EN 410
Energy Management

Gurubalan Annadurai
guru.a@iitm.ac.in

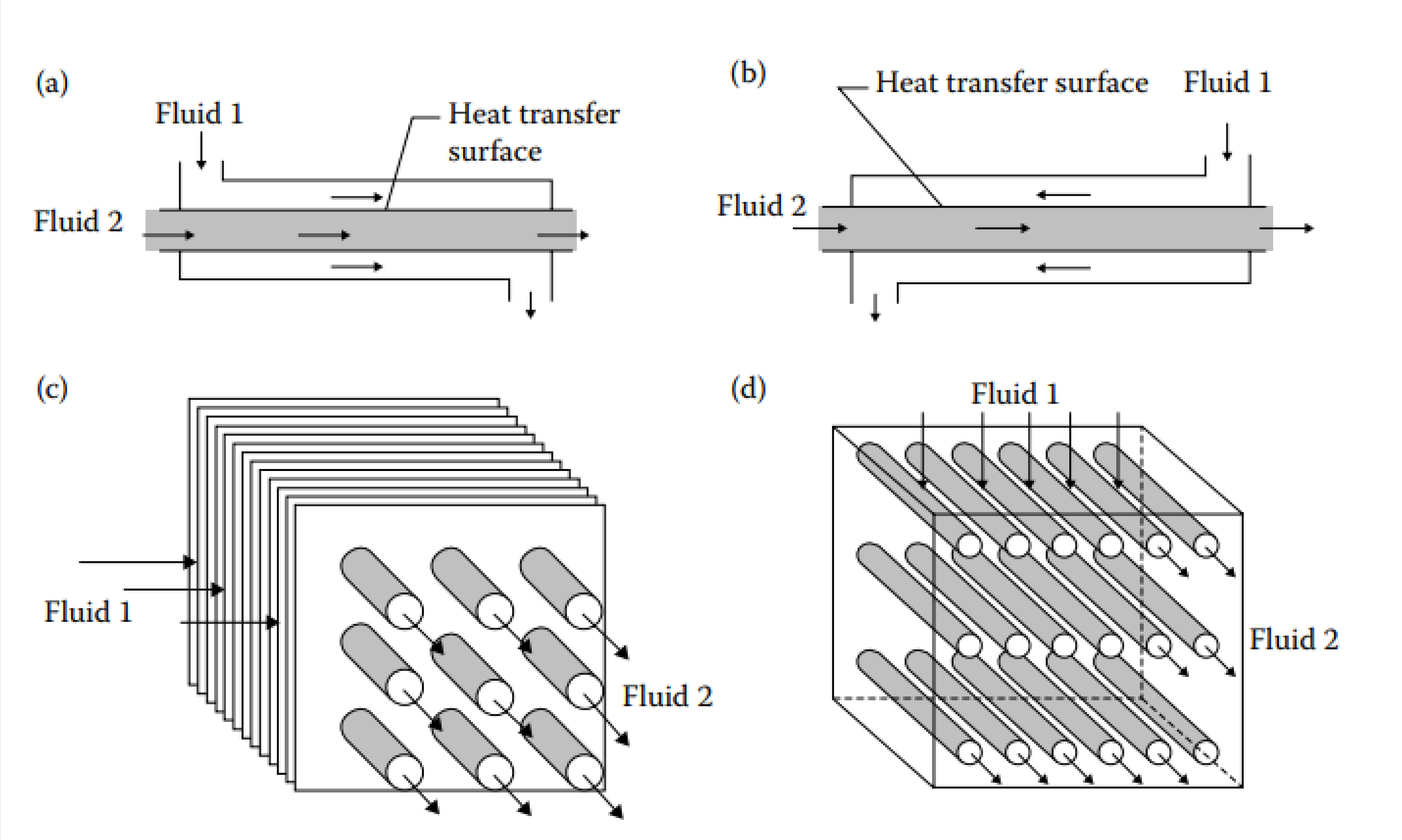
Heat Exchanger

A heat exchanger is a device which allows transfer of heat energy from one fluid to another fluid, generally without mixing.

- To get fluid streams to the right temperature for the next process (reactions often require feeds at high temp)
- To condense vapours
- To evaporate liquids
- To recover heat to use elsewhere
- To reject low-grade heat
- To drive a power cycle

Types according to flow

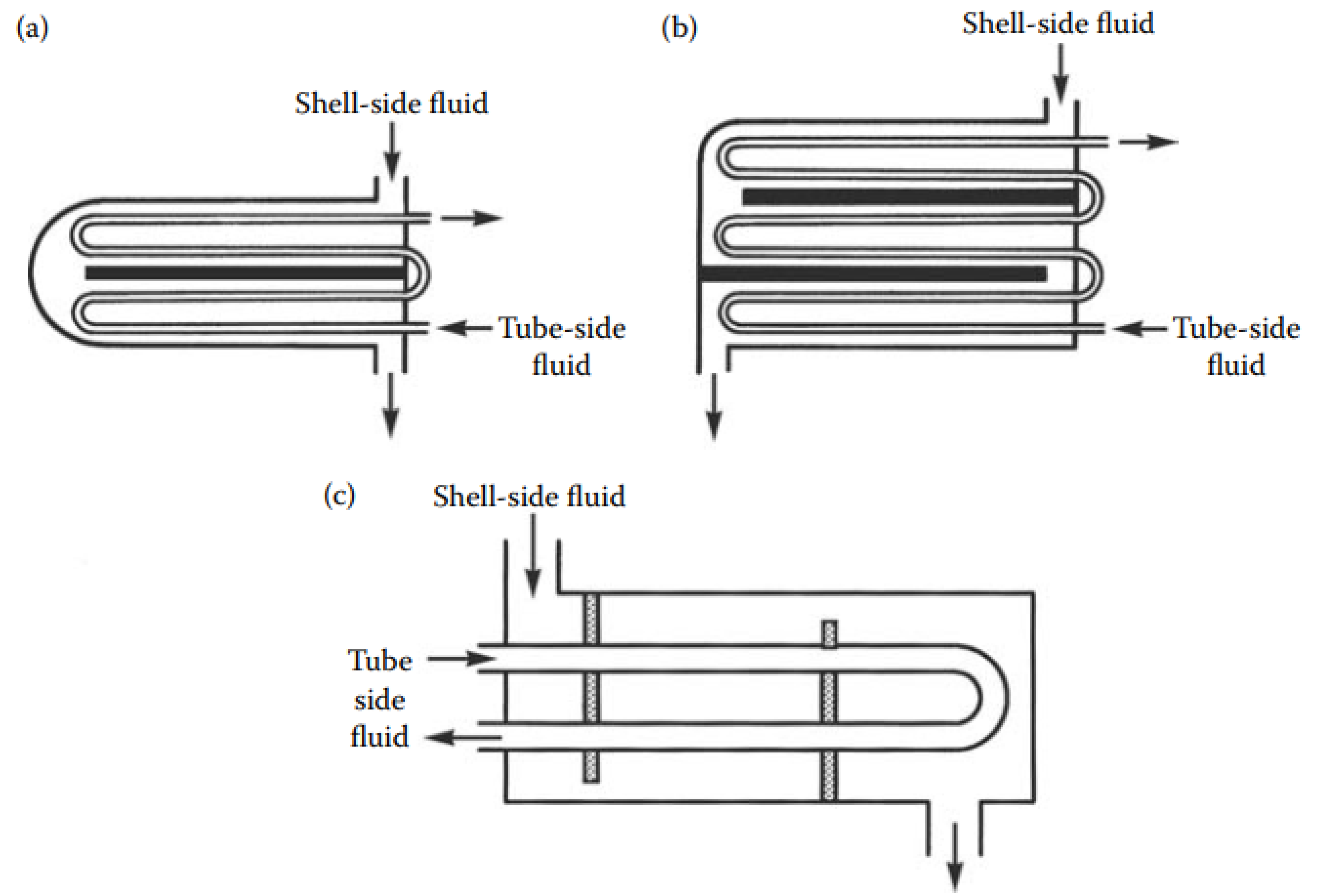
- Pumping power
- Both at almost same exit temperature
- Moderate wall temperature



Best performance (later proved based on LMTD)

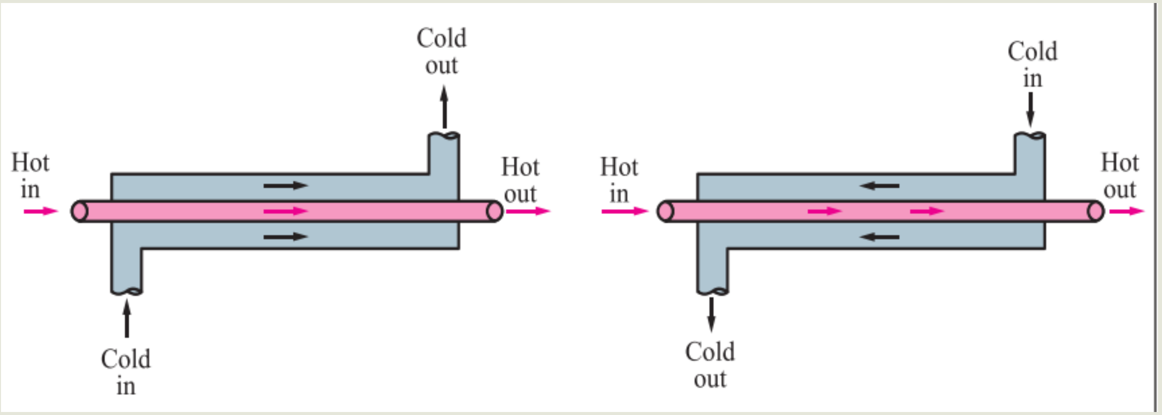
- Multi-pass requirement
- Header arrangement

Multipass arrangement

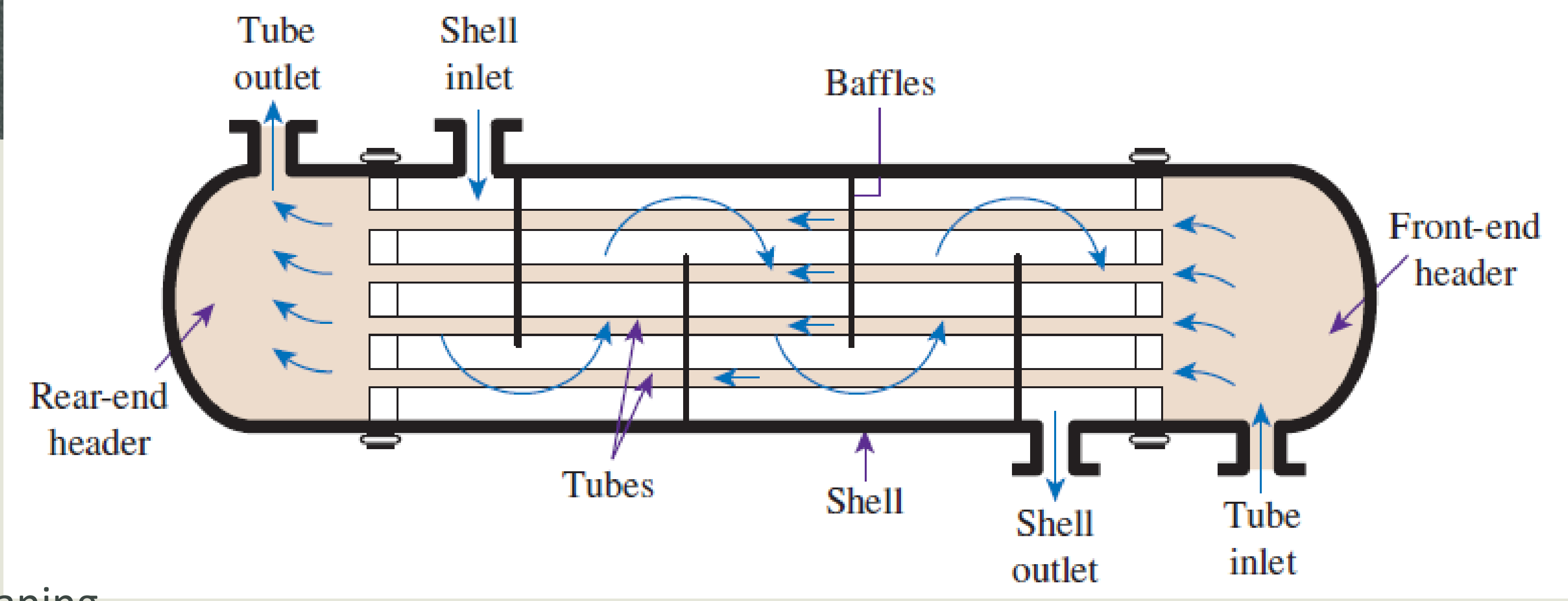


Types by construction – Double pipe HX

- Simplest type has one tube inside another
- Normal size - 0.25 to 200 m^2
- Multiple units are often used
- Advantages
  - Easy to obtain counter-current flow
  - Can handle high pressure
  - Easy to maintain and repair
  - Modular construction
- Disadvantage
  - Become expensive for large duties (above 1 MW)



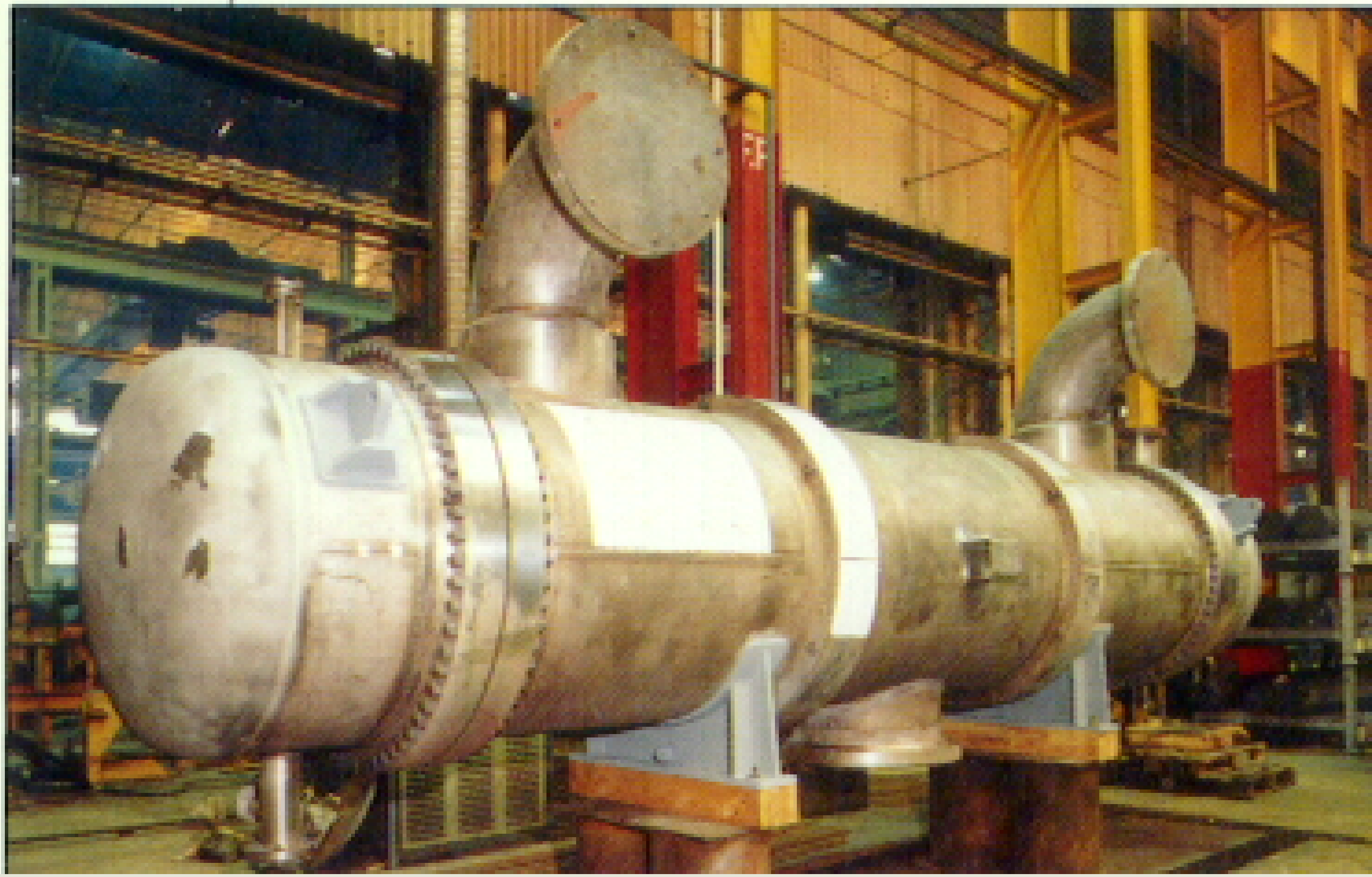
Shell and tube HX



- Size per unit - 10 - 1000 m^2
- Easy to build multiple units
- Advantages
    - Extremely flexible and robust design
    - Easy to maintain and repair
    - Can be designed to be dismantled for cleaning
    - Many suppliers
- Disadvantages
    - Require large plot (footprint) area - often need extra space to remove the bundle
    - Flow-induced vibrations, noise, thermal stresses, and entry impingement problems

Scope of shell and tube HX

- Maximum pressure
  - 300 bar (abs) on shell side
  - 1400 bar (abs) on tube side
- Temperature range
  - -100 to 600°C (-150 to 1100°F)
  - possibly wider with special materials
- Fluid limitations
  - Few since can be built of many metals



Allocation of Fluids

- Put dirty stream on the tube side - easier to clean inside the tubes
- Put high pressure stream in the tubes to avoid thick, expensive shell
- When special materials required for one stream, put that one in the tubes to avoid expensive shell
- Cross flow gives higher coefficients than in plane tubes, hence put fluid with lowest coefficient on the shell side

Plate HX

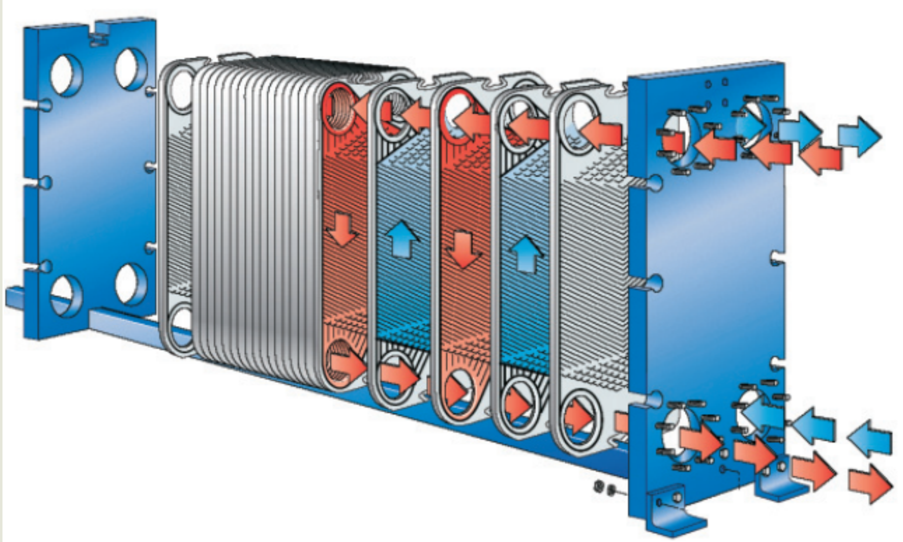
“Plate exchanger” normally refers to a gasketed plate- and-frame exchanger

Advantages

- High heat transfer coefficients
- Even distribution of heat transfer no hot/cold spot
- Contains small amount of fluid which is useful for quick transient
- Low pressure drop
- Easy cleaning

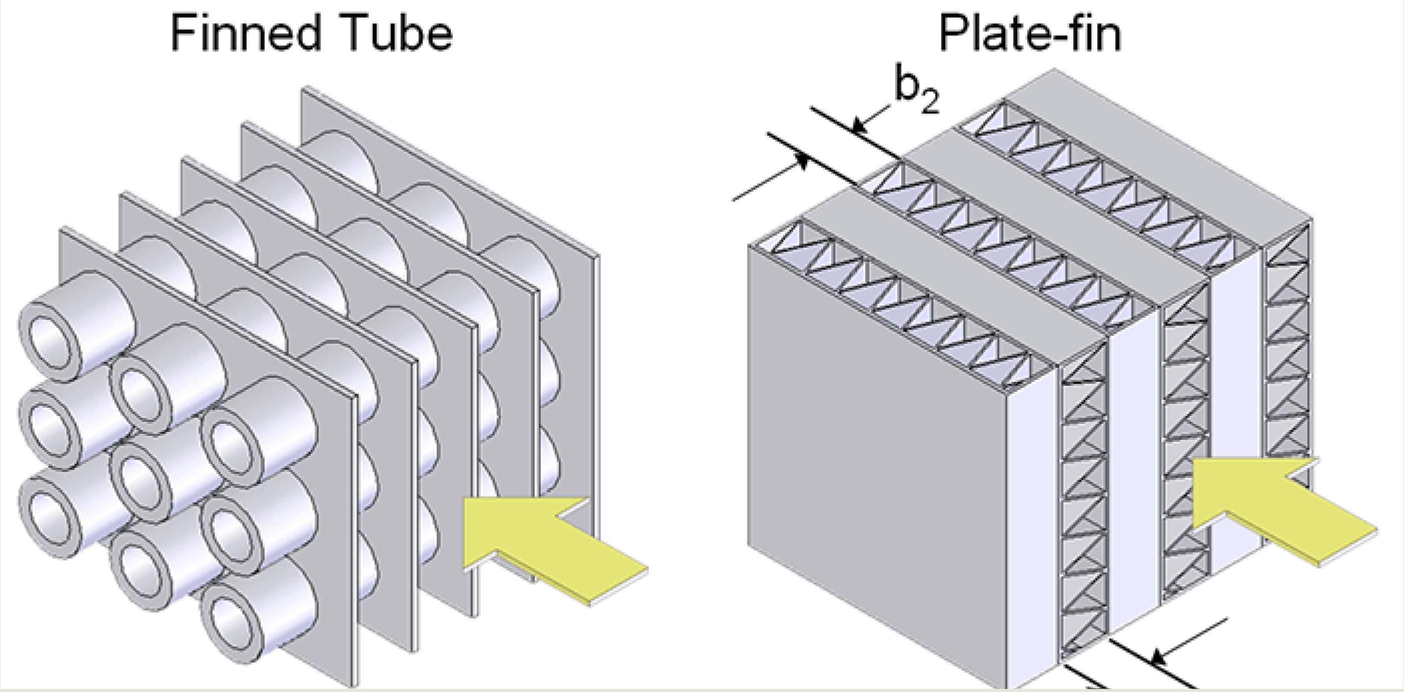
Disadvantages

- Due to gasket issue, not favourable for high vacuum, erosive duties
- Relatively low pressure capability



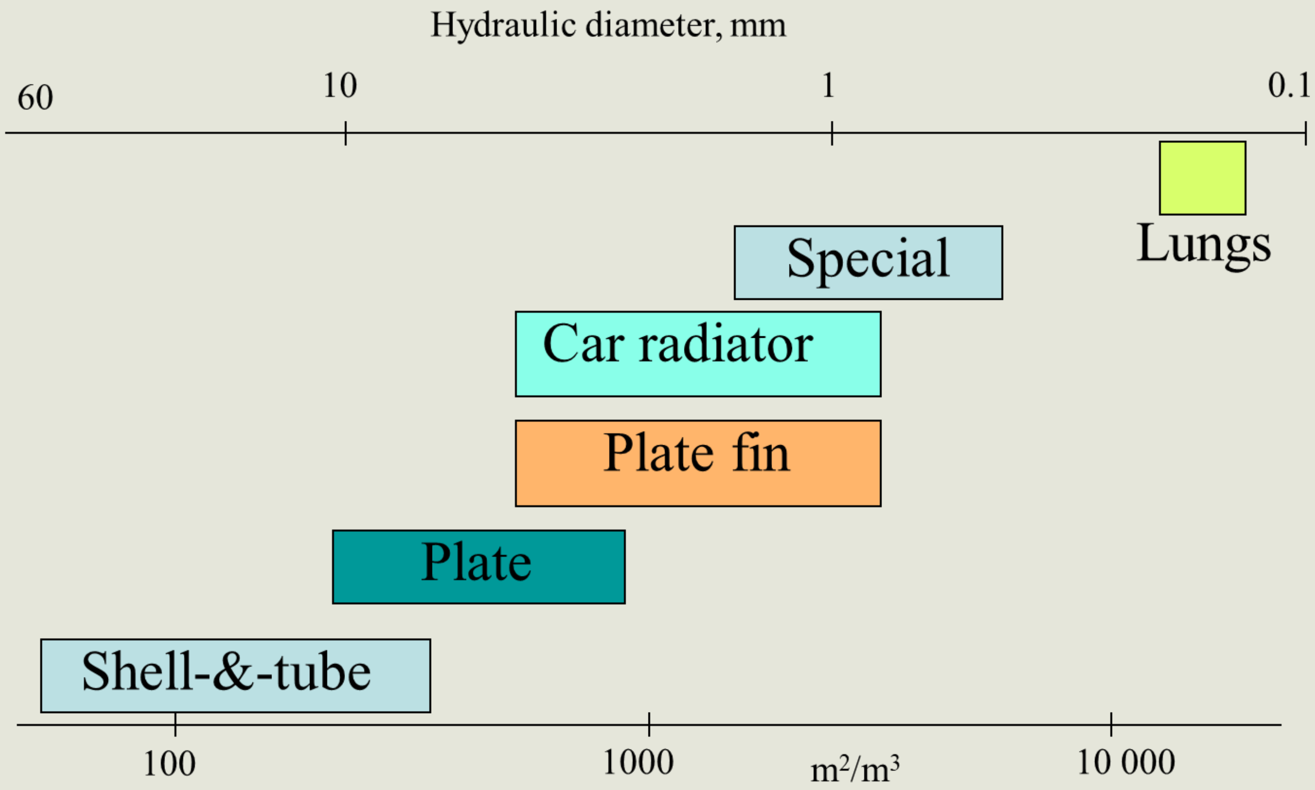
Extended surface heat exchangers

- High effectiveness is needed (>98%)
- Compactness > 700m^2/m^3
- High pressure drop

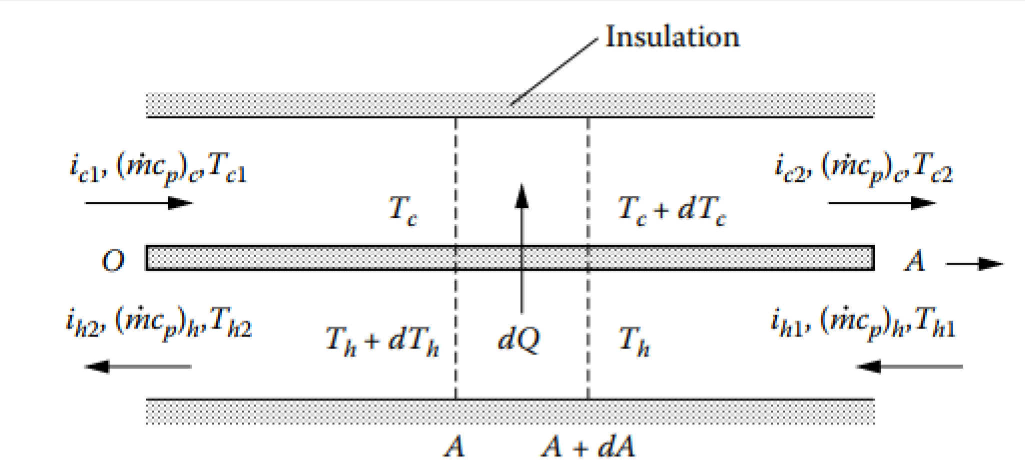


Compactness

- Can be measured by the heat-transfer area per unit volume **or** by channel size
- Conventional exchangers (shell and tube) have channel size of 10 to 30 mm giving about 100 m^2/m^3
- Plate-type exchangers have typically 5 mm channel size with more than 200 m^2/m^3
- More compact types available



Heat Exchanger Analysis



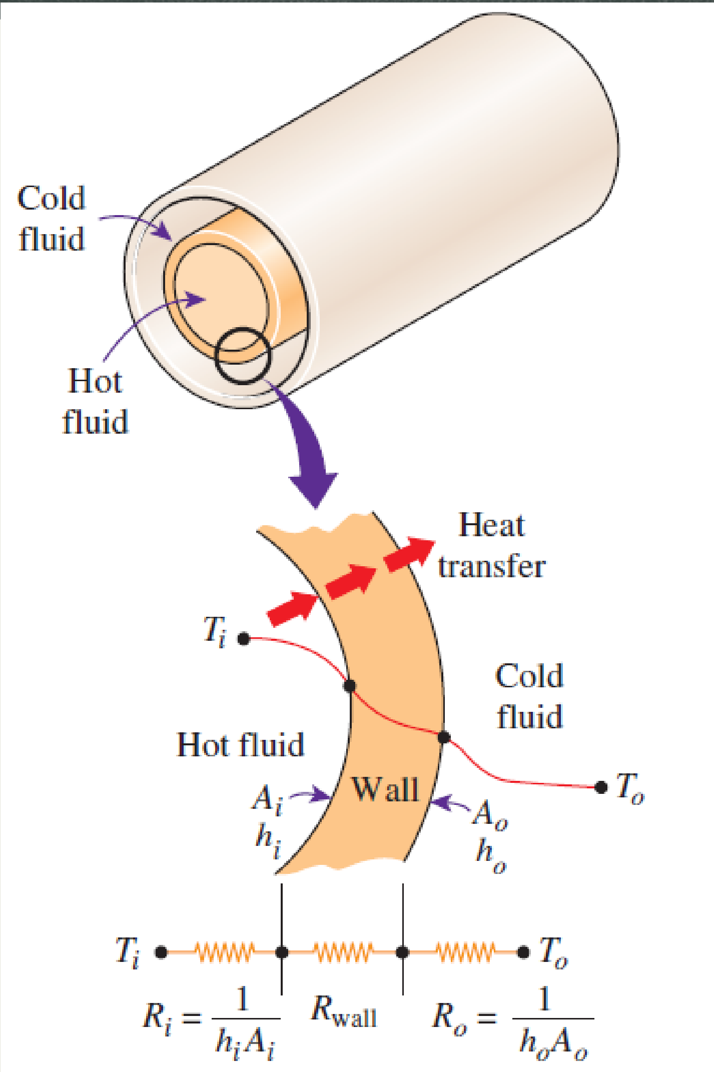
$$Q = (\dot{m}c_p)_c (T_{c_2} - T_{c_1})$$

$$Q = (\dot{m}c_p)_h (T_{h_1} - T_{h_2})$$

$$Q = UA\Delta T_m$$

i – enthalpy
T – Temperature
m – mass flow rate
Cp – specific heat capacity
Q – Heat transfer

Overall heat transfer coefficient, U (W/m²·°C)



$$\dot{Q} = \frac{\Delta T}{R} = UA_s \Delta T = U_i A_i \Delta T = U_o A_o \Delta T$$

$$R_{wall} = \frac{\ln(D_o/D_i)}{2\pi k L}$$

$$U_o A_o = U_i A_i = \frac{1}{R_t} = \frac{1}{\frac{1}{h_i A_i} + \frac{\ln(r_o/r_i)}{2\pi k L} + \frac{1}{h_o A_o}}$$

For tubular type

$$UA = \frac{1}{R_t} = \frac{1}{\frac{1}{h_i A} + \frac{t}{kA} + \frac{1}{h_o A}}$$

For plate type

LMTD Method for Heat Exchanger Analysis

$$\delta Q = -(\dot{m}\, c_p)_h\, dT_h = \pm(\dot{m}\, c_p)_c\, dT_c$$

$$\delta Q = -C_h\, dT_h = \pm C_h\, dT_c$$

$$\delta Q = U(T_h - T_c)dA$$

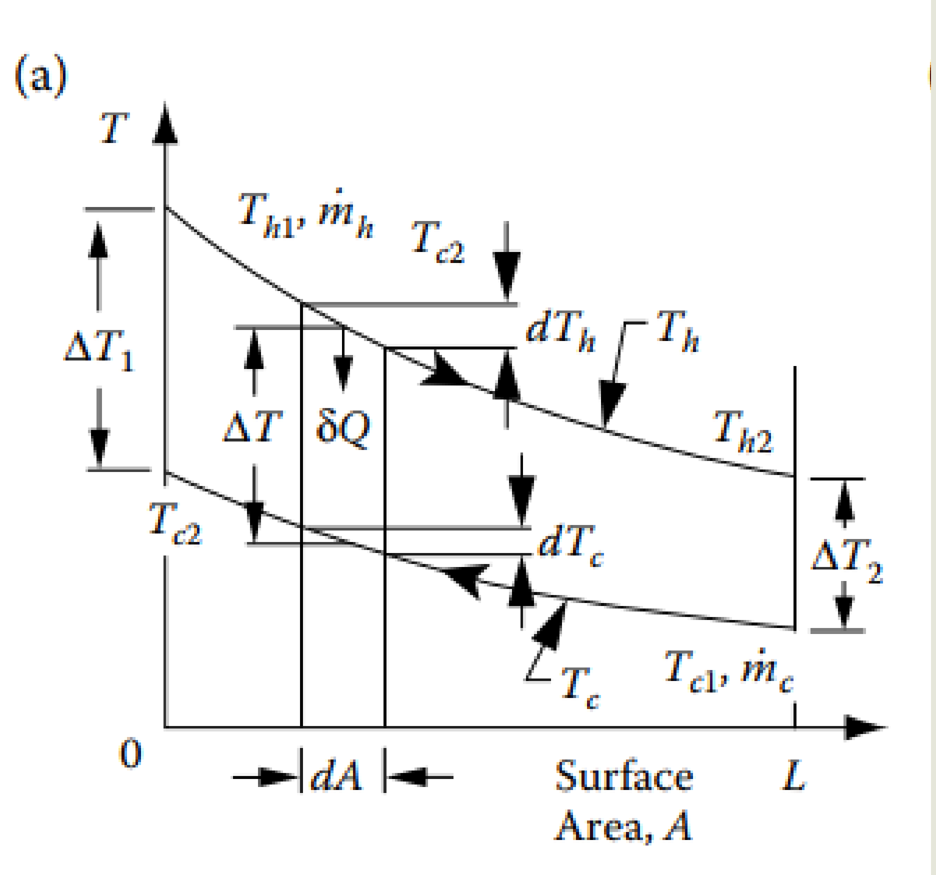
$$\ln\frac{T_{h2} - T_{c1}}{T_{h1} - T_{c2}} = UA\left(\frac{1}{C_c} - \frac{1}{C_h}\right)$$

$$Q = UA\frac{(T_{h1} - T_{c2}) - (T_{h2} - T_{c1})}{\ln\left(\frac{T_{h1} - T_{c2}}{T_{h2} - T_{c1}}\right)}$$

$$Q = UA\frac{\Delta T_1 - \Delta T_2}{\ln(\Delta T_1/\Delta T_2)}$$

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln(\Delta T_1/\Delta T_2)}$$

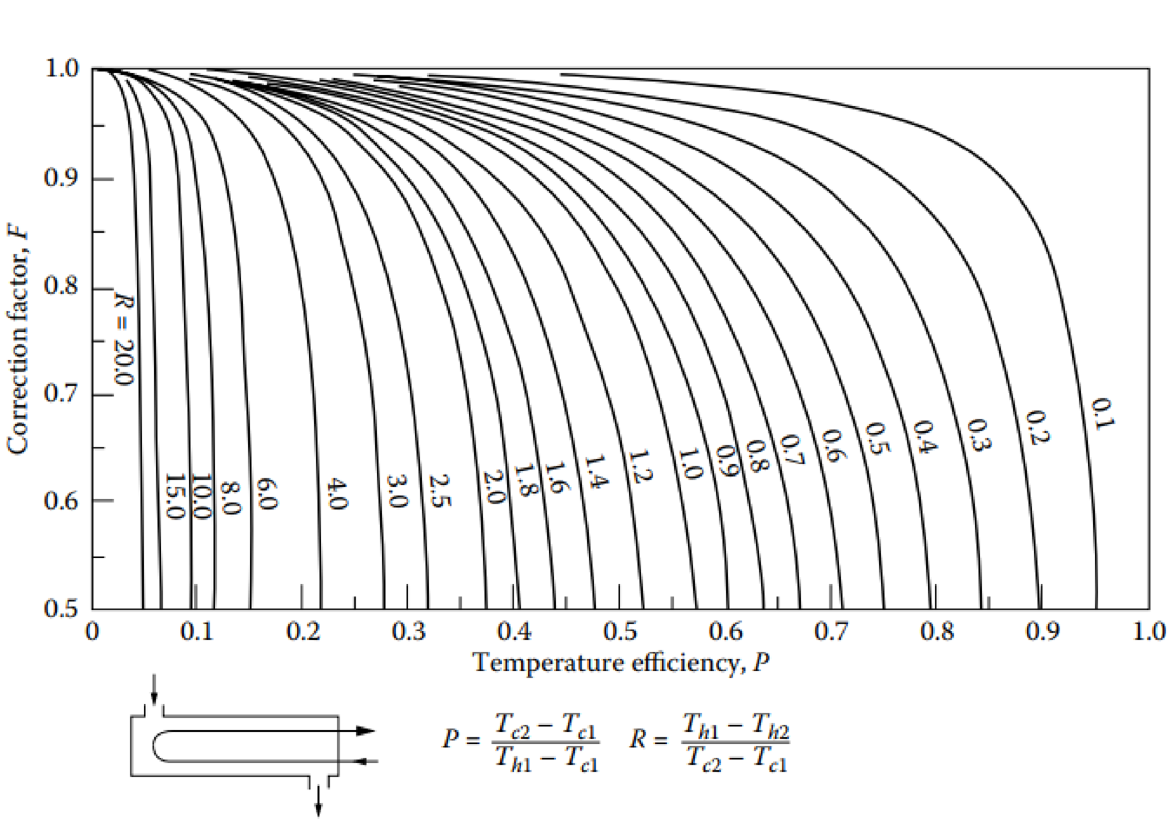
$$Q = AU\,\Delta T_{lm}$$



Analysis for other flow arrangement

F – Correction factor

$$Q = UA\Delta T_{lm} = UAF\Delta T_{lm,cf}$$



Procedure for selecting heat exchanger

With the LMTD method, the task is to *select* a heat exchanger that will meet the prescribed heat transfer requirements. The procedure for the selection process is

1. Select the type of heat exchanger suitable for the application.
2. Determine any unknown inlet or outlet temperature and the heat transfer rate using an energy balance.
3. Calculate the log mean temperature difference ΔT_{lm} and the correction factor F, if necessary.
4. Obtain (select or calculate) the value of the overall heat transfer coefficient U.
5. Calculate the heat transfer surface area A_s .

The task is completed by selecting a heat exchanger that has a heat transfer surface area equal to or larger than A_s.

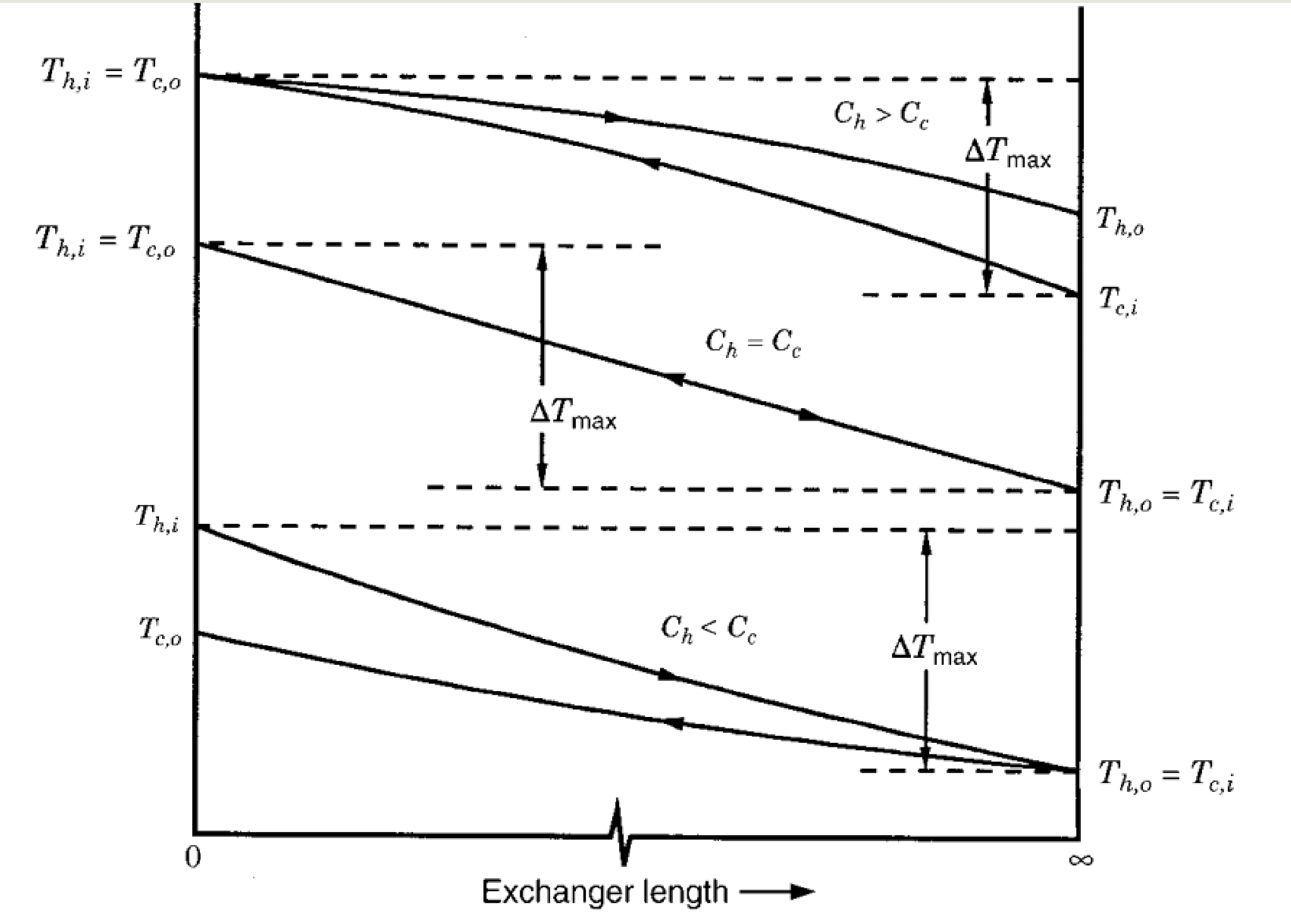
Effectiveness–NTU method

- A second kind of problem encountered in heat exchanger analysis is the determination of the *heat transfer rate* and the *outlet temperatures* of the hot and cold fluids for prescribed fluid mass flow rates and inlet temperatures when the *type* and *size* of the heat exchanger are specified.

Effectiveness

$$\varepsilon = \frac{\dot{Q}}{\dot{Q}_{max}} = \frac{\text{Actual heat transfer rate}}{\text{Maximum possible heat transfer rate}}$$

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



Effectiveness–NTU method

$$\varepsilon = \text{function}\,(UA_s/C_{\min}, C_{\min}/C_{\max}) = \text{function}\,(\text{NTU}, c)$$

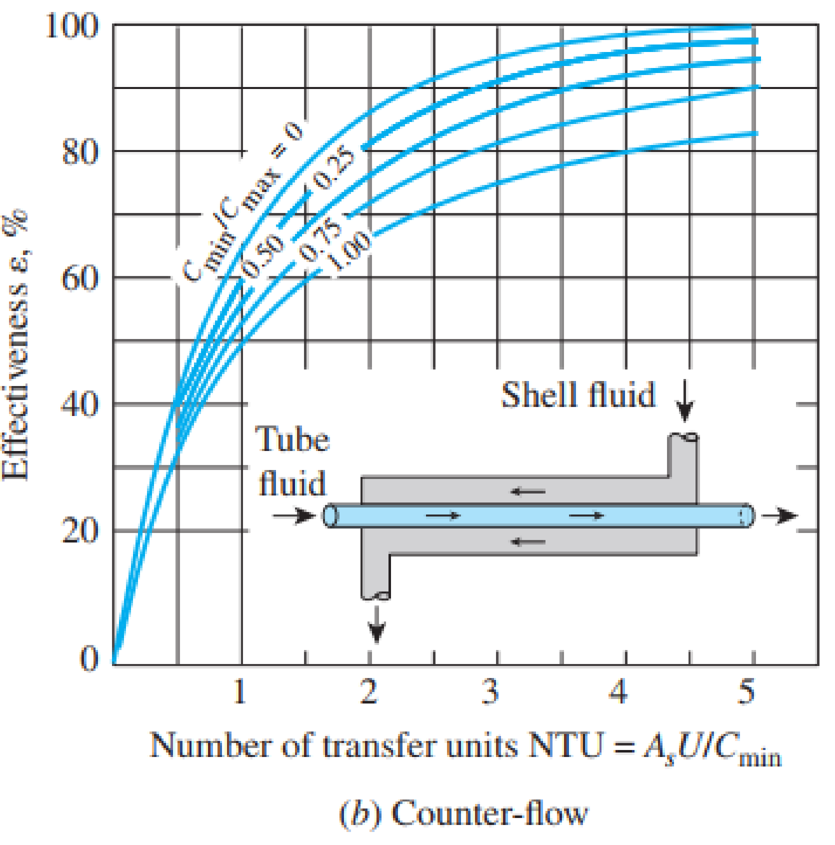
$$\text{NTU} = \frac{UA_s}{C_{\min}} = \frac{UA_s}{(\dot{m}c_p)_{\min}}$$

For specified values of U and $C_{\min}$, the value of NTU *is a measure of the surface area A_s*. Thus, the larger the NTU, the larger the heat exchanger.

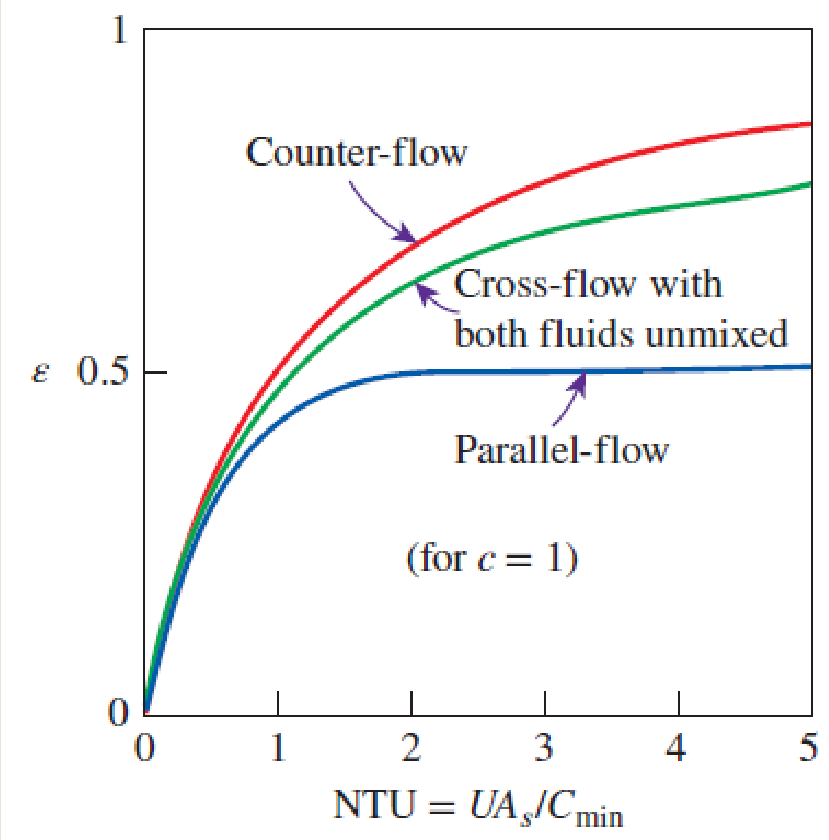
Capacity ratio $c = \dfrac{C_{\min}}{C_{\max}}$

Heat Exchanger Type		Effectiveness Relation
1	*Double pipe:* Parallel-flow	$\varepsilon = \dfrac{1 - \exp[-\text{NTU}(1+c)]}{1+c}$
	Counterflow	$\varepsilon = \dfrac{1 - \exp[-\text{NTU}(1-c)]}{1 - c\exp[-\text{NTU}(1-c)]}$ (for $c < 1$) $\varepsilon = \dfrac{\text{NTU}}{1+\text{NTU}}$ (for $c = 1$)
2	*Shell-and-tube:* One-shell pass 2, 4, . . . tube passes	$\varepsilon_1 = 2\left\{1 + c + \sqrt{1+c^2}\,\dfrac{1 + \exp[-\text{NTU}_1\sqrt{1+c^2}]}{1 - \exp[-\text{NTU}_1\sqrt{1+c^2}]}\right\}^{-1}$
	n-shell passes $2n$, $4n$, . . . tube passes	$\varepsilon = \left[\left(\dfrac{1-\varepsilon_1 c}{1-\varepsilon_1}\right)^n - 1\right]\left[\left(\dfrac{1-\varepsilon_1 c}{1-\varepsilon_1}\right)^n - c\right]^{-1}$
3	Crossflow (*single-pass*) Both fluids unmixed	$\varepsilon = 1 - \exp\left\{\dfrac{\text{NTU}^{0.22}}{c}[\exp(-c\,\text{NTU}^{0.78}) - 1]\right\}$
	$C_{\max}$ mixed, $C_{\min}$ unmixed	$\varepsilon = \dfrac{1}{c}(1 - \exp\{-c[1 - \exp(-\text{NTU})]\})$
	$C_{\min}$ mixed, $C_{\max}$ unmixed	$\varepsilon = 1 - \exp\left\{-\dfrac{1}{c}[1 - \exp(-c\,\text{NTU})]\right\}$
4	All heat exchangers with $c = 0$	$\varepsilon = 1 - \exp(-\text{NTU})$

Effectiveness–NTU method



(*b*) Counter-flow



- ε increases with increasing values of NTU for a specified *C**
- ε increases with decreasing values of *C** for a specified NTU
- For ε < 40%, the capacity rate ratio *C** does not have a significant influence on ε
- When C* =0?

Fouling

- Fouling is general term that includes any kind of deposits that appears on the heat exchanger surface over the lifetime of the exchanger.
- It introduces an additional resistance to heat transfer
- Sometimes the deposit is heavy enough to interfere with the flow and increase the pressure drop
- *Keeping velocities sufficiently high to avoid deposits*
- *Avoiding stagnant regions where dirt will collect*
- *Avoiding hot spots where coking or scaling might occur*
- *Avoiding cold spots where liquids might freeze or where corrosive products may condense from gases*

Selection of HX

The proper selection of a heat exchanger depends on several factors:

- Heat Transfer Rate
- Cost
- Pumping Power
- Size and Weight
- Type
- Materials

Waste heat recovery options

- The waste heat of hot exhaust gases from a heat treating furnace at 427℃ with a flow rate of 1.72 kg/s. The minimum allowable exit temperature is 204℃. Specific heat is 1.05 kJ/kg.K. The furnace burns coal whose heating value is 26749 kJ/kg with an air fuel ratio of 20, and has an efficiency of 75%. There are two options
  - Preheat the combustion air entering the furnace at 27℃ (U = 23 W/m^2K)
  - Generate steam at 8 bar (2770 kJ/kg)at the rate of 0.136 kg/s. Liquid water enters the waste heat boiler at 116℃ (485 kJ/kg). U is 142 W/M2k

Calculate the fuel savings, and required surface area and effectiveness of the heat exchanger for both options.

References

- Heat Exchangers - Selection, Rating, and Thermal Design

By Sadik Kakaç, Hongtan Liu, Anchasa Pramuanjaroenkij

- *Heat And Mass Transfer Fundamentals And Applications*

by Yunus A. Cengel and Afshin G. Ghajar