EPFL

Heat Pumps Systems

Heat Exchangers: Introduction

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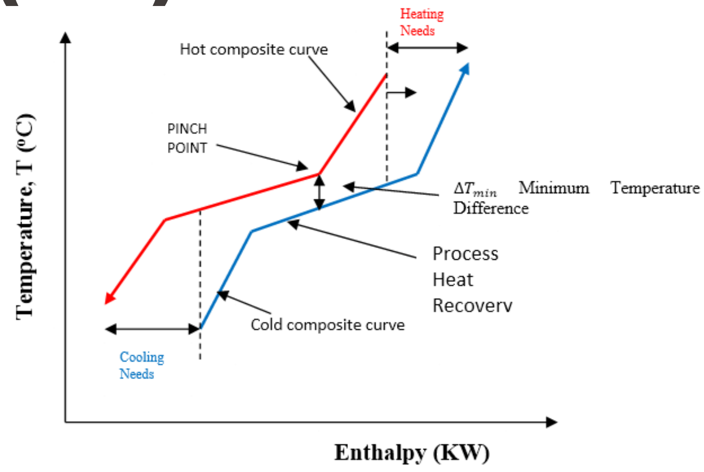
Learning Outcomes

- Identify common types of heat exchangers, including their typical applications, advantages, and limitations.
- Explain fundamental heat transfer mechanisms (conduction, convection, and radiation) relevant to heat exchanger analysis.
- Calculate the overall heat transfer coefficient (U) for specified heat exchanger applications.
- Design and evaluate heat exchanger performance based on given operational requirements.

Application of Heat Exchangers (HEX)

Heat Exchanger Definition:

Devices designed to transfer thermal energy between two or more fluids at different temperatures.



Application:

Chemical / Petroleum

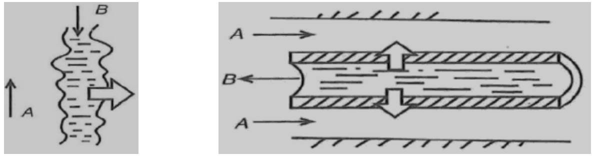
Food / Pharmaceutical

Domestic Housing

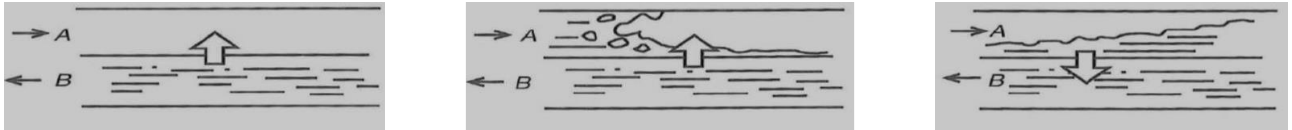
[10,11,12,20]

Classification of HEX

1. **Fluid Interaction:**
Direct contact vs. Indirect contact

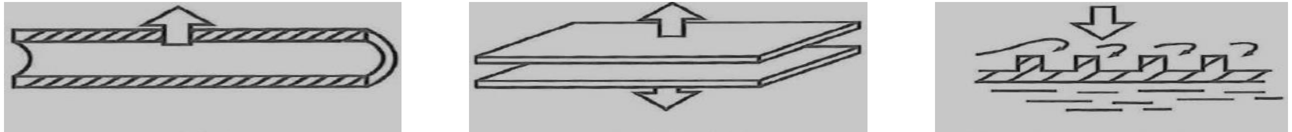


2. **Fluid Phases:** Single-phase vs. Multi-phase



(a) Single Phase (b) Evaporation (c) Condensation

3. **Geometry and Construction:** Shell-and-tube, plate, finned-tube, or other specialized geometries

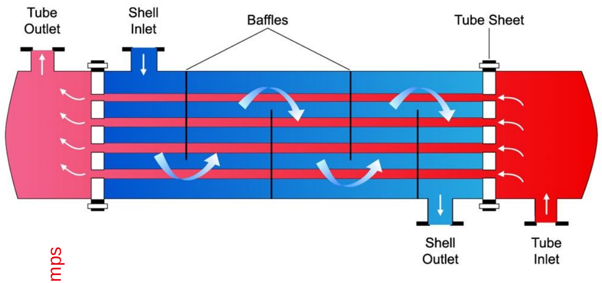


(a) Tubes (b) Plates (c) Enhanced Surfaces

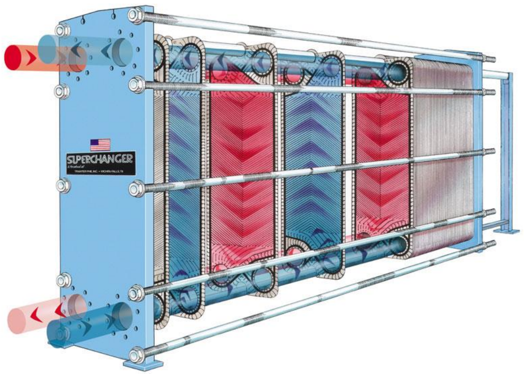
[3]

Types of HEX

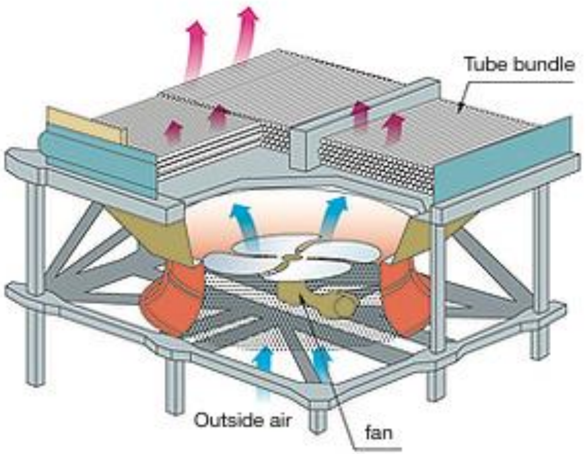
1) Shell and Tube



2) Plate

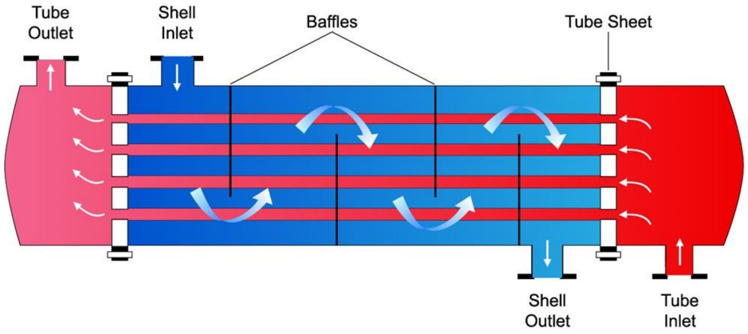


3) Air-Cooled (open)



Types of HEX: Shell and Tube

- Composed of a bundle of tubes enclosed in a cylindrical shell
- One fluid flows through the tubes (tube side), the other flows over the tubes within the shell (shell side)
- Baffles direct flow and enhance heat transfer by promoting turbulence
- Tube sheets hold the tubes and separate the fluids



[13,14]

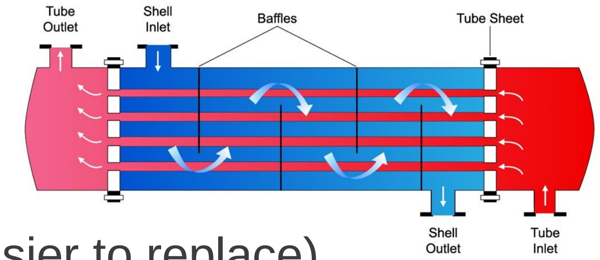
Types of HEX: Shell and Tube

Characteristics:

- Most common HEX in chemical/process industries
- Easy to access and clean (especially with removable tube bundles)
- Handles high pressures and temperatures
- Not suitable for low flow rates
- Established and reliable manufacturing
- Straightforward material selection
- Standardized, well-documented design

[15]

Types of HEX: Shell and Tube



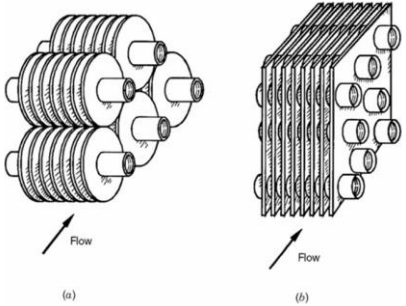
Design Considerations:

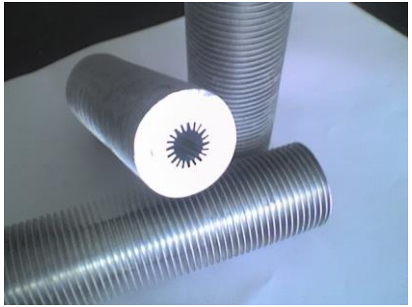
- Corrosion: More corrosive fluid in tube side (easier to replace)
- Fouling: Higher fouling fluid in tube side (higher velocity → less fouling; easier to clean)
- Temperature: Hottest fluid in tube side (lower heat loss; reduced safety and insulation costs)
- Pressure: Higher pressure fluid in tube side (easier to handle wall thickness)
- Pressure Drop: Low ΔP fluid in tube side (higher heat transfer at same ΔP)
- Viscosity: Higher viscosity fluid in shell side (Re > 200, promotes turbulence → better heat transfer)
- Flow Rate: Lower flow rate fluid in shell side

[14]

Types of HEX: Shell and Tube - Enhanced Designs

External and Internal Fins:





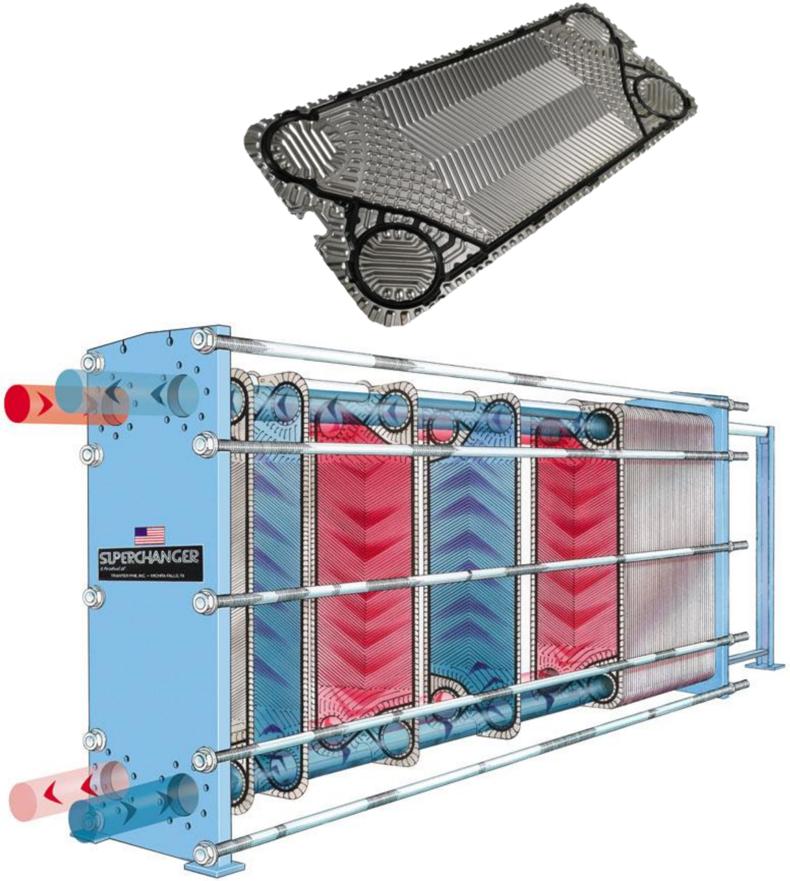
Advantages:
- Increases surface area
- Increases swirl / turbulence
- Enhances heat transfer

Disadvantages:
- Higher pressure drop
- Cleaning difficulty
- Higher cost

[24,25,26]

Types of HEX: Plate Heat Exchangers

- Thin metal plates stacked to form parallel flow channels
- Fluids flow in alternating channels (hot, cold, hot, cold...)
- Corrugated plate surfaces create turbulence and boost heat transfer
- Gaskets (removable) or brazing (permanent) seal the channels and control fluid flow



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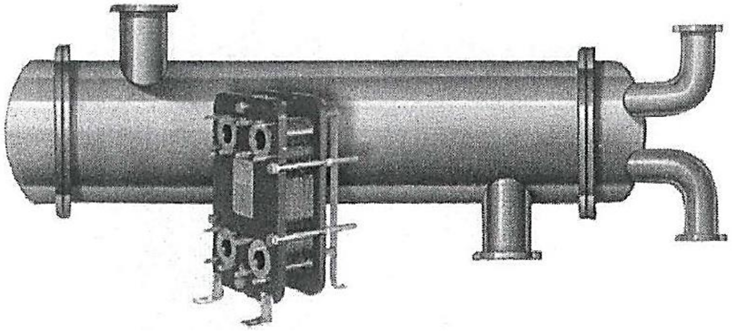
Types of HEX: Plate Heat Exchangers



Characteristics:

- Compact, high-performance design
- Small footprint
- Very high surface area density (>700 m^2/m^3, shell and tube ≈ 100 m^2/m^3)
- Flexible sizing for thermal duty (easy to add /remove plates)
- Easy to clean – ideal for food/pharma applications
- Allows close temperature approach (counter-current flow)
- High heat transfer efficiency: turbulence + thin flow paths

[3]

Types of HEX : Plate Heat Exchangers

Gasketed Plate:

- Plates not permanently bonded
- Max ~180°C, 16–30 bar
- Not suitable for aggressive solvents
- Gaskets direct flow and allow disassembly

Brazed Plate:

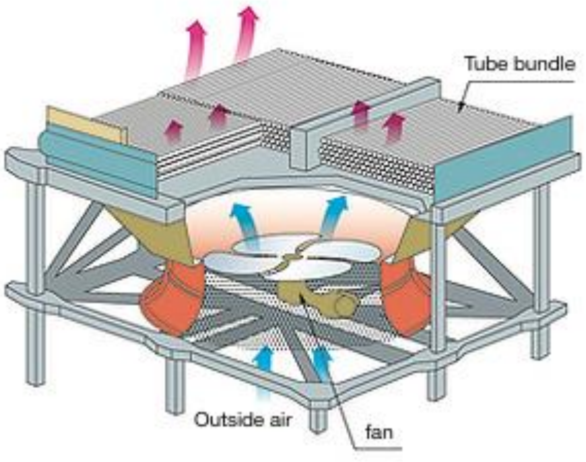
- Plates permanently bonded (no gaskets)
- More compact, non-serviceable
- Suitable for clean fluids and high pressure

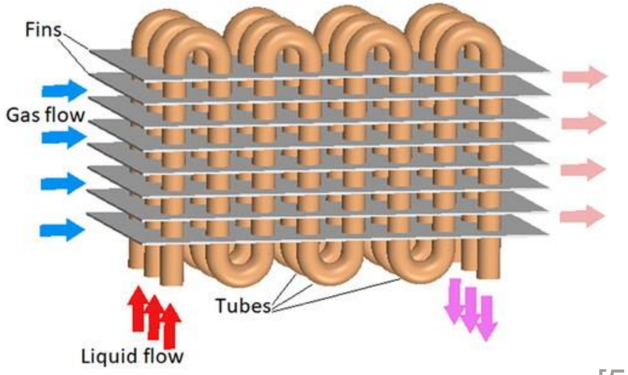
[16]

Types of HEX: Shell and Tube vs Plated

Types of HEX: Air-Cooled (Open)

- Open System: Uses ambient air (no separate fluid loop).
- Forced or Natural Convection: via fans/blowers (forced draft) or buoyancy (natural draft).
- Finned Tubes: Extended surface area compensates for air's lower heat transfer coefficient.
- Comparison to Shell & Tube/Plate:
  - No closed coolant circuit
  - Dust exposure risk
  - Larger footprint





[5,6]

Types of HEX: Air-Cooled (Open)

Advantages:

- Saves water
- Uses ambient air (readily available, lack of other options)
- No flow cross-contamination
- Lower maintenance (no fouling or chemical treatment)
- Lower capital cost

Disadvantages:

- Lower thermal efficiency (air has low conductivity, density, and heat capacity)
- Requires more space
- Noisy (high acoustic emissions)
- Climate sensitive: High temperatures or dust reduce performance and increase maintenance.

Types of HEX: Air-Cooled (Open)

Applications:

- HPS:



- Industrial Cooling:


- Transportation:

[17,18,19,3,21]

Heat Pumps Systems

Heat Exchangers: Heat Transfer

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Heat Transfer

Conduction:

- Heat transfer mechanism within solids or a stationary liquids
- Heat transferred by molecular scale energy diffusion

Convection:

- Heat transfer between a moving fluid and a surface
- Coupling between fluid motion and fluid conduction

Radiation:

- Heat transfer via electromagnetic radiation
- No medium required (→ vacuum, space)

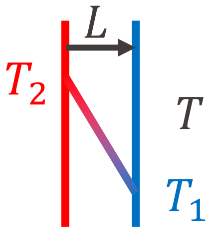
Heat Transfer - Conduction

- Governed by Fourier's law:

$$Q = -kA\nabla T = UA\Delta T \quad where\ UA = \frac{1}{R_{cond}}$$

Planar Wall:

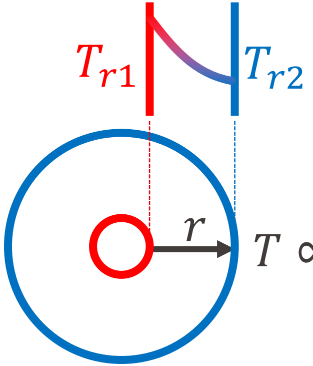
$$R_{cond} = \frac{L}{kA}$$



$T \propto L$

Radial Wall:

$$R_{cond-cyl} = \frac{\ln(\frac{r_2}{r_1})}{2\pi Lk}$$



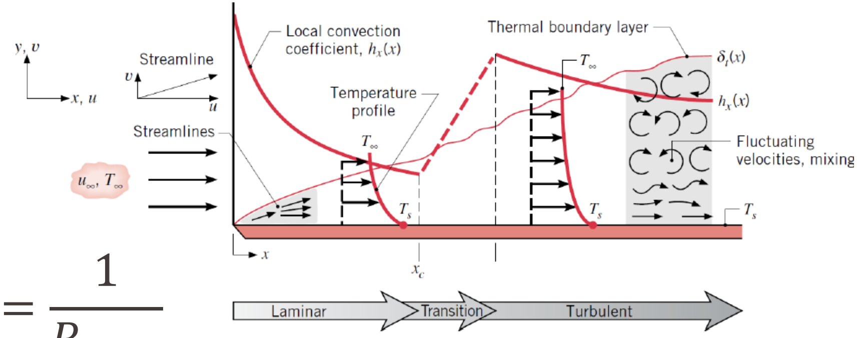
$T \propto ln(\mathrm{r})$

- Typical values for conductivity

	k[W/mK]
Gases	0.01 – 0.2
Liquids	0.1 - 1
Solids	1 - 450

	k[W/mK]
Insulating Materials	0.025-0.173
Steel	50
Aluminium	220
Copper	395

Heat Transfer - Convection



- Governed by Newton's law:

$$Q = hA(T_s - T_\infty) = UA\Delta T \quad where\ UA = \frac{1}{R_{conv}}$$

Planar Wall:

$$R_{conv} = \frac{1}{hA}$$

Radial Wall:

$$R_{conv-cyl} = \frac{1}{h2\pi rL}$$

- Convection Classification:

		Flow Regime	
		Laminar	Turbulent
Driving Mechanism	Natural (free)	Air rising near wall	Chimney flow at high T
	Forced	Slow flow in a pipe	Fan-driven air over heater

[9]

Heat Transfer – Convection: Forced

- **Forced Convection:** Driven by external forces (e.g. fans, pumps), fluid motion is imposed.

$$\mathrm{Nu} = \frac{hx}{k_f} = \frac{\text{convection}}{\text{conduction}} = f(Re, Pr) \quad \text{where} \quad Re = \frac{vx}{\nu} = \frac{\text{inertial forces}}{\text{viscous forces}}$$

- Fluid properties condensed into Pr-number:

$$\mathrm{Pr} = \frac{\nu}{\alpha} = \frac{\text{momentum diffusivity}}{\text{thermal diffusivity}} \quad \text{where} \quad \alpha = \frac{k}{\rho c_p} = \frac{\text{conduction}}{\text{energy storage}}$$

Heat Transfer – Convection: Natural

- **Natural (Free) Convection:** Driven by buoyancy forces arising from temperature-induced density differences. Fluid motion occurs naturally due to gravity acting on these density gradients.

$$\mathrm{Nu} = \frac{hx}{k_f} = f(Gr, Pr) \quad \text{where} \quad Gr = \frac{x^3 g\beta\Delta T}{\nu^2} = \frac{\text{buoyancy forces}}{\text{viscous forces}}$$

- Fluid properties condensed into Pr-number:

$$\mathrm{Pr} = \frac{\nu}{\alpha} = \frac{\text{momentum diffusivity}}{\text{thermal diffusivity}} \quad \text{where} \quad \alpha = \frac{k}{\rho c_p} = \frac{\text{conduction}}{\text{energy storage}}$$

Heat Transfer – Convection: Correlations

- Forced Convection: Plate, turbulent

$$\overline{Nu_x} = 0.664 Re_x^{1/2} Pr^{1/3}$$

- Forced Convection: Cylinder, external, turbulent (Churchill-Bernstein)

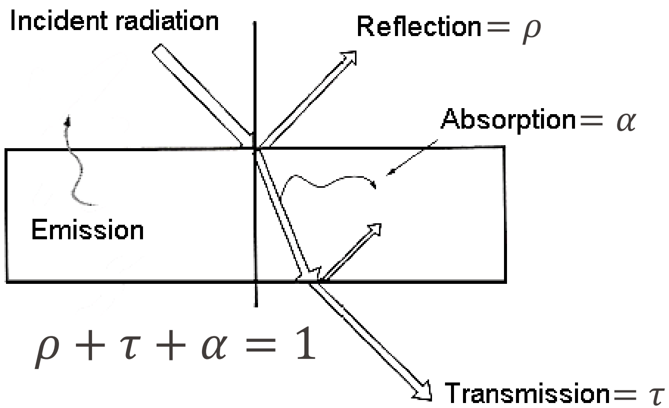
$$\overline{Nu_D} = 0.3 + \frac{0.62 Re_D^{1/2} Pr^{1/3}}{\left[1 + (0.4/Pr)^{2/3}\right]^{1/4}} \left[1 + \left(\frac{Re_D}{282000}\right)^{5/8}\right]^{4/5}$$

- Empirical correlations only valid within designed operating conditions (Re, Pr) and geometry limits.
- Typical uncertainty in h: $\pm 30[\%]$.
- Convection coefficients are the bottleneck in HEX design.

Heat Transfer - Radiation

- Governed by the Stefan-Boltzmann law:

$$Q = A\epsilon\sigma T^4, where\ \sigma = 5.67 * 10^{-8}\left[\frac{W}{m^2K^4}\right]$$



$$\rho + \tau + \alpha = 1$$

- Kirchhoff's Law: at thermal equilibrium $\epsilon_\lambda(T,\theta,\phi) = \alpha_\lambda(T,\theta,\phi)$
- Blackbody: Perfect absorber and emitter.
- Emissivity ($0 < \epsilon \leq 1$): Measure of emissive power of real surfaces (non-blackbody) relative to blackbody ($\epsilon = 1$).

$$e_{non-black} = \epsilon e_b = \epsilon\sigma T^4$$

- Emissivity depends on: surface shape, material properties, surface finish, and orientation.

[4]

Heat Transfer – Fouling

- **Fouling:** Buildup of unwanted materials on heat transfer surfaces that reduces efficiency and increases pressure drop.
- Major issue in heat exchanger performance

Common fouling types:

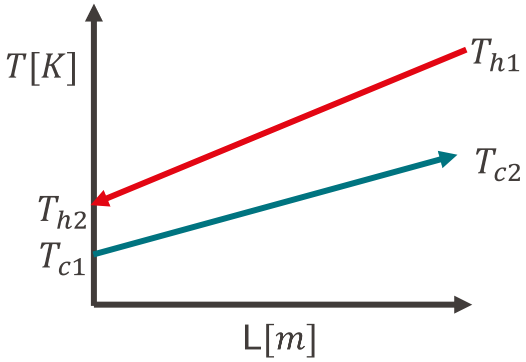
- Scaling (e.g., calcium carbonate deposits)
- Corrosion (metal oxide layers)
- Biological (biofilms in cooling water)
- Particulate (suspended solids)
- Chemical (reaction byproducts)

[3]

Heat Transfer – Overall Heat Transfer Coefficient

- Overall heat transfer coefficient U: represents the heat exchanger's ability to transfer heat per unit area per unit temperature difference.

$$\dot{Q} = UA\Delta T_{lm} = \frac{\Delta T_{lm}}{R_{tot}}$$



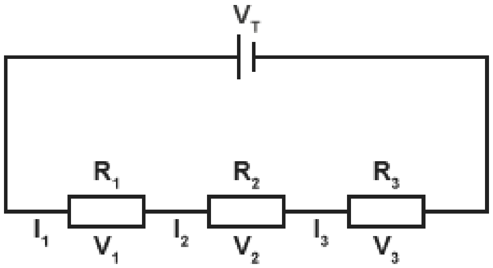
- Logarithmic mean temperature difference:

$$\Delta T_{lm}(\text{counter flow}) = \frac{T_{h2} - T_{c1} - T_{h1} + T_{c2}}{\ln\left(\frac{T_{h2} - T_{c1}}{T_{h1} - T_{c2}}\right)}$$

- If $T_{h2} - T_{c1} = T_{h1} - T_{c2}$ then $\Delta T_{lm} = T_{h1} - T_{c2}$

Heat Transfer – Thermal Resistance

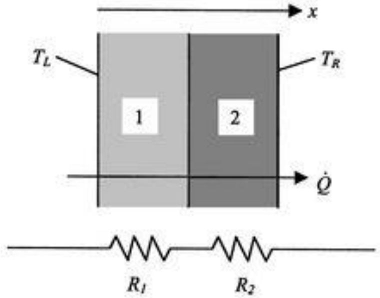
- Electrical Circuit:



$$I = \frac{\Delta V}{R}$$

$$R = R_1 + R_2 + R_3$$

- Thermal Circuit:



$$\dot{Q} = \frac{\Delta T}{R_{tot}}$$

$$R_{tot} = R_1 + R_2$$

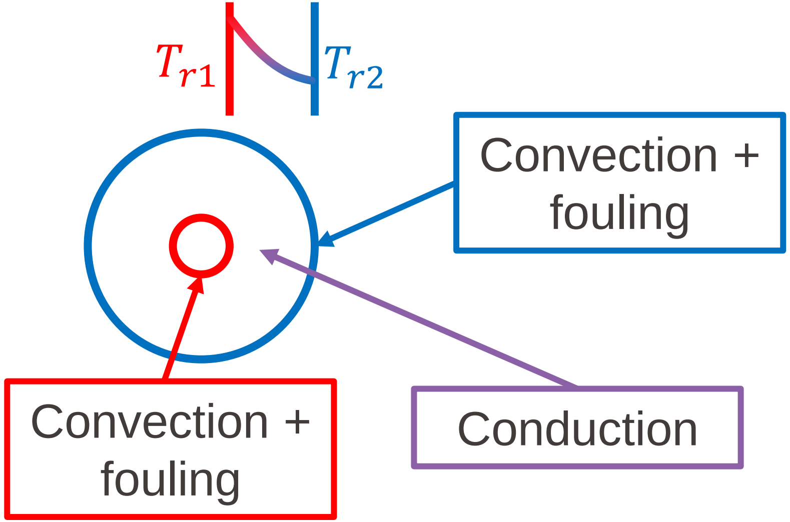
	Electrical Circuits	Thermal Circuits
Driving Force	Voltage difference ΔV [V]	Temperature Difference ΔT[K]
What Flows	Electric current I [A]	Heat Rate $\dot{Q}$ [W]
Opposition to Flow	Resistance R [Ω]	Thermal Resistance R_{tot} [K/W]

[22,23]

Heat Transfer – Thermal Resistance

- Pipe Flow

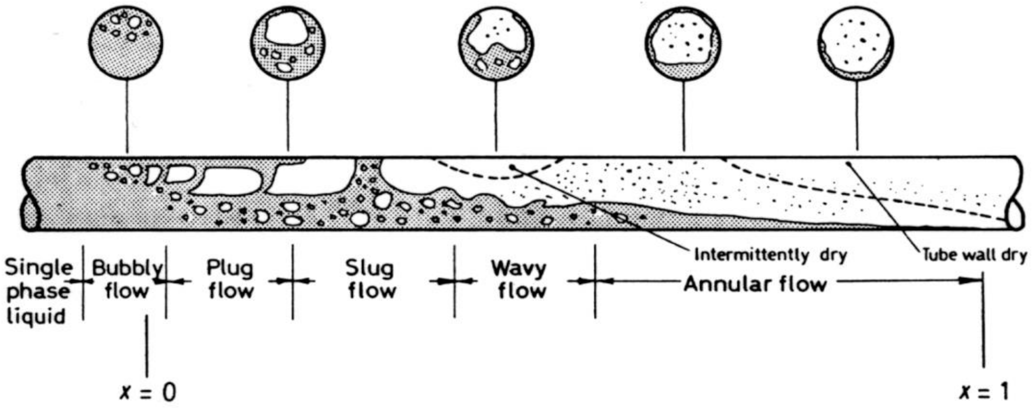
$$\dot{Q} = UA\Delta T_{lm} = \frac{\Delta T_{lm}}{R_{tot}}$$



$$\frac{1}{R_{tot}} = \sum \frac{1}{R} = \frac{1}{R_{\text{conv,h}}} + \frac{1}{R_{\text{foul,h}}} + \frac{1}{R_{\text{cond}}} + \frac{1}{R_{\text{foul,c}}} + \frac{1}{R_{\text{conv,c}}}$$

- R_{tot} is dominated by largest resistance (i.e., lowest heat transfer coefficient).
- Assumption: steady state, no phase change, constant properties

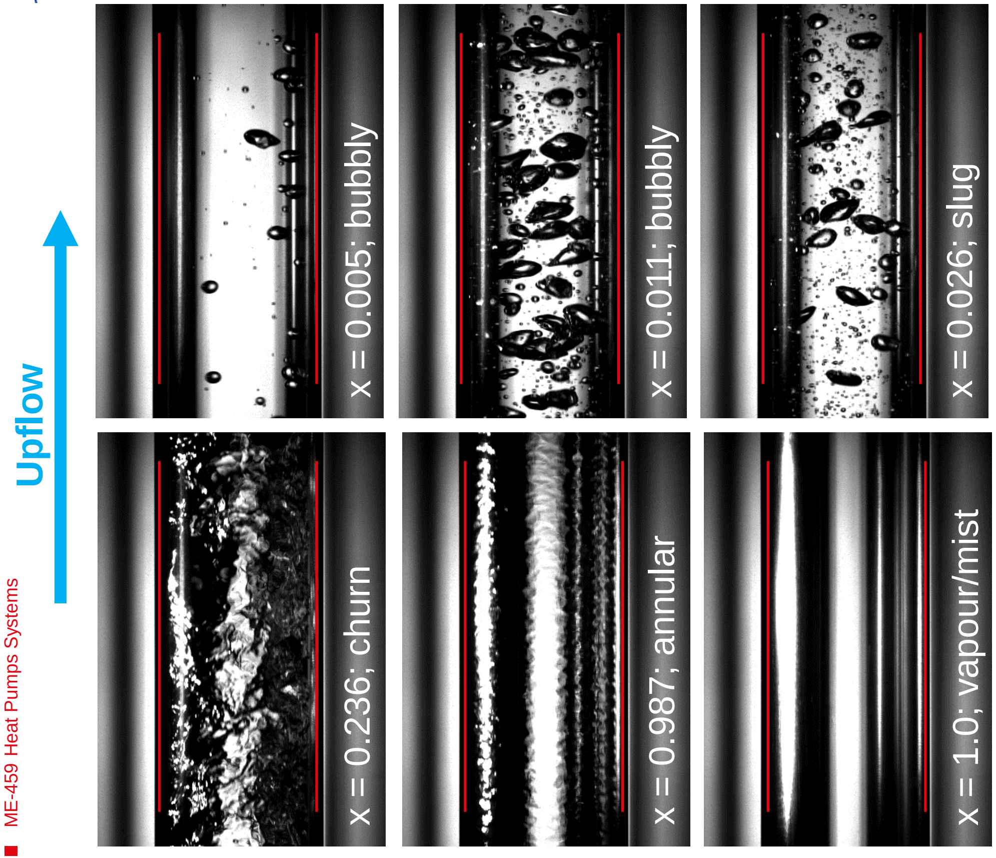
Heat Transfer – 2 Phase



- **x = 0:** Single-phase liquid enters; heating initiates bubble formation.
- **Bubbly → Plug/Slug flow:** Bubbles grow, coalesce, and form vapor slugs.
- **Wavy flow:** Vapor dominates core; liquid intermittently wets wall.
- **Annular flow:** Thin liquid film on walls, central vapor core.
- **Near x = 1:** Wall intermittently or fully dry.

[2]

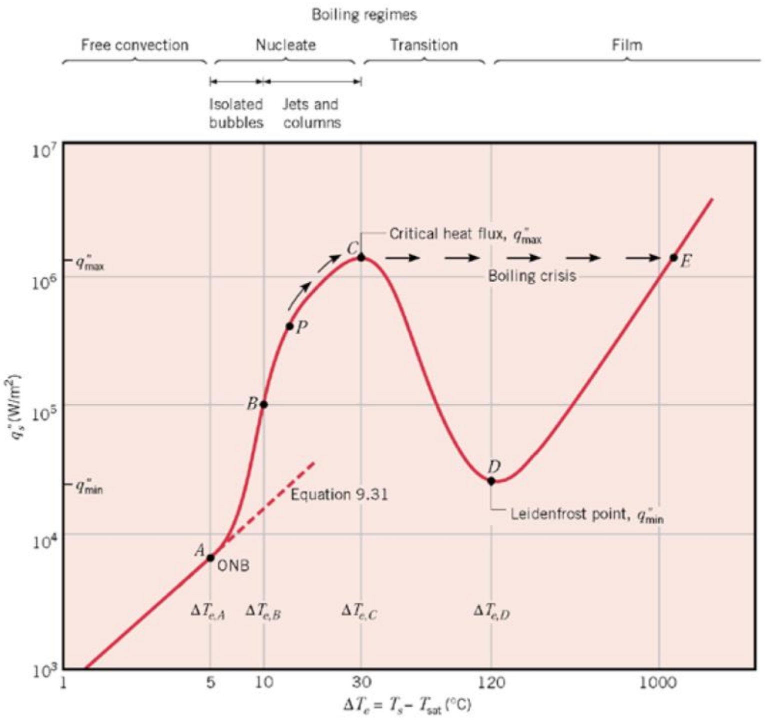
Heat Transfer – 2 Phase: Flow Pattern



CO_2, T = -25°C; G = 200 $\mathrm{kg\,m^{-2}\,s^{-1}}$

D. Schmid, B. Verlaart, P. Petagna, R. Revellin, J. Schiffmann. **Flow Pattern Observations and flow pattern map for adiabatic two-phase flow of carbon-dioxide in vertical upward and downward direction**. Experimental Thermal and Fluid Sciences, vol. 131, 110526, 2022.

Heat Transfer – 2 Phase: Boiling Crisis

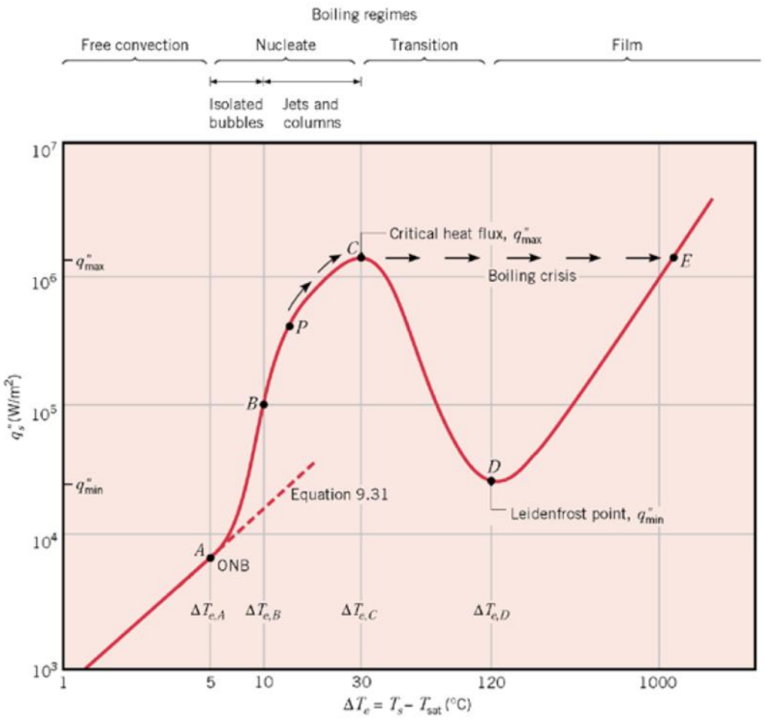


$$q_s" = h(T_s - T_{sat}) = h\Delta T_e$$
$$T_s = \text{surface } T, T_{sat} = \text{saturation } T, \Delta T_e = \text{excess } T$$

- A: Onset of nucleate boiling
- A->C: Nucleate boiling
- C: Critical heat flux ($q"_{max}$)
- C->D: Transition boiling
- D: Leidenfrost point ($q"_{min}$)
- D->E: Film boiling

[1]

Heat Transfer – 2 Phase: Boiling Crisis



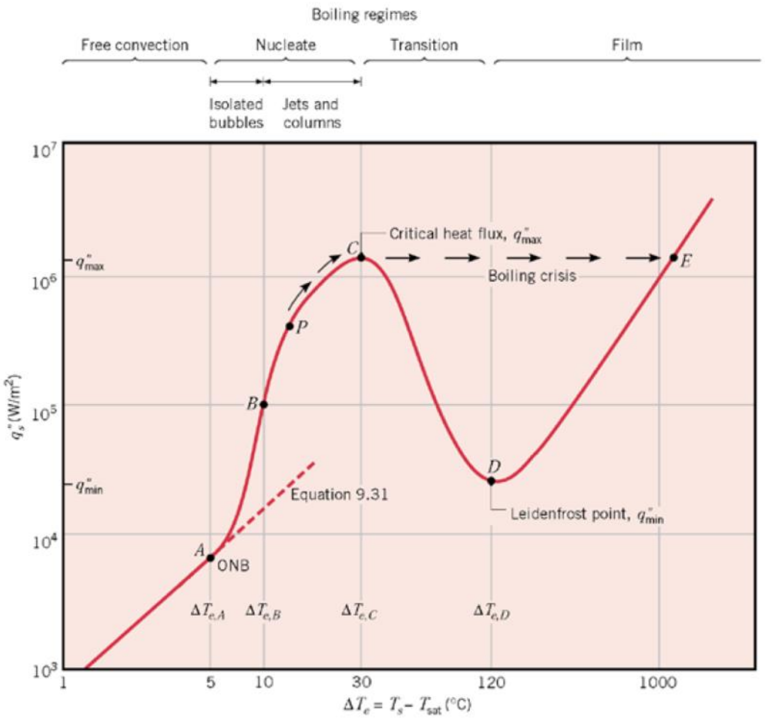
$$q_s" = h(T_s - T_{sat}) = h\Delta T_e$$
$$T_s = \text{surface } T, T_{sat} = \text{saturation } T, \Delta T_e = \text{excess } T$$

Nucleate Boiling:

- Liquid contacts the hot surface.
- Bubbles form, grow, and depart.
- Phase change efficiently removes heat (via latent heat).
- Surface is well-wetted, and heat transfer is very high.

[1]

Heat Transfer – 2 Phase: Boiling Crisis



$$q_s'' = h(T_s - T_{sat}) = h\Delta T_e$$

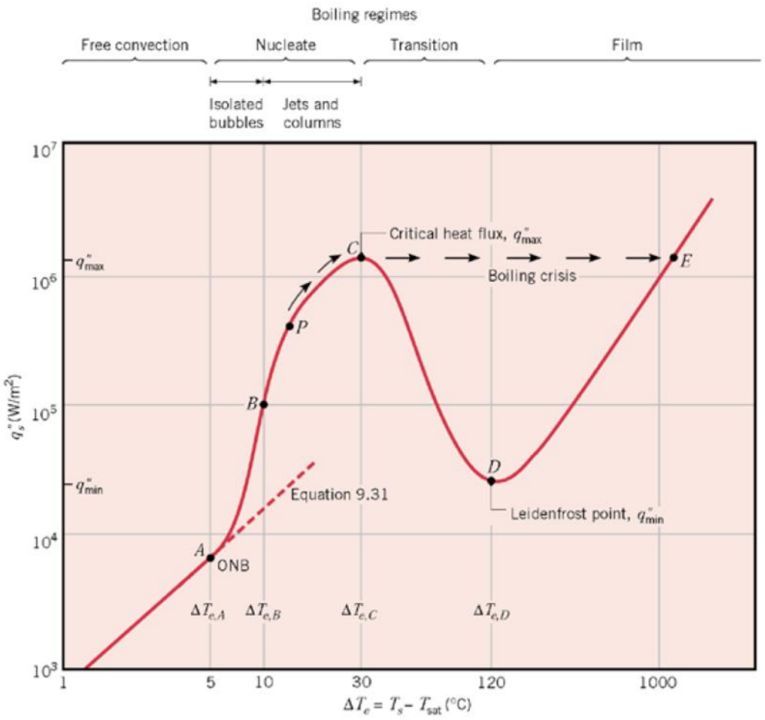
$$T_s = \text{surface } T, T_{sat} = \text{saturation } T, \Delta T_e = \text{excess } T$$

Critical Heat Flux:

- Heat input becomes so intense that bubbles form too fast to detach or be replaced by liquid.
- Bubbles coalesce into a vapor film that blankets the surface.
- Liquid can no longer reach the surface.

[1]

Heat Transfer – 2 Phase: Boiling Crisis



$$q_s" = h(T_s - T_{sat}) = h\Delta T_e$$

$$T_s = \text{surface } T, T_{sat} = \text{saturation } T, \Delta T_e = \text{excess } T$$

Beyond Critical Heat Flux:

- A vapor film forms with much lower thermal conductivity than liquid.
- The surface becomes insulated → surface temperature spikes → heat transfer drops.
- This is the boiling crisis: risk of overheat and thermal failure/burnout.

[1]

Heat Pumps Systems

Heat Exchangers: Design

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HEX Design Steps: Shell and Tube

Step 1: Define Problem Bounds

- Establish specifications (size, pressure losses, cost)
- Calculate energy balance (load)
- Estimate unspecified flow rates or temperatures
- Collect thermophysical properties

HEX Design Steps: Shell and Tube

Step 1: Define Problem Bounds

Step 2: Estimate Heat Transfer Coefficients / Performance

- Estimate overall heat transfer coefficient U (literature)
- Estimate the heat transfer area required

HEX Design Steps: Shell and Tube

Step 1: Define Problem Bounds

Step 2: Estimate Heat Transfer Coefficients / Performance

Step 3: Initial Sizing

- Decide number of passes within HEX
- Decide tube size and material
- Decide number of baffles
- Assign fluid to shell or tube side

- Calculate number of tubes
- Calculate shell diameter

HEX Design Steps: Shell and Tube

Step 1: Define Problem Bounds

Step 2: Estimate Heat Transfer Coefficients / Performance

Step 3: Initial Sizing

Step 4: Calculate Heat Transfer Coefficients

- Calculate tube side heat transfer coefficient
- Calculate shell side heat transfer coefficient
- Calculate remaining thermal resistances
- Calculate overall heat transfer coefficient

If $0\% < \frac{U_{calc} - U_{ass}}{U_{ass}} < 30\% \rightarrow$ Step 2

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HEX Design Steps: Shell and Tube

Step 1: Define Problem Bounds

Step 2: Estimate Heat Transfer Coefficients / Performance

Step 3: Initial Sizing

Step 4: Calculate Heat Transfer Coefficients

Step 5: Evaluate Against Specification

- Calculate tube and shell side pressure drop

$$\Delta P = 8 j_f \left(\frac{l}{d}\right)\left(\frac{\rho u^2}{2}\right)\left(\frac{\mu}{\mu_w}\right)^{-m}$$

- Calculate HEX cost

If $P_{drop-calc} > P_{drop-spec}$ → Step 2

If $Cost_{calc} > Cost_{spec}$ → Step 2

Accept Design !!

Content Summary

- Identify common types of heat exchangers, including their typical applications, advantages, and limitations.
- Explain fundamental heat transfer mechanisms (conduction, convection, and radiation) relevant to heat exchanger analysis.
- Calculate the overall heat transfer coefficient (U) for specified heat exchanger applications.
- Design and evaluate heat exchanger performance based on given operational requirements.

Complimentary Literature

- A Heat Transfer Textbook (https://ahtt.mit.edu/)
- VDI Heat Atlas (https://link.springer.com/referencework/10.1007/978-3-540-77877-6)
- Chemical Engineering Design (https://www.sciencedirect.com/book/9780080966595/chemical-engineering-design)

Outlook for W13

- Transcritical Heat Pumps

- Ejectors in Heat Pumps

Exercises W12

- Theory questions / Exam style multiple choice
- Heat CO_2
- Designing a counter flow shell and tube heat exchanger

Sources

1. https://edu.epfl.ch/coursebook/en/heat-and-mass-transfer-ME-341
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