Design Methodology of Heat Exchanger (Radiator)
2.1 DESIGN PROCEDURE OF HEAT EXCHANGER (RADIATOR):

Introduction:

Heat Exchanger is a device in which the exchange of energy takes place between two fluids at different temperature.

A heat exchanger utilizes the fact that, 'wherever there is a temperature difference, flow of energy occurs'. The flowing fluids provide the necessary temperature difference and thus force the energy to flow between them. The energy flowing in a heat exchanger may be either sensible energy or latent heat of the fluids.

The fluid which gives its energy is known as *Hot Fluid*. While the fluid which receives energy is known as *Cold Fluid*. It is but obvious that, temperature of hot fluid decreases while the temperature of cold fluid increases in heat exchanger (except in case of phase change). Accordingly, the function of heat exchanger is to heat or cool the desired fluid.

![Diagram of Heat Exchanger](image)

*Fig. 2.1 : A basic construction of Heat Exchanger*
In a special case, when one of the fluids undergoes change in its phase, its temperature remains unchanged. These types of heat exchanger are known as condensers or evaporators.

Some of the familiar examples of heat exchangers are,

(i) In car radiator, the water gets cooled by giving its energy to the atmospheric air.
(ii) In oil coolers, the oil gets cooled by giving its energy to the cooling water.
(iii) In economizer, the water gets heated by taking energy from flue gases and gets condensed.
(iv) In steam condensers, the steam gives its energy to cooling water and gets heated.
(v) In cooling tower, the water is cooled by giving its energy to the air which is in direct contact with water.

In general, the performance of an heat exchanger is measured in different parameter as:
1. Heat transfer per unit surface area
2. Heat transfer per unit volume occupied

Heat exchangers are one of the basic components of process industries and they are used in almost all process industries. Hence, it is the application of heat transfer principles, which draws maximum attention of a process design engineer. Thus heat exchangers or radiators are very important components and the proper most efficient design plays important role.

Hence, efforts are made to optimize the design, to reduce size, cost and to increase the efficiency of heat exchangers (radiators).

2.2 CLASSIFICATION OF HEAT EXCHANGERS:

Heat exchangers are classified in the following manner:
2.3 COMPACT HEAT EXchanger:

A heat exchanger which achieves a high heat transfer surface area per unit volume is known as “Compact Heat Exchanger.” The compactness of the heat exchanger is measured in terms of surface area to volume ratio ($\alpha$) [16].
Compact Heat Exchangers usually have dense arrays of finned tubes or plates and are accordingly classified as:

(i) Plate and Tube type Compact Heat Exchanger (Ref. Fig. 2.3 (a))
(ii) Plate and Fin type Compact Heat Exchanger (Ref. Fig. 2.3 (b))
(iii) Fin and Tube type Compact Heat Exchanger. (Ref. Fig. 2.4)

The first two types of heat exchangers give a higher value of temperature coefficient, but they are complicated to manufacture. On the other hand, the fin–tube type heat exchanger has a relatively smaller value of temperature coefficient, but different types of finned tubes are readily available in the market and hence, they are relatively simpler to manufacture. Hence, the fin–tube type compact heat exchangers are preferred for various applications [13].

Some of the salient features of Compact Heat Exchanger are,

1. They are highly effective when at least one of the flowing fluids is gas.
2. They are normally used when flow passages are typically small (Dh_5 mm).
3. They are normally used when flow is usually laminar.
2.4 ENERGY BALANCE EQUATION:

In heat exchanger, the exchange of energy takes place between two fluids. Initially, let us assume that the energy being exchanged is the sensible energy. Now, the various terms in concern with heat exchanger can be defined as,

The fluid which gives its energy to the other fluid is known as “Hot fluid”. Due to loss of the internal energy, the temperature of the hot fluid decreases [17].

On the hand, the fluid which receives energy is known as “Cold fluid”. The internal energy as well as the temperature of cold fluid increases.[18].

Neglecting the energy losses from the heat exchanger to atmosphere, we can say that Rate at which energy given by hot fluid = Rate at which energy is gained by cold fluid i.e. Rate of change of I.E. of hot fluid = Rate of change of I.E. of cold fluid

i.e. 

\[
(\dot{m} \ C_p \Delta T)_{\text{hot}} = (\dot{m} \ C_p \Delta T)_{\text{cold}}
\]

Where \( \dot{m} \) is mass flow rate (Kg/sec)

Let

\[
\begin{align*}
T_{hi} & \quad \text{Inlet temperature of hot fluid} \\
T_{he} & \quad \text{Outlet temperature of hot fluid} \\
T_{ci} & \quad \text{Inlet temperature of cold fluid} \\
T_{ce} & \quad \text{Outlet temperature of cold fluid}
\end{align*}
\]

Then,

\[
(\Delta T)_h = T_{hi} - T_{he}
\]

and

\[
(\Delta T)_c = T_{ce} - T_{ci}
\]

Substituting in eqn. (I) , we get,

\[
(\dot{m} C_p)_h (T_{hi} - T_{he}) = (\dot{m} C_p)_c (T_{ce} - T_{ci}) \quad \ldots(1)
\]

This is known as energy balance equation. The heat transfer in a heat exchanger is same as heat given by hot fluid or heat received by cold fluid. Thus,

\[
q = (\dot{m} C_p \cdot T)_{\text{hot or cold}} \quad \ldots(2)
\]
2.5 FOULING FACTOR

The Equations (1) is valid for clean surfaces only. But in direct transfer type heat exchanger, the pipe surface gets coated with deposited impurities and a scale which is formed due to the chemical reaction between pipe material and the fluids. This coating has very low thermal conductivity and hence results in a high thermal resistance. Due to this additional resistance, the actual rate of heat flow from the heat exchanger becomes less than the theoretically estimated one. This deviation between the actual heat flow and the theoretical one, is known as Fouling. It is essential to estimate the extent of fouling while designing the heat exchanger. This is done with help of a parameter known as 'Fouling Factor'[11].

Let $F_i$ and $F_o$ be the inside and outside fouling factors respectively. Then, the equation for the overall heat transfer coefficient gets modified as,

$$UA = \frac{1}{\frac{1}{h_1 A_1} + \frac{F_i}{A_1} + \frac{F_o}{A_2} + \frac{1}{h_2 A_2}}$$ …(1)

$$\therefore \quad UA = \frac{1}{\frac{A_1}{A_1 (\frac{1}{h_1} + F_i)} + \frac{A_2}{A_2 (\frac{1}{h_2} + F_o)}}$$ …(2)

**Note:** The fouling factor divided by respective area gives the fouling thermal resistance.

Equation (1) gives the ‘UA’ value for clean surfaces while the equation (2) gives ‘UA’ value for unclean surface. From these equations we can conclude that,

$$\frac{1}{UA_{clean}} = \frac{1}{UA_{unclean}} - \left( \frac{F_i}{A_1} + \frac{F_o}{A_2} \right)$$

The term $\left[ \frac{F_i}{A_1} + \frac{F_o}{A_2} \right]$ represents ‘fouling’ caused due to the scale formation. Hence, it is called as Overall fouling factor ($F$).

$$F = \frac{F_i}{A_1} + \frac{F_o}{A_2}$$ … (3)

Substituting in eqn. (1) we get,
\[
\frac{1}{UA_{\text{clean}}} = \frac{1}{UA_{\text{unclean}}} - F
\] ... (4)

As mentioned above, the fouling factor depends upon the impurity contents as well as the probable chemical reaction between the fluid and surface. The values of Fouling factor used for some standard liquids are given below [32].

2.6 METHODS OF ANALYSIS

2.6.1 LMTD Method of Heat Exchanger Analysis

Concept of LMTD:
With the help of the concept of overall heat transfer coefficient, we can estimate the rate of heat flow through a composite object (conduction - convection system) using the formula [2].

\[ q = UA \Delta T \]

While applying this formula for a heat exchanger, a difficulty is faced due to the fact that, the temperature of both fluids varies from inlet to outlet. Thus, the temperature difference (\(\Delta T\)) also varies from one end to another end of heat exchanger [35].

It is a common practice that, when one has to substitute the value of some variable parameter in a formula, the value of parameter taken is its mean value. Accordingly, we can use above formula as

\[ q = UA \theta_m \]

Where \(\theta_m\) is the mean temperature difference. It is a fact that, in a heat exchanger, the temperature difference varies logarithmically.

Hence, the mean value is known as Log Mean Temperature Difference (LMTD). It is denoted as \(\theta_m\).

Thus, for a heat exchanger, we get

\[ q = UA \theta_m = (m \cdot Cp \Delta T) \text{ hot or cold} \] ... (5)
LMTD can also be defined as the temperature difference which, when maintained constant along the length of the heat exchanger, will give the same rate of heat transfer as that from the actual heat exchanger.

The value of $\theta_m$ for counter flow heat exchanger is obtained as follows.

(i) **Cross Flow Heat Exchanger with both fluids unmixed [43]:**

2.6.2 Procedure of Analysis using LMTD Method:

1. Calculate the rate of heat transfer from heat exchanger using

   \[ q = m \, C_p \, (\Delta T) \, \text{hot or cold} \]
2. Calculate the overall heat transfer coefficient. Get the value of U as a function of A, using the formula, $UA = \frac{1}{R}$

3. Calculate LMTD as

For parallel or counter flow,

$$\theta_m = \frac{\theta_1 - \theta_2}{\ln \frac{\theta_1}{\theta_2}}$$

For any other type

$$\theta_m = F \times \theta_{m\text{,counter}}$$

4. Calculate the area (or area related parameter) using

$$q = UA \theta_m$$

### 2.7 Design Aspects of Heat Exchanger:

Some basic considerations in the design of heat exchangers are:

(i) **Heat transfer rate:** The heat transfer requirements decides the inlet temperatures of both fluids, the outlet temperatures of both fluids and the type of flow path in the heat exchanger.

(ii) **Flow rates:** It decides the velocity of fluid. Low velocity results in low heat transfer while high velocity causes erosion, noise, vibrations, large frictional losses and high pressure drops. Hence, the cross section of the flow passage is adjusted so as to get velocity in the range 5 to 7 m/s.

(iii) **Fouling factor:** The material selection, estimation of life of heat exchangers, its maintenance requirements and servicing schedule are decided by taking into account the 'fouling factor'. Fouling factor depends upon various properties of fluid such as corrosiveness, tendency of scale forming etc. Minimum inside and outside fouling resistances result in high overall heat transfer coefficient.

(iv) **Outer shape and overall dimension:** According to the existing set up, the outer physical size and shape of the heat exchanger is decided. Depending upon the outer physical size and shape, the tube length, the pattern of tube layout (triangular or square or zigzag etc.), the outer shell dimensions, shape of dish ends, positions of various nozzles etc. are decided.

(v) **Strength factor:** The mechanical design of various parts is done by taking into account the pressure and temperature of the fluid. The heat exchanger is designed to have high strength, to be light in weight and to have low initial and maintenance cost [8].
1.8 DESIGN CALCULATIONS FOR RADIATOR

Available Data:

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Observations</th>
<th>Air (Cold)</th>
<th>Water (Hot)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Inlet Temperature (°C)</td>
<td>28</td>
<td>52</td>
</tr>
<tr>
<td>2</td>
<td>Outlet Temperature (°C)</td>
<td>34.376</td>
<td>44</td>
</tr>
<tr>
<td>3</td>
<td>m i.e mass flow rate (kg/hr)</td>
<td>525.35</td>
<td>100</td>
</tr>
<tr>
<td>4</td>
<td>Cp. Specific Heat (kJ/kg °C)</td>
<td>1</td>
<td>4.187</td>
</tr>
<tr>
<td>5</td>
<td>K Thermal Conductivity (W/mK)</td>
<td>0.024</td>
<td>0.66</td>
</tr>
<tr>
<td>6</td>
<td>ρ Density (kg/m³)</td>
<td>1.1</td>
<td>1000</td>
</tr>
</tbody>
</table>

Table 2.1 Observations Of Air And Water

Assume: For this air cooled heat exchanger we use aluminum tubes of following dimension,

1. Outer Diameter = 11.25 mm
2. Inner Diameter = 10.00 mm
3. Thickness = \( \frac{1.25}{2} = 0.0625 \) mm

From the chart of typical values of overall heat transfer coefficient, we know that for air cooled heat exchanger value of overall heat transfer coefficient (U) ranges from 300-450 W/m²K. So here we assume it to be equal to 350 W/m²K[42].

\[ U = 350 \text{ W/m}^2\text{K} \]

Using Energy balance equation,

\[
(mC_p)_h (T_{hi} - T_u) = (m C_p)_c (T_{ce} - T_{ci})
\]

\[
100 \times 4.187 \times (52 - 44) = 525.35 \times 1 \times (T_{ce} - 28)
\]

\[ T_{ce} = 34.376 \degree \text{C} \]

So outlet temperature of air is = 34.746 °C.

We know that,

\[ q = m_w \times C_{pw} \times \Delta T_w \]
\[ q = 100 \times 4.187 \times (52 - 44) \]
\[ q = 3349.6 \text{ Watt} \]

Assuming the Heat Exchanger (Radiator) to be counter flow we get,

\[ \theta_1 = (52 - 34.376) \]
\[ \theta_1 = 17.624^\circ\text{C} \]

\[ \theta_2 = (44 - 28) \]
\[ \theta_2 = 16^\circ\text{C} \]

Substituting these values in equation (5.10) we get,

\[ \theta_m = \frac{\theta_1 - \theta_2}{\ln \left( \frac{\theta_1}{\theta_2} \right)} \]
\[ \theta_m = \frac{(17.624 - 16)}{\ln (17.624 / 16)} \]
\[ \theta_m = 16.8^\circ\text{C} \text{ i.e.} \ 289.8^\circ\text{K} \]

i.e.
\[ \text{LMTD} = 16.8^\circ\text{C} \]

Now, using the average velocity of water in tubes and its flow rate the total flow area is given as,

\[ A_f = \frac{m}{V \infty \rho} \]
Where,  
\[ A_f = \text{Total flow area} \]
\[ V = \text{Average velocity of water} \]
\[ \rho = \text{Density of water} \]

Here, we have average velocity of water = 65 m/hr

\[ V = 65 \text{ m/hr} \]

So we get,  
\[ A_f = \frac{100}{65 \cdot 1000} \]
\[ A_f = 1.538 \times 10^3 \text{ m}^2 \]

But we know that,  
\[ A_f = n \times \frac{\pi}{4} \times d_i^2 \]

Where,  
\[ n = \text{Number of tubes} \]
\[ d_i = \text{Inlet diameter of tube} \]

Substituting respective values, we get

\[ 1.538 \times 10^{-3} = n \times \frac{\pi}{4} \times (10 \times 10^{-3})^2 \]

After solving the above equation we get,

- \[ n = 19.582 \quad \text{approximate } = 20 \]
- \[ n = 20 \]

For correction factor required dimension parameters are,

\[ P = \frac{(T_{ce} - T_{cl})}{(T_{hi} - T_{cl})} \]
\[ P = \frac{34.376 - 28}{52 - 28} = 0.3985 \]

\[ R = \frac{(T_{hi} - T_{he})}{(T_{ce} - T_{cl})} \]
\[ R = \frac{52 - 44}{34.376 - 28} = 1.26 \]
So referring the chart 5.14, we get value of correction factor as 0.96,

\[ F = 0.96 \]

That area of the heat transfer after considering correction factor is given as,

\[ A = \frac{q}{U \cdot F \cdot \theta_m(\text{counterflow})} \]

\[ A = \frac{3349.6}{350 \cdot 0.96 \cdot 16.8} \]

\[ A = 0.5934 \text{ m}^2 \]

2.9 FINAL ACCEPTABLE DESIGN PARAMETERS:

1. Number of tubes per pass = 20
2. Number of passes = 1
3. Length of tube per pass = 0.284 m

2.10 EFFECTIVENESS OF HEAT EXCHANGER:

(I)  
\[ C_h = (m \times C_p)_{\text{water}} \]
\[ C_h = \frac{(100 \cdot 4.18 \cdot 1000)}{3600} \]
\[ C_h = 116.306 \text{ W/K} \]

(II)  
\[ C_c = (m \times C_p)_{\text{air}} \]
\[ = \frac{(525.35 \cdot 1 \cdot 1000)}{3600} \]
\[ C_c = 145.931 \text{ W/K} \]

i.e
\[ C_{\text{min}} = 116.306 \text{ W/K} \]
\[ C_{\text{max}} = 145.931 \text{ W/K} \]

Now
(a) Capacity ratio (C) : 
\[ C = \frac{C_{\text{min}}}{C_{\text{max}}} \]
\[ C = \frac{116.306}{145.931} \]
\[ C = 0.797 \]

(b) NTU :
\[ \text{NTU} = \frac{U \cdot A}{C_{\text{min}}} \]
\[ \text{NTU} = \frac{350 \cdot 0.5934}{116.306} \]
\[ \text{NTU} = 1.786 \]

Using NTU-\( \varepsilon \) correlation for cross flow HE with both fluids unmixed, we have
\[ \varepsilon = 1 - \exp \left[ \frac{1}{C} \right] (\text{NTU})^{0.22} \{ \exp [-C (\text{NTU})^{0.78}] - 1 \} \]
\[ \varepsilon = 1 - \exp \left[ \left( \frac{1}{0.797} \right) (1.786)^{0.22} \{ \exp [- 0.797 (1.786)^{0.78}] - 1 \} \right] \]
\[ \varepsilon = 0.6388 \]

So we get effectiveness equal to 0.6388

2.11 DIMENSIONS DESIGN FOR DIFFERENT PARTS :

(i) Tube Material: Aluminum
(ii) Length of tubes = 0.284 m.
(iii) Number of tubes per pass = 20
(iv) Number of passes = 1
(v) I.D. of tubes = 10 mm.
(vi) O.D. of tubes = 11.25 mm.
(vii) Thickness = 1.25 mm[10]