Paper No. : 04

Paper Title : Unit Operations in Food processing

Module –8 : Principles of Heat Exchangers

# What are Heat exchangers?

- Heat exchangers are devices that facilitate the exchange of heat between two fluids that are at different temperatures without the fluids coming into contact.
- Heat is transferred from the hot fluid to the cold fluid. Heat exchangers are classified according to heat transfer process, type of construction and flow arrangement as follows.
- **Heat Transfer Process**

**1. Direct contact heat exchangers**

- These have no physical barrier between the hot and the cold fluids. Direct mixing of the fluids takes place which results in simultaneous heat and mass transfer.
- This setup is only employed when the mixing of fluids does not pose problems, or is actually required. eg. cooling tower.

## 2. Regenerative Exchangers

- Heat is alternately stored and removed from a heat surface in a regenerative exchanger.
- The heat transfer surface is moved into and out of the fixed hot and cold fluid streams or, the cold and the hot currents is switched into and out of it as the case may be.
- These two types are called rotary and fixed regenerative matrix exchangers respectively.

## 3. Recuperators

- It is one of the most vital types of heat exchanger.
- There is a clear demarcating physical barrier between the hot and the cold fluids all along their flow. It is perfect for cases where one cannot afford to mix the fluids. Eg. Evaporators of an ice plant and automobile radiators.

- **Design And Construction**
  - **Shell and heat tube exchangers**
- If larger flows are involved, a shell and tube exchangers is used, which is the most important type of exchanger in use in the process industries.
- In these exchangers the flows are continuous.
- Many tubes in parallel are used where one fluid flows inside these tubes. The tubes arranged in bundle, are enclosed in a shell and the other fluid flows outside the tubes in the shell side.
  - **Plate and frame heat exchanger**
- This exchanger consists of a series of thin plates normal to the direction of flow of the fluids.
- The plates provide a large surface area for heat exchange and are, at some places, more convenient than the shell and heat tube exchanger primarily because of its unique shape.

- This has a major advantage over a conventional heat exchanger in that the fluids are exposed to a much larger surface area because the fluids spread out over the plates.
- The high heat transfer efficiency for such a small physical size has increased the domestic hot water (DHW) flowrate of combination boilers.

### – Spiral heat exchangers

- This exchanger is formed by spiraling two parallel flat sheets to form a spiral consisting of two flow channels.
- The fluids flow through these channels and because of the shape, get a lot of surface area for heat transfer.
- The fluids generally flow in a counter current fashion in a spiral heat exchanger.

## – Double-pipe Heat Exchanger

- It consists of two concentric tubes with one fluid flowing in the inner tube and the other fluid flowing in the annular space between the two pipes. The fluids can be in concurrent or countercurrent flow. The exchangers can be made from a pair of single lengths of pipe with fittings at the ends or from a number of pairs interconnected in series. These can be used for small flow rates.

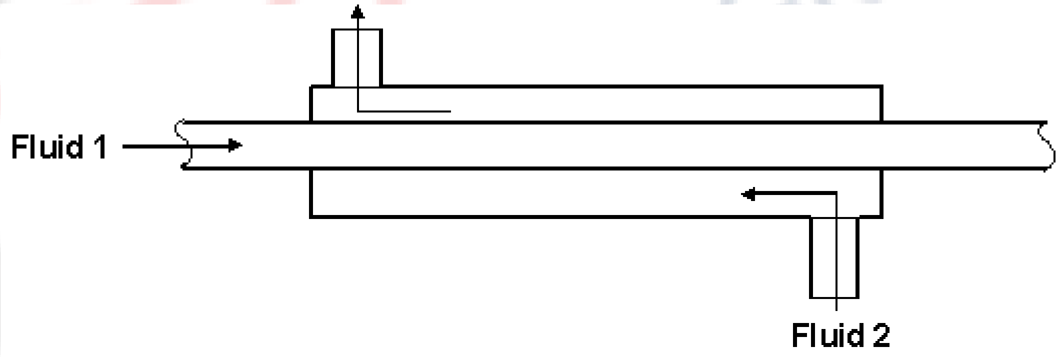



Fig 1: Flow in a double-pipe exchanger

## – Cross flow Heat Exchanger

- The fluids move in cross flow (perpendicular to each other) with one fluid flowing in the tubes and the other fluid flowing over the tubes in the transverse direction.
- The fluid inside the tubes is considered to be unmixed since it is mixed it can move about freely between the tubes and there will be a tendency for the gas temperature to equalize in the direction of normal to the flow.
- For the unmixed fluid inside the tubes there will be a temperature gradient both parallel and normal to the direction of flow. There are two configurations of cross flow exchangers
  - Finned with both fluids unmixed
  - Unfinned with one fluid mixed and the other unmixed

## Flow arrangements

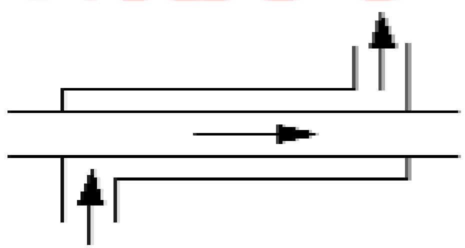
- Heat exchangers are classified by their flow arrangements. There are three basic types of heat exchangers

1.Parallel Flow

2.Counter Current Flow

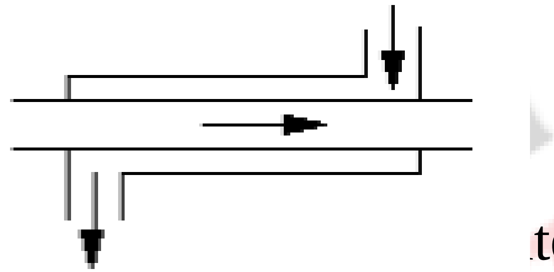
3.Cross Flow

## 1 Parallel flow



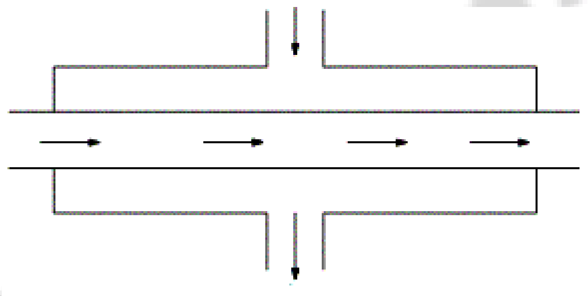
- Heat exchangers where the fluids move in the same direction are referred to as parallel flow.
- In Parallel flow heat exchangers, the outlet temperature of the "cold" fluid can never exceed the outlet temperature of the "hot" fluid.
- The exchanger is performing at its best when the outlet temperatures are equal.

## 2.Counter flow



- Exchangers where … te direction are referred to as counter flow.
- Counter flow heat exchangers are inherently more efficient than parallel flow heat exchangers because they create a more uniform temperature difference between the fluids, over the entire length of the fluid path.
- Counter flow heat exchangers can allow the "cold" fluid to exit with a higher temperature than the exiting "hot" fluid.
- The efficiency of a counter flow heat exchanger is sometimes characterized by the Log Mean Temperature Difference (LMTD) between the fluids.
- Lower values of LMTD indicate better heat exchanger performance.

## 3.Cross flow



- In cross flow exchangers, the hot and cold fluids move perpendicular to each other.
- This is often a convenient way to physically locate the inlet and outlet ports in a small package, however, it is less thermally efficient than a purely counter flow design.
- Many actual heat exchangers are a mixture of cross flow and counter flow due to space constraints that force the flow paths to wind back and forth.

## Heat Exchanger Analysis

- Overall Heat Transfer Coefficient
- LMTD
- Effectiveness of heat exchangers

## Overall Heat Transfer Coefficient

Under steady operation, the mass flow rate of each fluid stream flowing through a heat exchanger remains constant.

## Region I: Hot Liquid – Solid Convection

$$q_x = h_h.(T_h - T_{iw})A_i$$

$h_h$ = Heat Transfer Coefficient of hot fluid(W/(m$^2$K)

$T_h$ = Temperature of hot fluid.

$T_{iw}$ = Temperature of inner wall.

$A_i$ = Inner wall area.

## Region II: Conduction across Wall

$$q_x = \frac{k \, .A_{lm}}{(r_o - r_i)}(T_{ow} - T_{iw})$$

$T_{iw}$ = Temperature of inner wall(K).

$T_{Ow}$ = Temperature of outer wall(K).

$A_{lm}$ = Log mean cross sectional area ($m^2/S$)

$r_0$ = Outer radius; $r_i$ = Inner radius

## Region III : Solid – Cold Liquid Convection

$$q_x = h_c(T_{ow} - T_c)A_0$$

$h_c$ = Heat Transfer Coefficient of cold fluid ($W/(m^2K)$).

$A_o$ = Cross sectional area of outer wall ($m^2/s$).

$T_c$ = Temperature of cold fluid.

$$T_h - T_{iw} = \frac{q_x}{h_h . A_i}$$

$$T_{ow} - T_{iw} = \frac{q_x .(r_o - r_i)}{kA_{lm} .}$$

$$T_{ow} - T_c = \frac{q_x}{h_c . A_o}$$

Adding the above three Equations

$$T_h - T_c = q_x \left[ \frac{1}{h_h . A_i} + \frac{(r_o - r_i)}{k . A_{lm}} + \frac{1}{h_c . A_o} \right]$$

$$T_h - T_c = q_x (R_1 + R_2 + R_3)$$

$$q_x = U . A . (T_h - T_c) \qquad U = \frac{q_x}{(T_h - T_c) A}$$

## Fouling factors and U values

- Dirt, soot, scale, and other deposits from on one or both sides of the tubes of an exchange and on other heat- transfer surfaces.
- These deposits form additional resistances to the flow of heat and reduce the overall heat-transfer coefficient U. To avoid or lessen these fouling problems chemicals inhibitors are often added to minimize corrosion, salt deposition, and algae growth.
- The effect of such deposits and fouling is usually taken care of in design by adding a term for the resistance of the fouling on the inside and the outside of the tube.

$$\frac{1}{R_{fi}} = \frac{1}{A_i h_{di}}$$

$$\frac{1}{R_{fo}} = \frac{1}{A_i h_{do}}$$

$1/R_{fo}$ = Fouling coefficient for the inside of the tube in $W/m^2K$.

$1/R_{fi}$ = Fouling coefficient for the outside of the tube in $W/m^2K$.

Overall heat-transfer coefficient U for the case of fouling can be presented as

$$\frac{1}{U}=\left[\frac{1}{h_i}+\frac{1}{h_{di}}+\frac{(r_o-r_i)}{k.A_{lm}}+\frac{A_i}{A_o h_o}+\frac{A_i}{A_o h_{do}}\right]$$

$h_{di}$=fouling coefficient for the inside of the tube, W/$m^2$K

$h_{do}$=fouling coefficient for outside of the tube W/$m^2$K

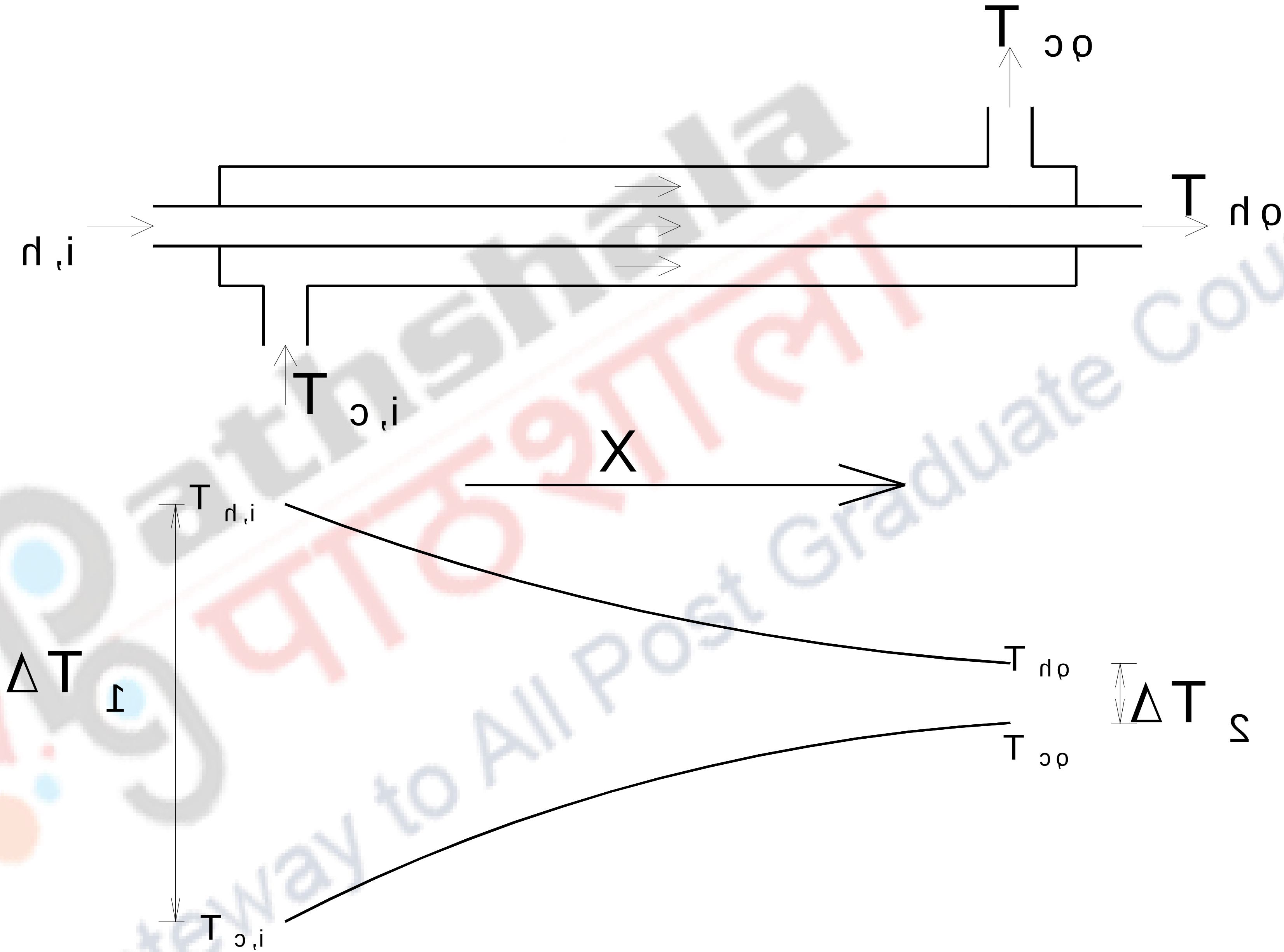
## Log-Mean Temperature Difference (LMTD)

- Log-Mean Temperature Difference is used to relate the total heat transfer rate to inlet and outlet fluid temperatures.
- It determines the temperature driving force for heat transfer in flow systems.
- The LMTD is a logarithmic average of the temperature difference between the hot and cold streams at each end of the exchanger.
- The larger the LMTD, the more heat is transferred.

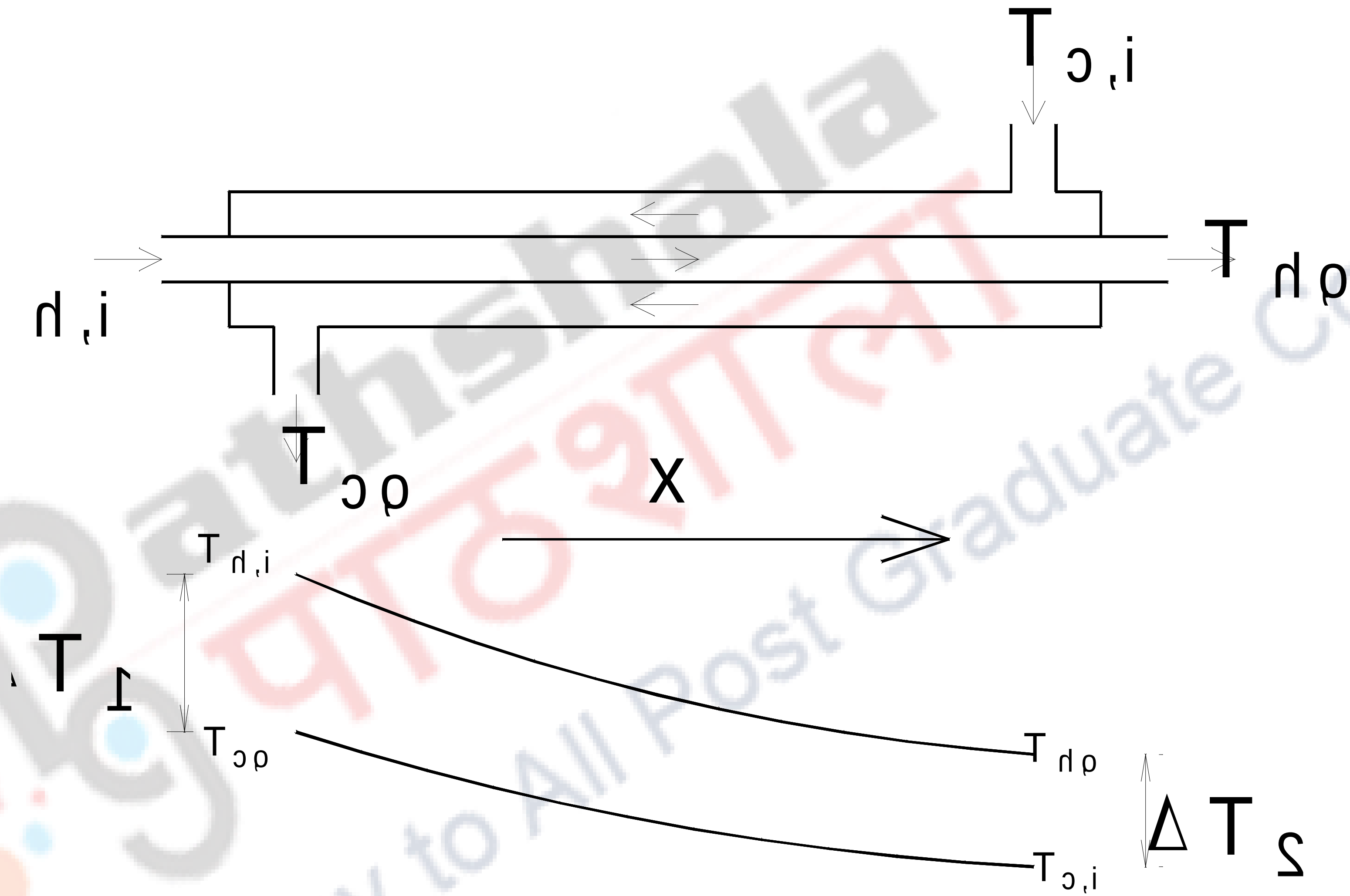
$$Q = UA\Delta T_{LM}$$

$$\Delta T_{LM} = \frac{\Delta T_2 - \Delta T_1}{\ln(\Delta T_2 / \Delta T_{1)}}$$

$\Delta T_{lm}$ = Log-mean temperature difference.




Parallel flow heat exchangers




Counter current flow heat exchangers

- Parallel flow

$$\Delta T_1 = T_{h,1} - T_{c,1} = T_{h,i} - T_{c,i}$$

$$\Delta T_2 = T_{h,2} - T_{c,2} = T_{h,o} - T$$

- For counter current flow

$$\Delta T_1 = T_{h,1} - T_{c,1} = T_{h,i} - T_{c,o}$$

$$\Delta T_2 = T_{h,2} - T_{c,2} = T_{h,o} - T$$

$\Delta T_1$ = Temperature difference at one end

$\Delta T_2$ = Temperature difference at other end

$\Delta T_{hc}$ = $T_{h1}$ = Inlet temperature of hot fluid.

$\Delta T_{hc}$ = $T_{c1}$ = Inlet temperature of cold fluid.

$\Delta T_{co}$ = $T_{h2}$ =Outlet temperature of hot fluid.

$\Delta T_{h2}$ = $T_{c2}$ =Outlet temperature of hot fluid.

$$\Delta T_{lm,CF} > \Delta T_{lm,PF}$$

$\Delta T_{lm,CF}$ = Log mean temperature difference for counter flow.

$\Delta T_{lm,PF}$ = Log mean temperature difference for parallel flow.

If U is same for parallel and counter flow then

$$A_{CF} < A_{PF}$$

If both streams exchange either latent heat or sensible heat, but not both, then

$$\Delta T_{avg} = \Delta T_{lm} \equiv \frac{\Delta T_{end1} - \Delta T_{end2}}{\ln \Delta T_{end1} - \ln \Delta T_{end2}}$$

For both co-current and countercurrent flow,

$\Delta T_{end1}$ = Temperature difference between the two streams at end 1 of the column (K)

$\Delta T_{end2}$ = Temperature difference between the two streams at end 2 of the column (K)

# The Effectiveness-NTU Method

- A heat exchanger effectiveness, is defined in terms of the actual heat transfer rate, q, and the maximum heat transfer rate, $q_{max}$, that would be obtained with a heat exchanger of infinite area

$$Q_{max} = C_{min}(T_{h,i} - T_{c,i})$$

For $C_c < C_h$ $\quad Q_{max} = C_c (T_{h,i} - T_{c,i})$

For $C_h < C_c$ $\quad Q_{max} = C_h (T_{h,i} - T_{c,i})$

$C_h = (mc_p)_h$ = Mass flow rate of hot fluid (kg/s).

$C_c = (mc_p)_c$ = Mass flow rate of cold fluid (kg/s).

$$\varepsilon = \frac{q}{q_{max}} = \frac{C_h(T_{hi} - T_{ho})}{C_{min}(T_{hi} - T_{ci})} = \frac{C_c(T_{co} - T_{ci})}{C_{min}(T_{hi} - T_{ci})}$$

$q_{max}$ = Maximum heat transfer.

$T_{ho}$ = Outlet temperature of hot fluid (K)

$T_{co}$ = Outlet temperature of cold fluid (K)

$T_{hi}$ = Inlet temperature of hot fluid.

$T_{ci}$ = Inlet temperature of cold fluid

$C_c$ = Heat capacity of cold fluid (W/K),

$C_h$ = Heat capacity of hot fluid (W/K).

(

The maximum possible heat transfer rate ($q_{max}$) will be based on

- The maximum temperature difference driving force in the heat exchanger – this would be the difference between the entering temperatures of the hot and cold fluids.
- The fluid that might undergo this maximum temperature difference is the one having the minimum value of $mc_p$. The product $mc_p$ is called the heat capacity rate.
- The maximum heat transfer is

$$q = (m\,c_P)_{min} = (T_{hi} - T_{ci})$$

- The “minimum” fluid may be either the hot or cold fluid depending on the product value.
- If the hot fluid is the minimum fluid ($C_h < C_c$), $T_{ho} = T_{ci}$

$$q_{max} = (m\, c_P)_h (T_{hi} - T_{ci})$$

- If the cold fluid is the minimum fluid ($C_c < C_h$), $T_{c.o} = T_{h,I}$

$$q_{max} = (m\, c_P)_c (T_{hi} - T_{ci})$$

- In both the cases

$$q_{max} = (m\, c_P)_{min} (T_{hi} - T_{ci}) = (m\, c_P)_{min} \Delta T_{max}$$

For the co-current (parallel) flow case

$$\varepsilon = \frac{1 - \exp\left\{- NTU\left(1 + \frac{C_{min}}{C_{max}}\right)\right\}}{\left[1 + \frac{C_{min}}{C_{max}}\right]}$$

for the counter-current flow case

$$\varepsilon = \frac{1 - \exp\left\{- NTU\left(1 - \frac{C_{min}}{C_{max}}\right)\right\}}{1 - \frac{C_{min}}{C_{max}} \exp\left\{- NTU\left(1 - \frac{C_{min}}{C_{max}}\right)\right\}}$$

This expression applies for $C_{min}/C_{max} < 1$

In the analysis of heat exchangers by this method, we define the number of transfer units, NTU, as the ratio , i.e.

$$NTU = \frac{UA}{(\dot{m}c_p)_{min}}$$

The NTU indicates a measure of the size of the heat exchanger.

For any heat exchanger e =f(NTU,$C_{min}/C_{max}$)

when $C_{min}/C_{max}$ = 1,

$$\varepsilon = \frac{NTU}{1 + NTU}$$

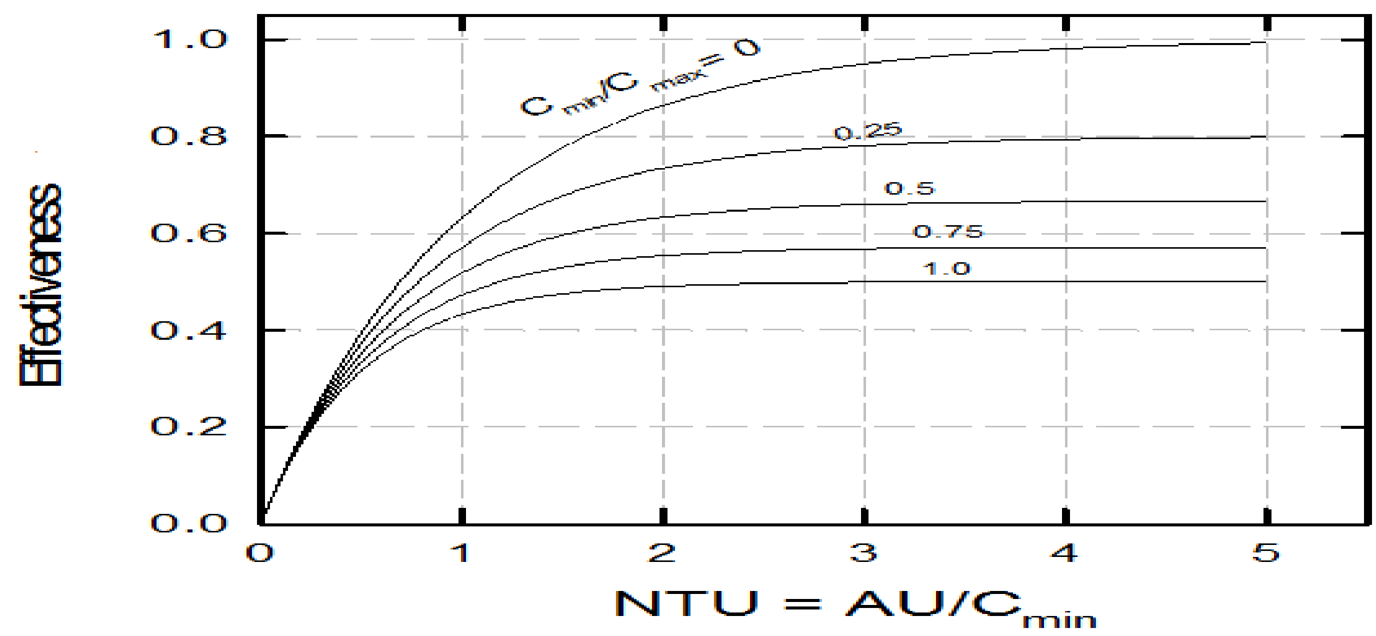
**Steps to calculate the Effectiveness-NTU**

- **Performance Analysis**

1) Calculate the capacity ratio $C_r = C_{min}/C_{max}$ and NTU $= UA/C_{min}$ from input data
1) Determine the effectiveness from the appropriate charts or e-NTU equations for the given heat exchanger and specified flow arrangement.
2) When e is known, calculate the total heat transfer rate
3) Calculate the outlet temperature.

**Sizing Analysis**

1) When the outlet and inlet temperatures are known, calculate e.
2) Calculate the capacity ratio $C_r = C_{min}/C_{max}$
3) Calculate the overall heat transfer coefficient, U
4) When e and C and the flow arrangement are known, determine NTU from the e-NTU equations. When NTU is known, calculate the total heat transfer surface area.



# THANK YOU