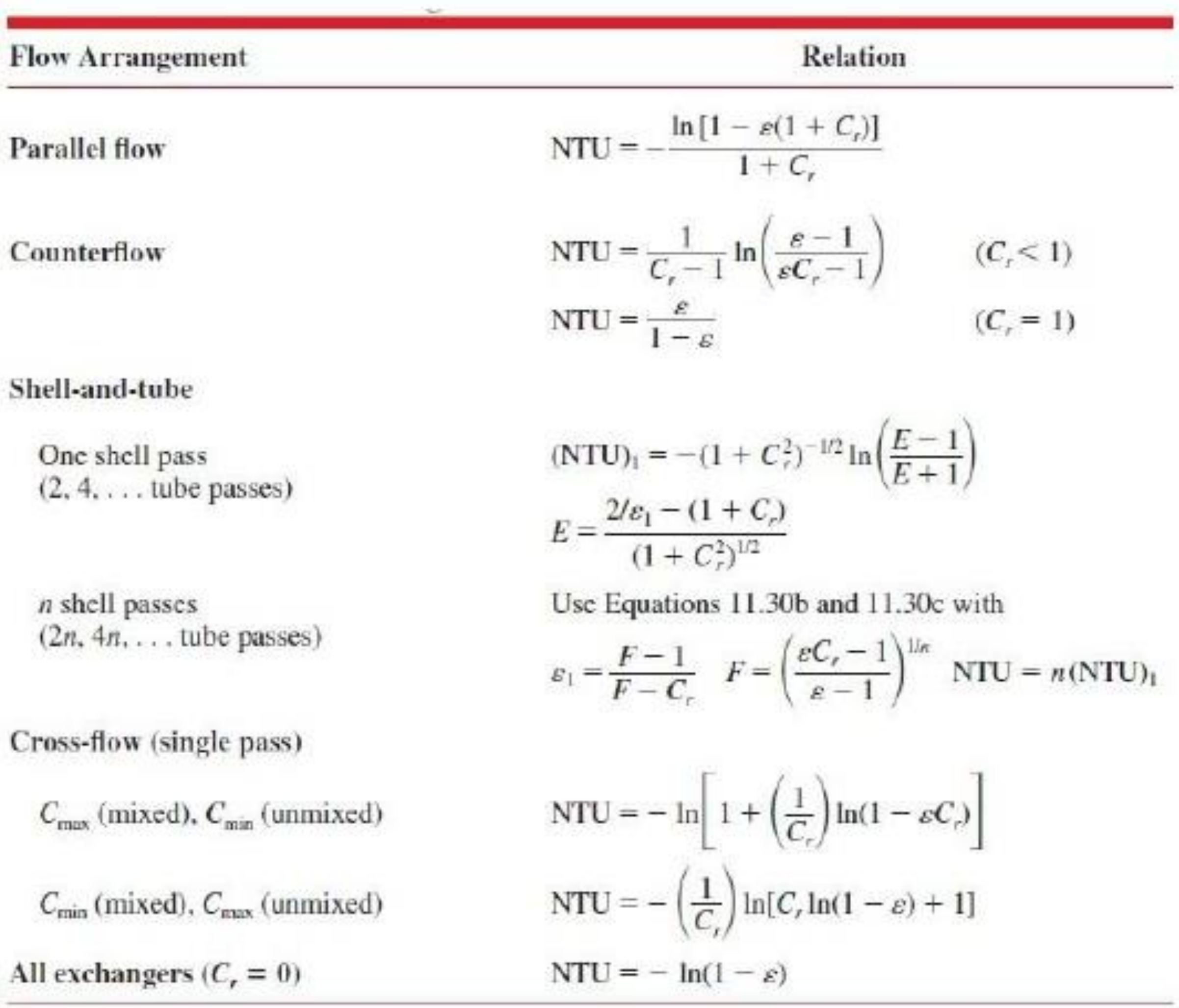
$$\varepsilon = \frac{T_{h,i} - T_{h,o}}{T_{h,i} - T_{c,i}}$$

$$C_r = \frac{C_{min}}{C_{max}} = \frac{T_{c,o} - T_{c,i}}{T_{h,i} - T_{h,o}}$$

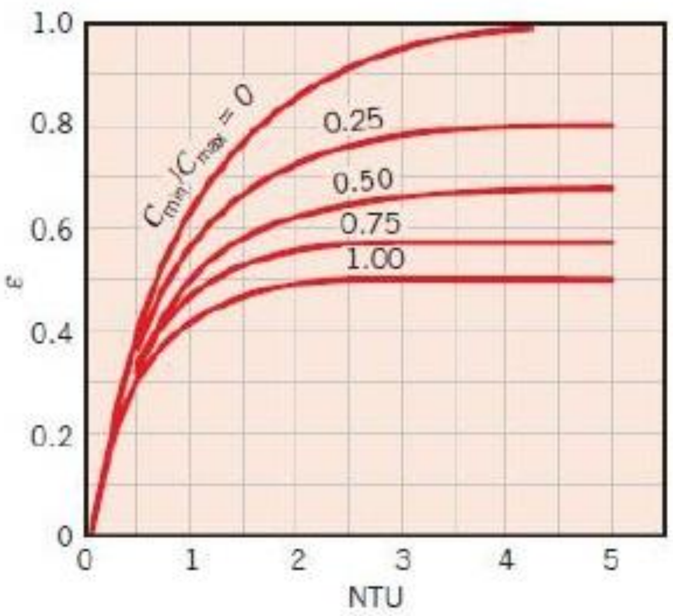
$$\varepsilon = \frac{1 - e^{-\mathrm{NTU}(1+C_r)}}{1 + C_r}$$



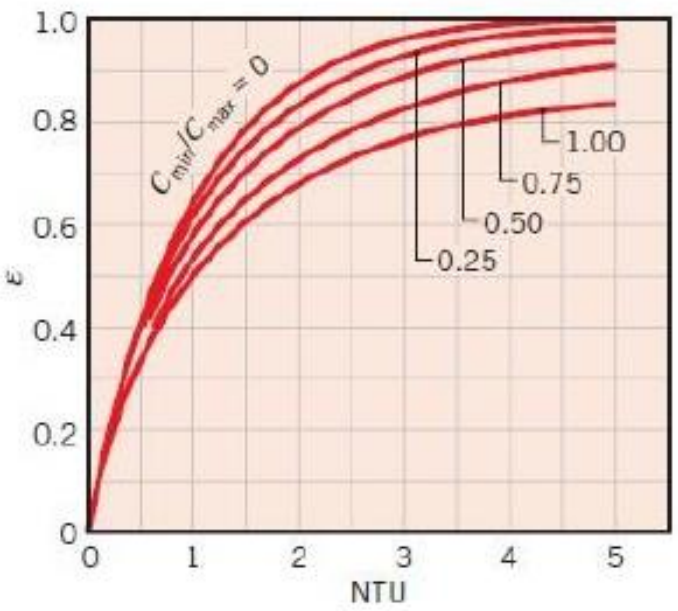
Flow Arrangement	Relation	
Parallel flow	$\varepsilon = \dfrac{1 - \exp[-\text{NTU}(1 + C_r)]}{1 + C_r}$	
Counterflow	$\varepsilon = \dfrac{1 - \exp[-\text{NTU}(1 - C_r)]}{1 - C_r \exp[-\text{NTU}(1 - C_r)]}$	$(C_r < 1)$
	$\varepsilon = \dfrac{\text{NTU}}{1 + \text{NTU}}$	$(C_r = 1)$
Shell-and-tube		
One shell pass (2, 4, . . . tube passes)	$\varepsilon_1 = 2\left\{1 + C_r + (1 + C_r^2)^{1/2} \times \dfrac{1 + \exp[-(\text{NTU})_1(1 + C_r^2)^{1/2}]}{1 - \exp[-(\text{NTU})_1(1 + C_r^2)^{1/2}]}\right\}^{-1}$	
n shell passes ($2n$, $4n$, . . . tube passes)	$\varepsilon = \left[\left(\dfrac{1 - \varepsilon_1 C_r}{1 - \varepsilon_1}\right)^n - 1\right]\left[\left(\dfrac{1 - \varepsilon_1 C_r}{1 - \varepsilon_1}\right)^n - C_r\right]^{-1}$	
Cross-flow (single pass)		
Both fluids unmixed	$\varepsilon = 1 - \exp\left[\left(\dfrac{1}{C_r}\right)(\text{NTU})^{0.22}\{\exp[-C_r(\text{NTU})^{0.78}] - 1\}\right]$	
$C_{\max}$ (mixed), $C_{\min}$ (unmixed)	$\varepsilon = \left(\dfrac{1}{C_r}\right)(1 - \exp\{-C_r[1 - \exp(-\text{NTU})]\})$	
$C_{\min}$ (mixed), $C_{\max}$ (unmixed)	$\varepsilon = 1 - \exp(-C_r^{-1}\{1 - \exp[-C_r(\text{NTU})]\})$	
All exchangers ($C_r = 0$)	$\varepsilon = 1 - \exp(-\text{NTU})$	



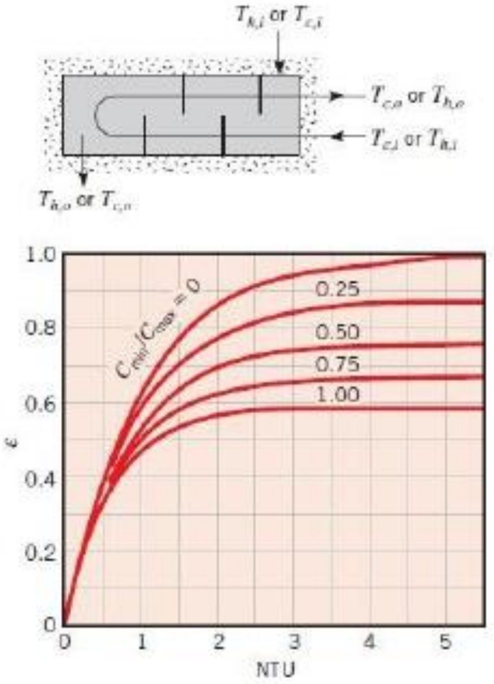
Flow Arrangement	Relation	
Parallel flow	$\mathrm{NTU} = -\frac{\ln[1-\varepsilon(1+C_r)]}{1+C_r}$	
Counterflow	$\mathrm{NTU} = \frac{1}{C_r - 1}\ln\left(\frac{\varepsilon - 1}{\varepsilon C_r - 1}\right)$	$(C_r < 1)$
	$\mathrm{NTU} = \frac{\varepsilon}{1-\varepsilon}$	$(C_r = 1)$
Shell-and-tube		
One shell pass (2, 4, . . . tube passes)	$(\mathrm{NTU})_1 = -(1 + C_r^2)^{-1/2}\ln\left(\frac{E-1}{E+1}\right)$ $E = \frac{2/\varepsilon_1 - (1+C_r)}{(1+C_r^2)^{1/2}}$	
n shell passes ($2n$, $4n$, . . . tube passes)	Use Equations 11.30b and 11.30c with $\varepsilon_1 = \frac{F-1}{F-C_r}$ $F = \left(\frac{\varepsilon C_r - 1}{\varepsilon - 1}\right)^{1/n}$ $\mathrm{NTU} = n(\mathrm{NTU})_1$	
Cross-flow (single pass)		
C_{max} (mixed), C_{min} (unmixed)	$\mathrm{NTU} = -\ln\left[1 + \left(\frac{1}{C_r}\right)\ln(1 - \varepsilon C_r)\right]$	
C_{min} (mixed), C_{max} (unmixed)	$\mathrm{NTU} = -\left(\frac{1}{C_r}\right)\ln[C_r \ln(1-\varepsilon) + 1]$	
All exchangers ($C_r = 0$)	$\mathrm{NTU} = -\ln(1 - \varepsilon)$	



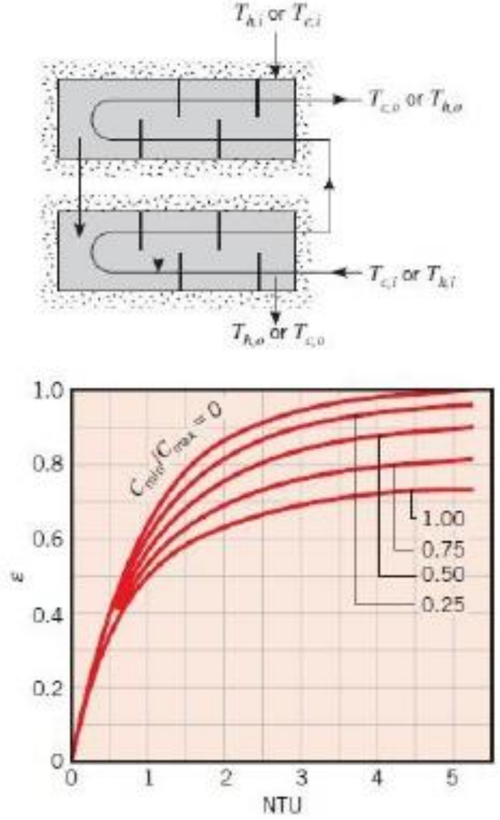
Effectiveness of a parallel- flow heat exchanger



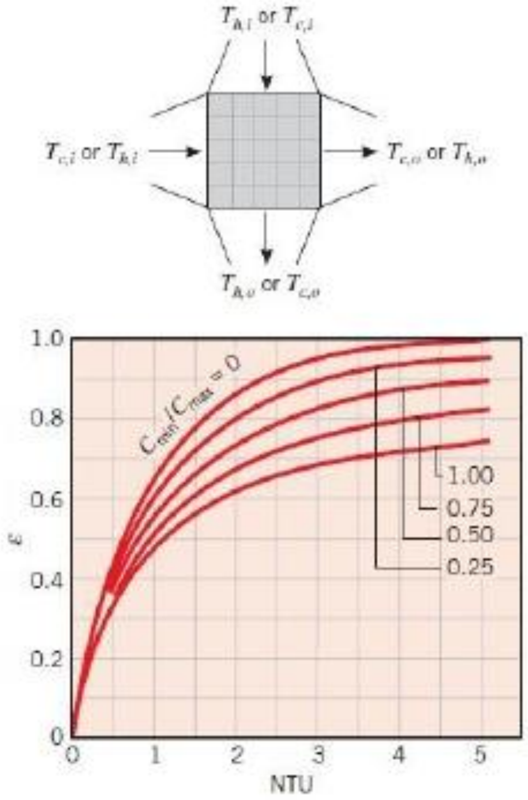
Effectiveness of a counterflow heat exchanger



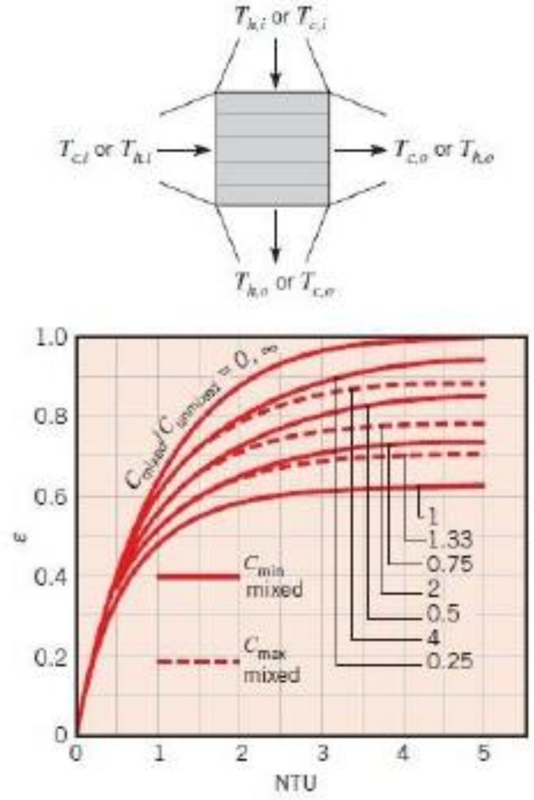
Effectiveness of a shell-and-tube heat exchanger with one shell and any multiple of two tube passes (two, four, etc., tube passes)



Effectiveness of a shell-and-tube heat exchanger with two shell passes and any multiple of four tube passes (four, eight, etc., tube passes) ($n = 2$).

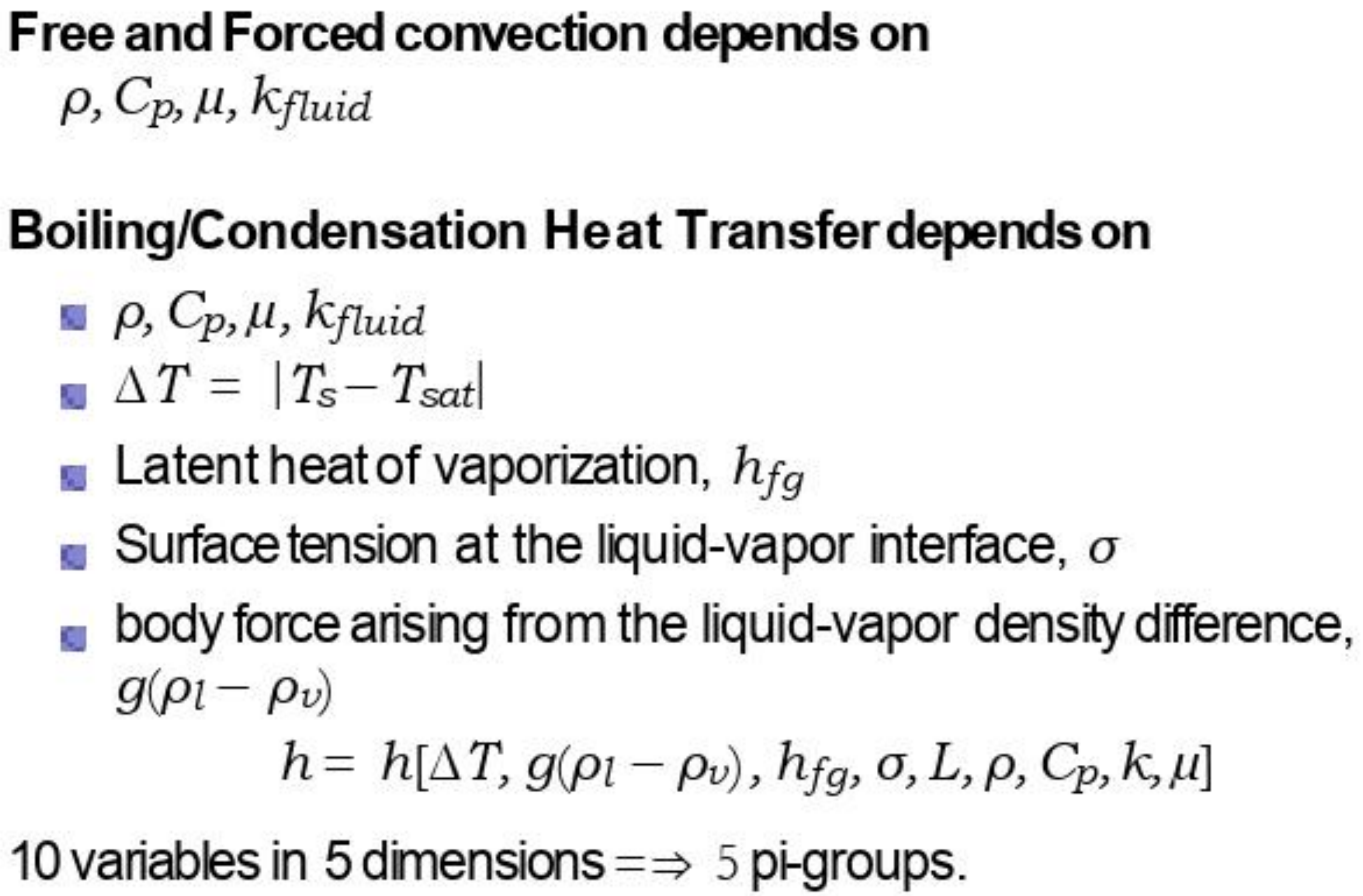


Effectiveness of a single-pass, cross-flow heat exchanger with both fluids unmixed



Effectiveness of a single-pass, cross-flow heat exchanger with one fluid mixed and the other unmixed

Boiling and Condensation: Physical Consideration



Free and Forced convection depends on

$\rho, C_p, \mu, k_{fluid}$

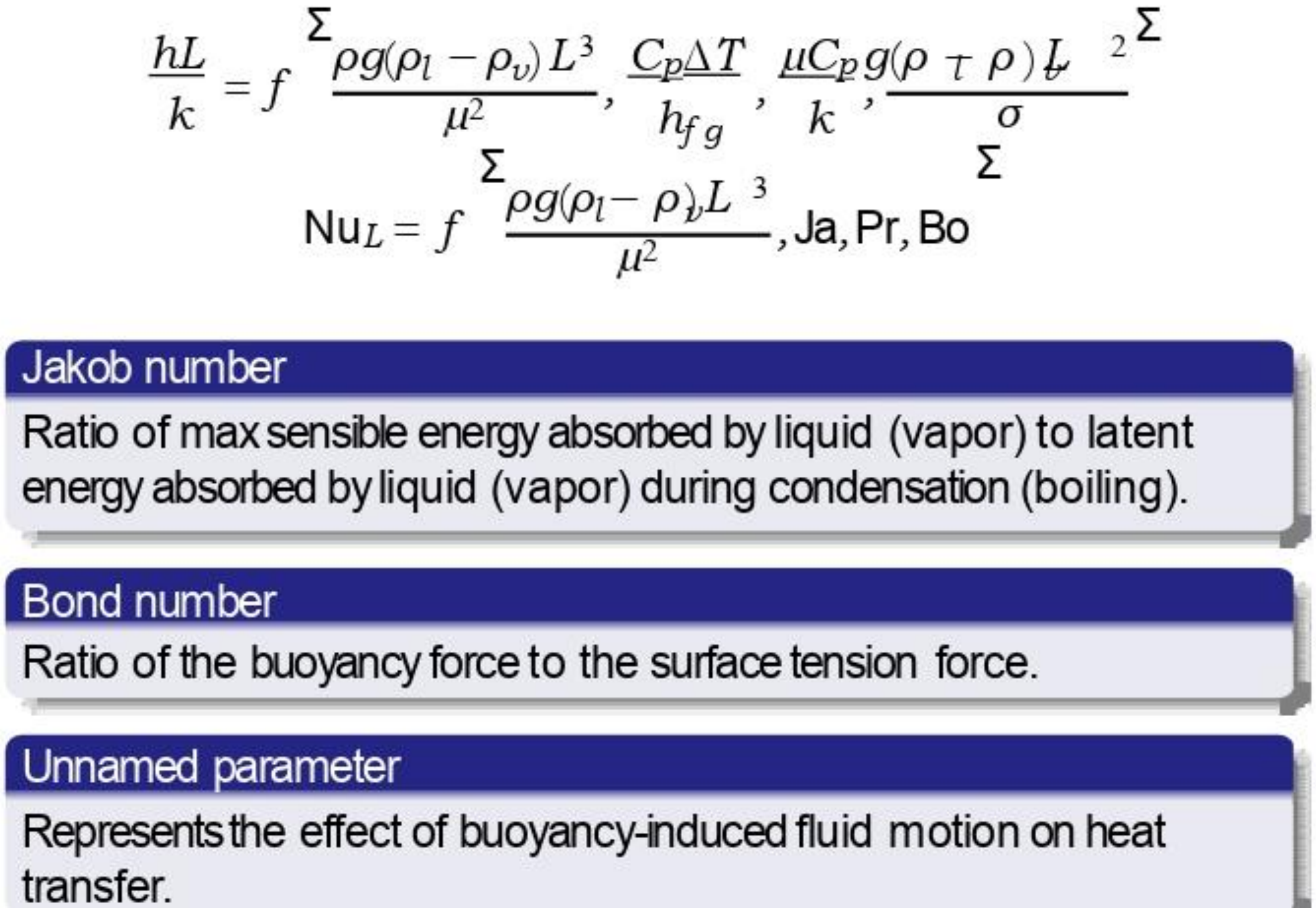
Boiling/Condensation Heat Transfer depends on

- $\rho, C_p, \mu, k_{fluid}$
- $\Delta T = |T_s - T_{sat}|$
- Latent heat of vaporization, h_{fg}
- Surface tension at the liquid-vapor interface, σ
- body force arising from the liquid-vapor density difference, $g(\rho_l - \rho_v)$

$$h = h[\Delta T, g(\rho_l - \rho_v), h_{fg}, \sigma, L, \rho, C_p, k, \mu]$$

10 variables in 5 dimensions $\Longrightarrow$ 5 pi-groups.

Dimensionless Parameters



$$\frac{hL}{k} = f\left[\frac{\rho g(\rho_l - \rho_v)L^3}{\mu^2}, \frac{C_p\Delta T}{h_{fg}}, \frac{\mu C_p}{k}, \frac{g(\rho_l - \rho_v)L^2}{\sigma}\right]$$

$$\mathrm{Nu}_L = f\left[\frac{\rho g(\rho_l - \rho_v)L^3}{\mu^2}, \mathrm{Ja}, \mathrm{Pr}, \mathrm{Bo}\right]$$

Jakob number

Ratio of max sensible energy absorbed by liquid (vapor) to latent energy absorbed by liquid (vapor) during condensation (boiling).

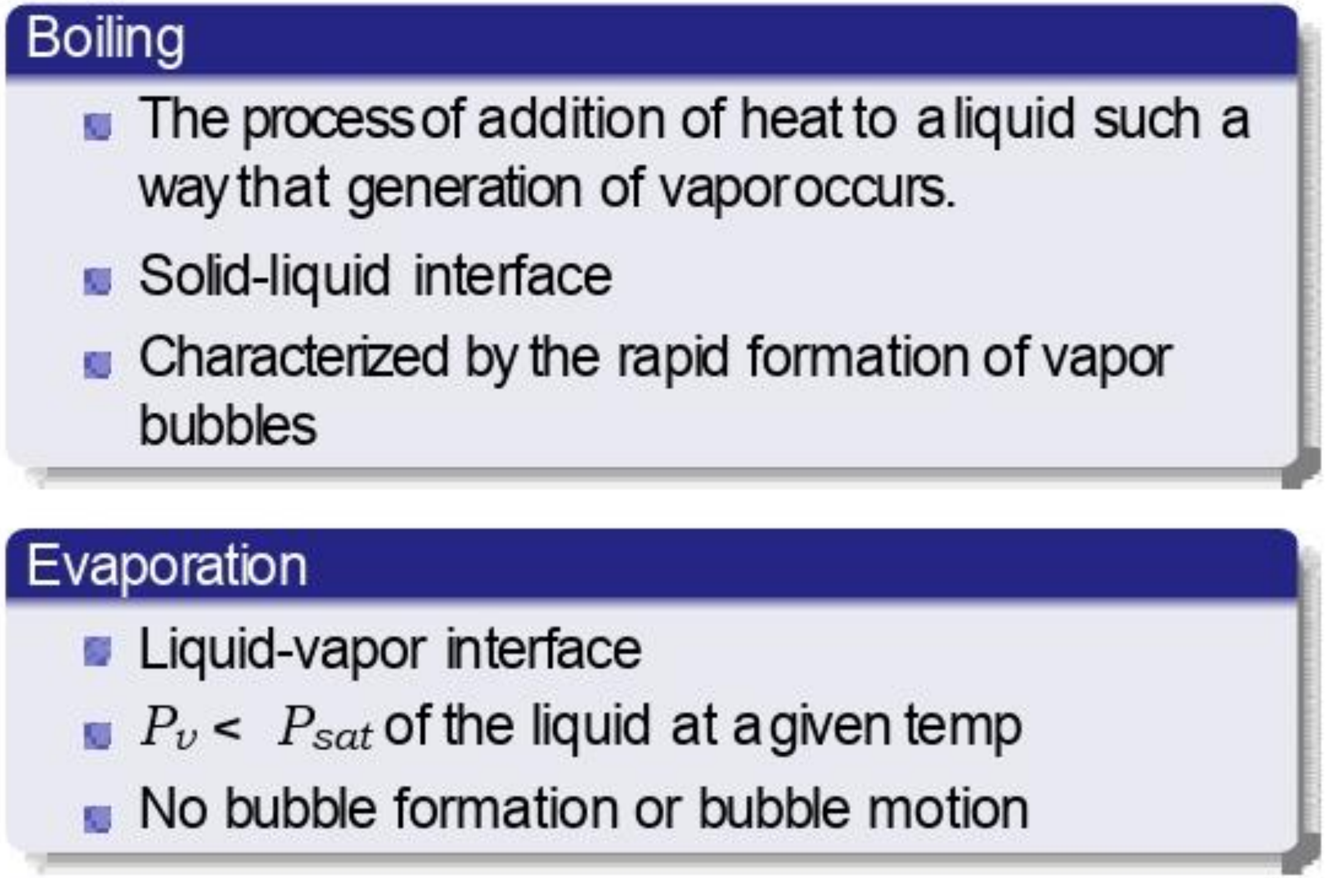
Bond number

Ratio of the buoyancy force to the surface tension force.

Unnamed parameter

Represents the effect of buoyancy-induced fluid motion on heat transfer.

Boiling and Evaporation



Boiling

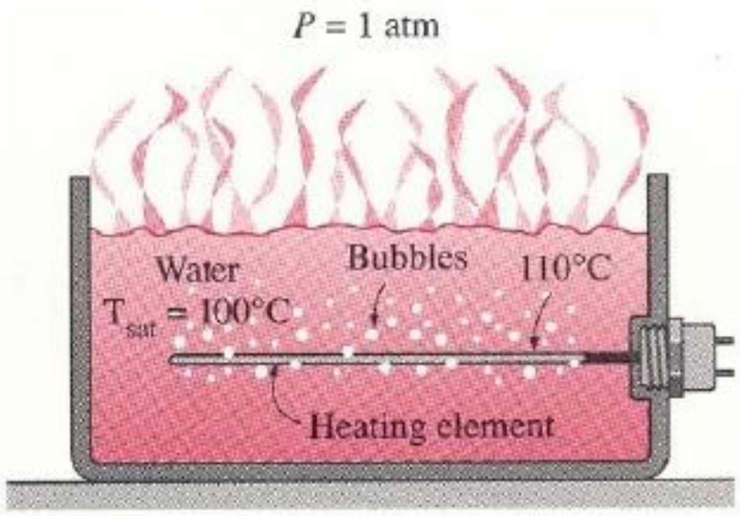
- The process of addition of heat to a liquid such a way that generation of vapor occurs.
- Solid-liquid interface
- Characterized by the rapid formation of vapor bubbles

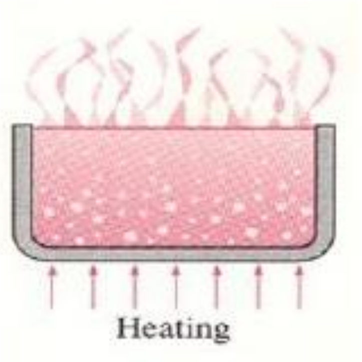
Evaporation

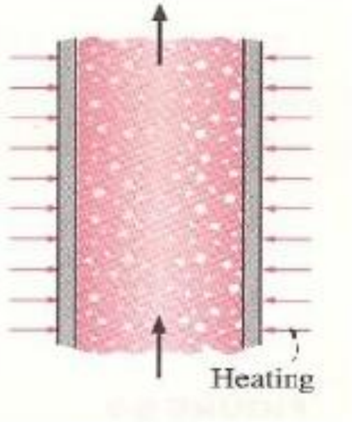
- Liquid-vapor interface
- $P_v < P_{sat}$ of the liquid at a given temp
- No bubble formation or bubble motion

Boiling occurs

- Solid-liquid interface
- when a liquid is brought into contact with a surface at a temperature above the saturation temperature of the liquid







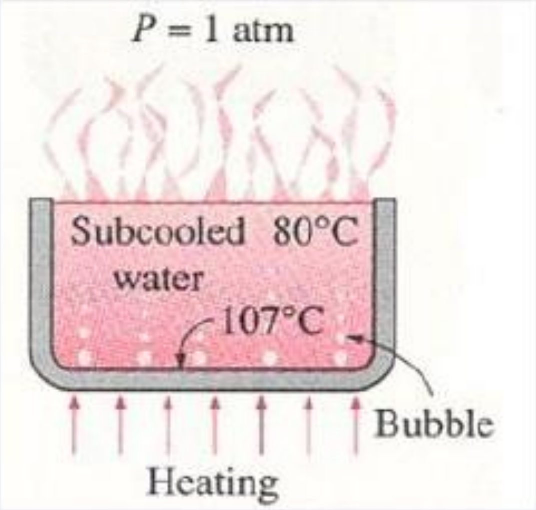
Pool boiling

- Fluid is stationary
- Fluid motion is due to natural convection currents
- Motion of bubbles under the influence of buoyancy

Flow boiling

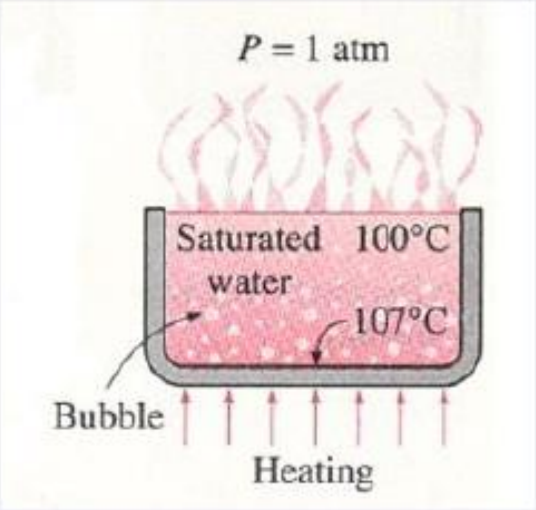
- Fluid is forced to move in a heated pipe or surface by external means such as pump
- Always accompanied by other convection effects

Subcooled boiling



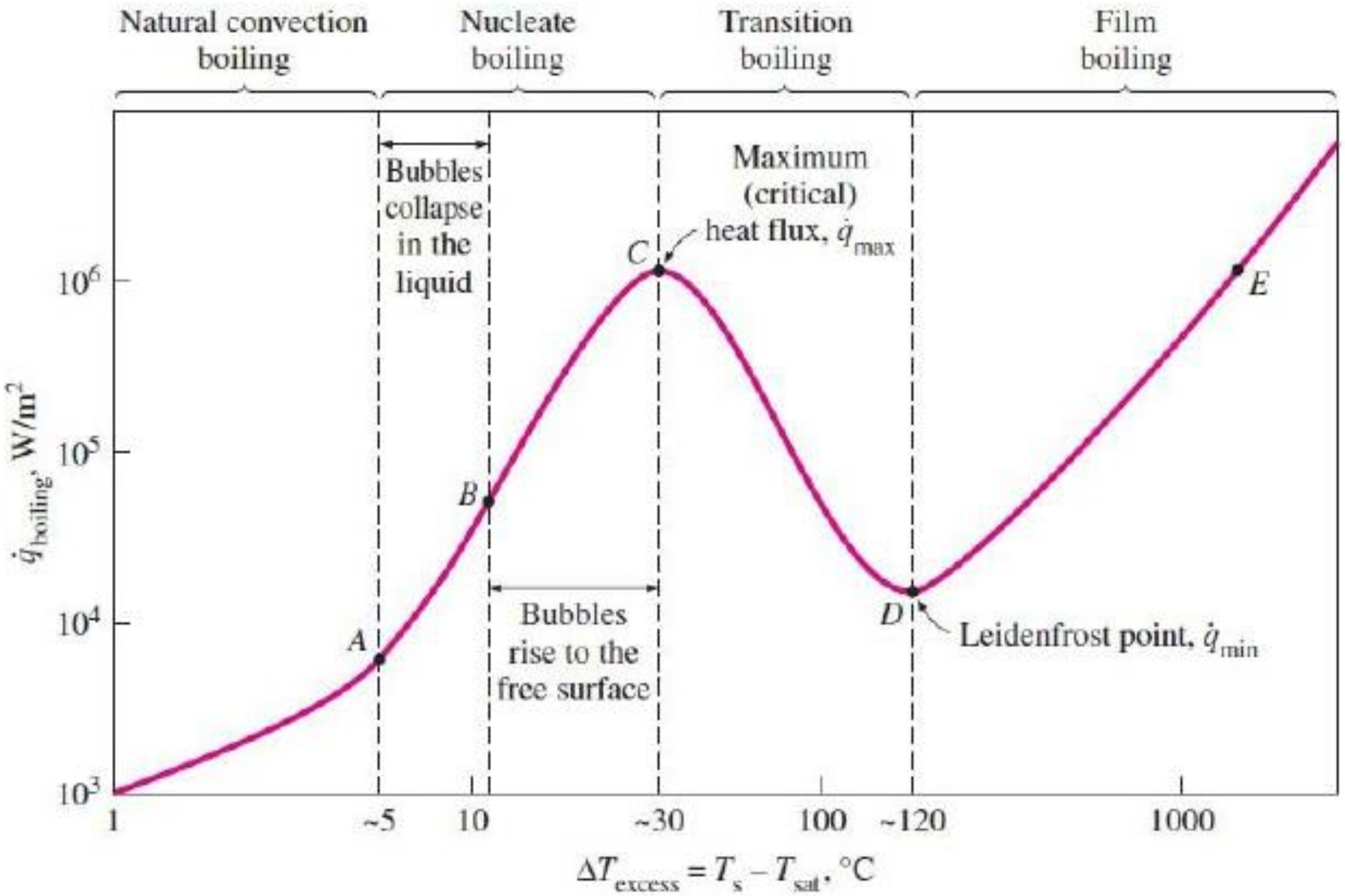
$T_{\text{bulk of liquid}} < T_{sat}$

Saturated boiling



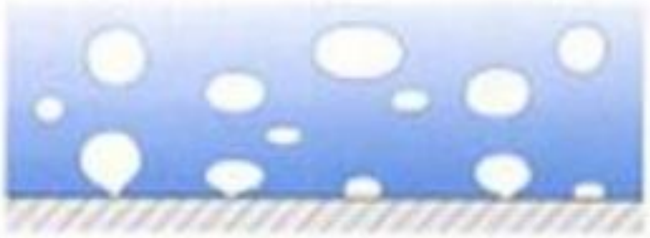
$T_{\text{bulk of liquid}} = T_{sat}$

Boiling curve for saturated water at atmospheric pressure



1. Natural convection

Onset of boiling



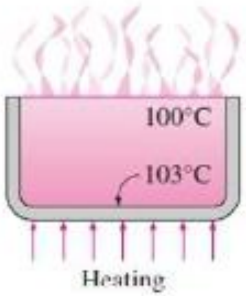
2. Individual bubble regime

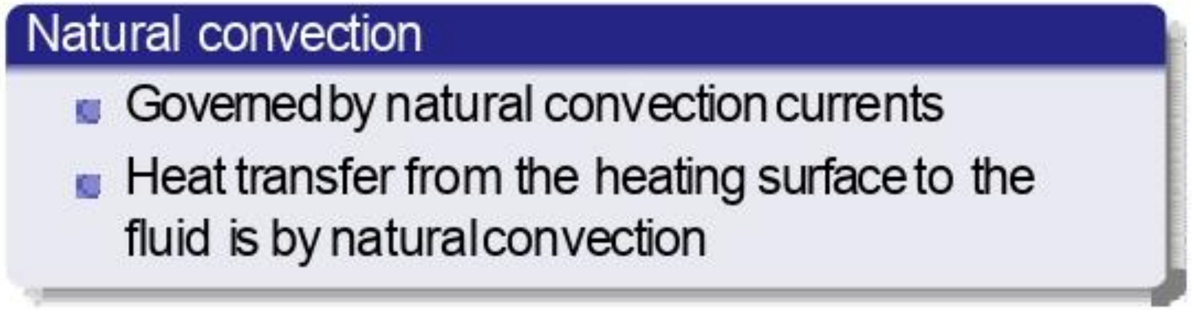
3. Regime of slugs and bubbles

4. Transition film boiling

5. Stable film boiling

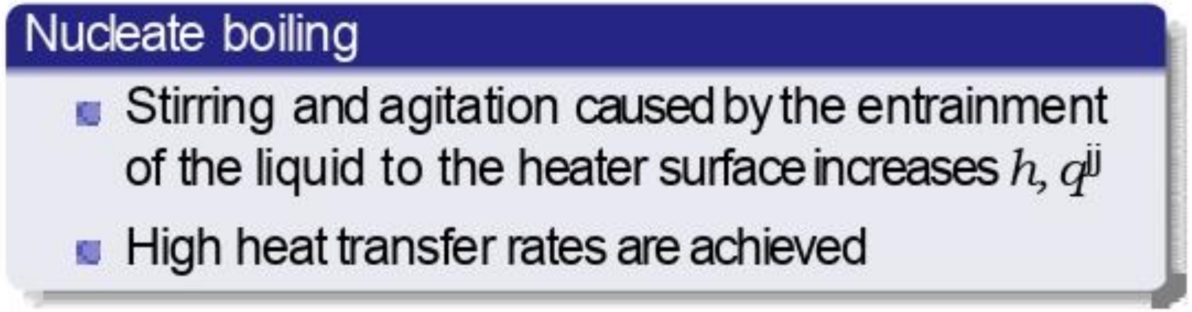
Boiling Regimes





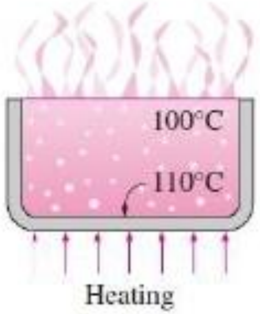
Natural convection

- Governed by natural convection currents
- Heat transfer from the heating surface to the fluid is by natural convection



Nucleate boiling

- Stirring and agitation caused by the entrainment of the liquid to the heater surface increases h, q''
- High heat transfer rates are achieved



Transition boiling

Unstable film boiling

- Governed by natural convection currents
- Heat transfer from the heating surface to the fluid is by natural convection

Film boiling

- Presence of vapor film is responsible for the low heat transfer rates
- Heat transfer rate increases with increasing ΔT_e as a result of heat transfer from the heated surface to the liquid through the vapor film by radiation.

Heat Transfer in Nucleate Boiling

Rohsenow postulated:

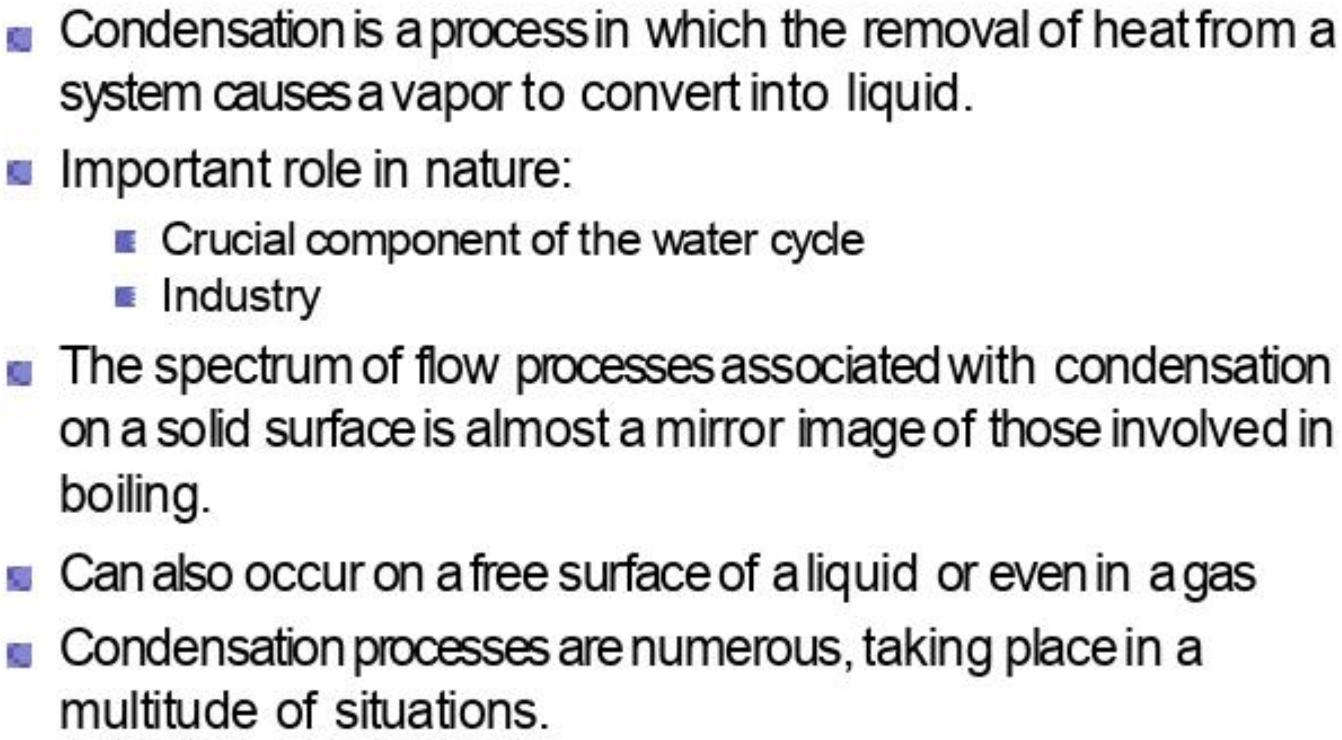
- Heat flows from the surface first to the adjacent liquid, as in any single-phase convection process
- High h is a result of local agitation due to liquid flowing behind the wake of departing bubbles

$$q''_s = \mu_l h_{fg} \left[\frac{g(\rho_l - \rho_v)}{\sigma}\right]^{1/2} \cdot \left(\frac{c_{p,l}\Delta T_e}{C_{s,f} h_{fg} \mathrm{Pr}_l^n}\right)^3$$

Nucleate boiling

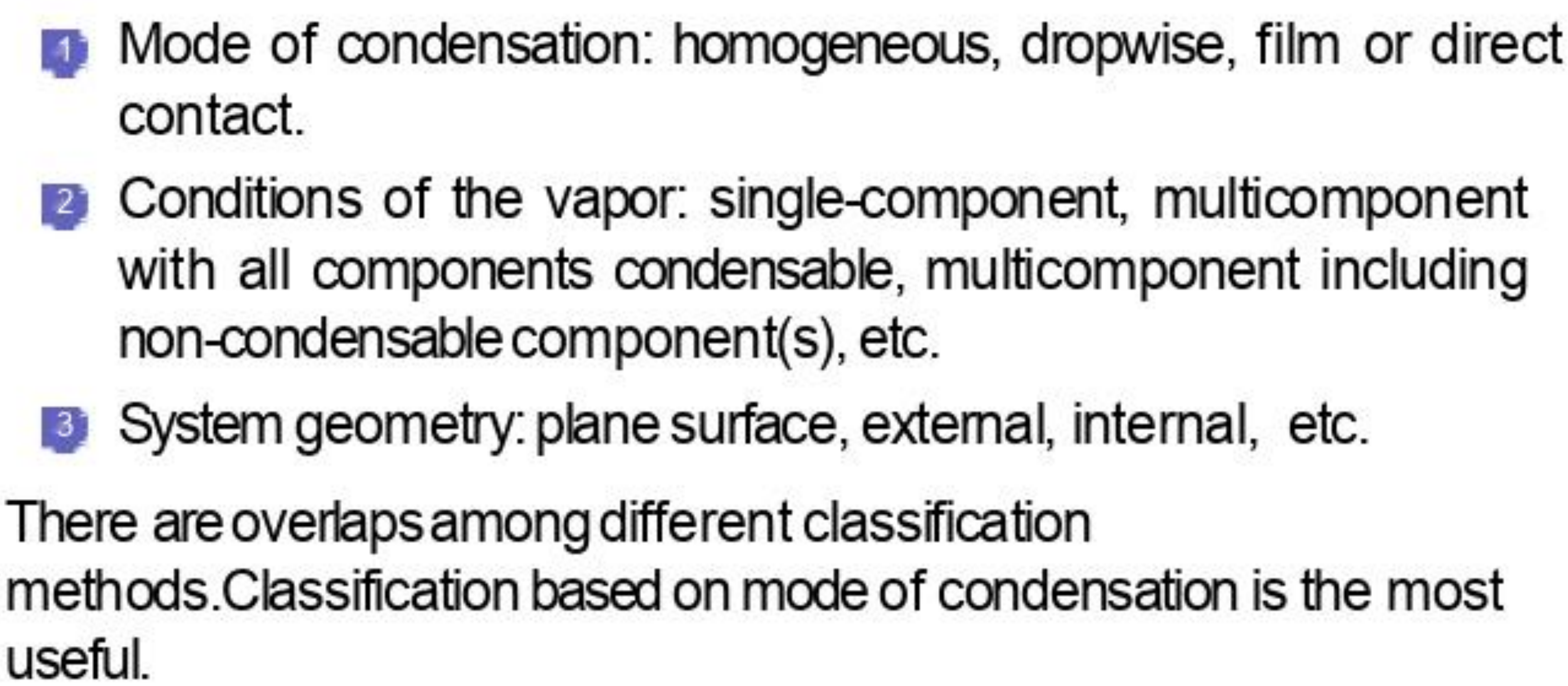
When used to estimate q'', errors can amount to $\pm 100\%$. The errors for estimating ΔT_e reduce by a factor of 3 $\because \Delta T_e \propto (q''_s)^{1/3}$

Condensation



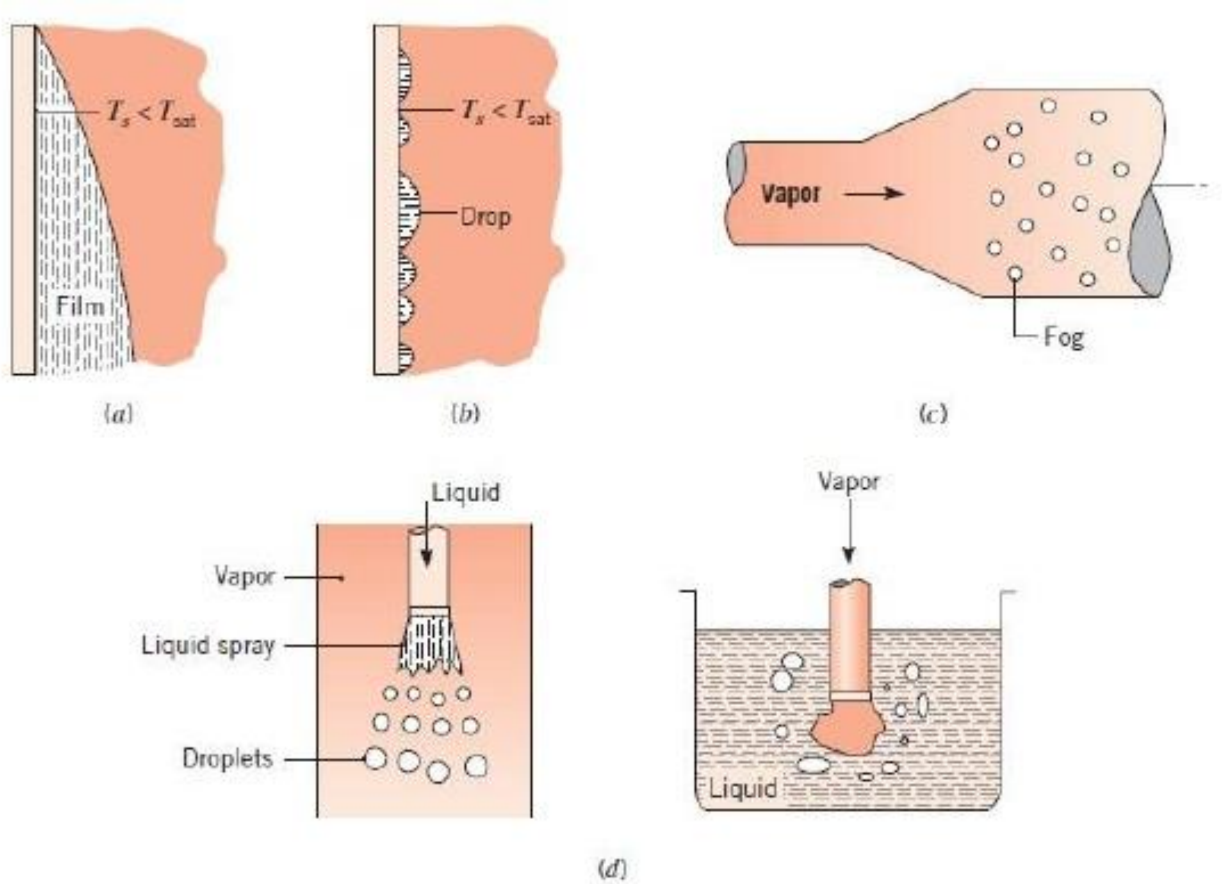
- Condensation is a process in which the removal of heat from a system causes a vapor to convert into liquid.
- Important role in nature:
  - Crucial component of the water cycle
  - Industry
- The spectrum of flow processes associated with condensation on a solid surface is almost a mirror image of those involved in boiling.
- Can also occur on a free surface of a liquid or even in a gas
- Condensation processes are numerous, taking place in a multitude of situations.

Classification of Condensation



1. Mode of condensation: homogeneous, dropwise, film or direct contact.
2. Conditions of the vapor: single-component, multicomponent with all components condensable, multicomponent including non-condensable component(s), etc.
3. System geometry: plane surface, external, internal, etc.

There are overlaps among different classification methods.Classification based on mode of condensation is the most useful.



Modes of condensation. (*a*) Film. (*b*) Dropwise condensation on a surface. (*c*) Homogeneous condensation or fog formation resulting from increased pressure due to expansion. (*d*) Direct contact condensation.

Film Condensation on Radial Systems

$$\mathrm{Nu}_D = \frac{h_D D}{k_l} = C \left[\frac{\rho_l g(\rho_l - \rho_v) h'_{fg} D^3}{\mu_l k_l (T_{sat} - T_s)} \right]^{1/4}$$

$C =$ 0.826 for sphere and 0.729 for the tube.

For N horizontal unfineed tubes, the average coeff.:

$$\bar{h}_{D,N} = \bar{h}_D N^n$$

$$n = -\frac{1}{4}$$