Chapter 5

Heat Exchanger, Boiling and Condensation

CHAPTER HIGHLIGHTS

- *Direct Contact Heat Exchangers*
- *Indirect Contact Heat Exchanger*
- *Recuperators*
- *Parallel Flow Heat Exchanger*
- *Counter Flow Heat Exchanger*
- *Cross Flow Heat Exchanger*
- *Concentric tubes*
- *Multiple Shell and Tube Passes*
- *Condensers*
- *Evaporator*
- *Analysis of Heat Exchanger*
- *Heat Exchanger Performance*
- *Logarithmic Mean Temperature Difference (LMTD)*
- *Boiling and Condensation*
- *Boiling*
- *Boiling Curve*
- *Natural Convection Boiling*
- *Nucleate Boiling*
- *Transition Boiling*
- *Film Boiling*
- *Condensation Heat Transfer*

Introduction

Heat exchanger is a device which transfers energy, providing necessary surface area, from one fluid to the another fluid stream . During the process the temperature of both the fluids will change Due to the difference in temperature across the heat transfer barrier, the quantity of heat transferred will vary over the length of the heat exchanger.

They are classified as

1. Parallel flow heat exchanger
2. Counter flow heat exchanger
3. Cross flow heat exchanger
4. Condenser or evaporators

Nature of heat exchange process

On the basis of nature of heat exchange they are classified as follows.

1. Direct contact or open heat exchangers.
2. Indirect contact heat exchangers.

Direct Contact Heat Exchangers

In direct contact or open heat exchangers, the exchange of heat take place by direct mixing of hot and cold fluids and transfer of heat and mass takes place simultaneously. It is used where mixing of two fluids is either harmless or desirable. e.g., a) Cooling towers b) Direct contact feed heaters.

Indirect contact heat exchanger in which steam mixes with cold water and non-condensable gases leave the container as shown.

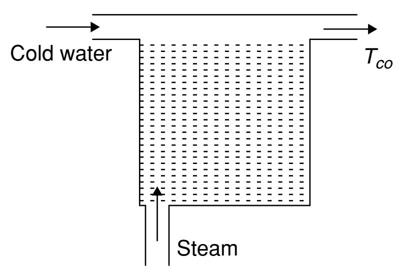


Figure 1 Direct contact type heat exchanger

Indirect Contact Heat Exchanger

When hot and cold fluids exchange heat by transmission through wall which separates the fluids, this includes the following.

1. Regenerators
2. Recuperators

Regenerators

Regenerators are type of heat exchangers, where hot and cold fluids pass alternatively through a space containing solid particles (matrix). These particles provide alternatively a sink and a source or heat flow. e.g. IC engines and gas turbines. A regenerator generally operates periodically (the solid matrix alternatively stores heat extracted from the hot fluid and then delivers it to the cold fluid. However in some regenerators, the matrix is rotated through the fluid passages arranged side by side which makes the heat exchange process continuous.

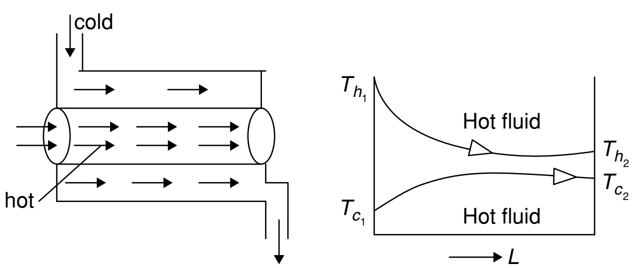
Recuperators

A recuperator is a special purpose counter flow energy recovering heat exchanger positioned within the supply and exhaust gases of an industrial process in order to recover the waste heat.

Based on the relative direction of fluid flow, heat exchangers are categorized in to the following groups:

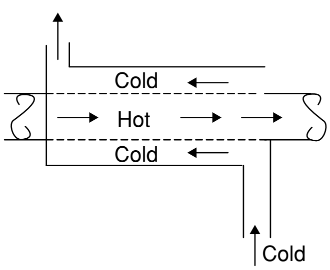
Parallel Flow Heat Exchanger

When two streams of fluids enters at one end and leaves at other end, the flow is known as parallel flow. The temperature difference goes on decreasing as we more along the length as shown in figure.



Counter Flow Heat Exchanger

In counter flow heat exchanger two fluids flow in opposite directions. The flow arrangement and temperature distribution for such a heat exchanger are shown in figure. The temperature differences between two fluids remain nearly constant. This type of heat exchanger, due to counter flow gives maximum rate of heat transfer for a given surface area. Hence such heat exchangers are mostly favoured.



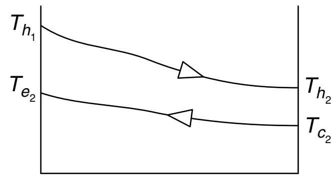
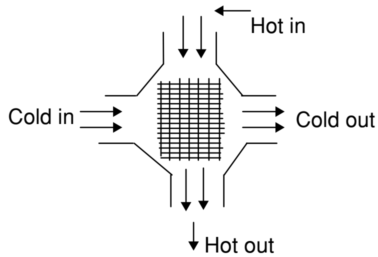


Figure 2 Counter flow heat exchanger

Cross Flow Heat Exchanger

When the two fluids cross one another usually at right angles, then the heat exchanger is called a cross flow heat-exchanger. The common example is auto mobile radiator.



On the basis of design and construction heat exchangers are classified as

Concentric Tubes

In this type, two concentric tubes are used, each carrying one of the fluids. The direction of flow may be parallel or counter as applicable. The effectiveness of heat exchanger is increased by using swirling flow.

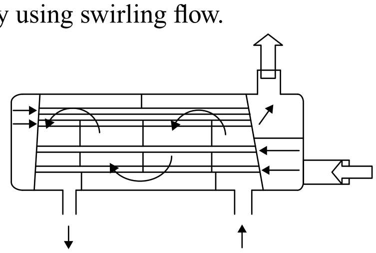


Figure 3 One shell pass and two tube pass heat exchanger

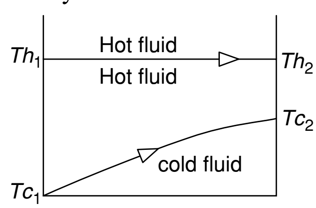
Multiple Shell and Tube Passes

Multiple shell and tube passes are used for increasing the overall heat transfer baffles are used to force the fluid back and forth across the tubes carrying the other fluid.

Based on the physical state of the fluids heat exchangers are classified as:

Condensers

In condensers the condensing fluid remains at constant temperature throughout the exchanger while temperature of the colder fluid gradually increases from inlet to outlet.



Evaporator

In this case, the boiling liquid (cold fluid) remains at constant temperature while temperature of hot fluid gradually decreases from inlet to outlet.

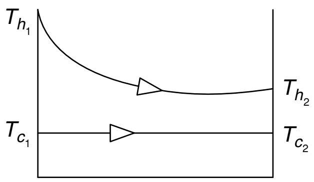


Figure 4 Evaporator

Analysis of Heat Exchanger

The following terms are used in the analysis of heat exchanger.

U = The overall heat transfer Coefficient.

A = The surface area of heat transfer

T_{h_1}, T_{h_2} = The inlet and outlet temperatures of hot fluid.

T_{c_1}, T_{c_2} = The inlet and outlet temperatures of cold fluid

m_c, m_h = Mass flow rate of cold and hot fluids

C_{ph}, C_{pc} = Specific heats of hot and cold fluids

C_h, C_c = Heat capacities of hot and cold fluids

Assume that the heat exchanger is perfectly insulated, so that there is no heat loss to the surroundings and potential and kinetic energy changes are negligible. Considering the energy balance we have,

Heat given by the hot fluid

$$Q = mhC_{ph}(T_{h_1} - T_{h_2})$$
$$= C_h(T_{h_1} - T_{h_2}) \qquad (1)$$

Heat gained by the cold fluid

$$Q = m_c C_{pc}(T_{c_2} - T_{c_1})$$
$$C_c(T_{c_2} - T_{c_1}) \qquad (2)$$

Total heat transfer rate in the heat exchanger,

$$Q = UA\Delta Tm$$

From energy balance concept,

$$Q = C_h(T_{h_1} - T_{h_2}) = C_c(T_{c_2} - T_{c_1}) = UA \cdot \Delta T_{\text{lm}}$$

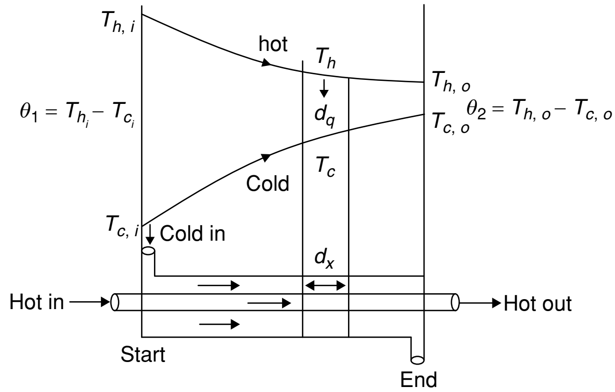
ΔT_{lm} is logarithmic mean temp difference.

Heat Exchanger Performance

Logarithmic Mean Temperature Difference (LMTD)

The heat transferred form one fluid to another is given by $Q = UA_s$(LMTD), where 'U' is the overall heat transfer coefficient, 'A_s' the surface area of heat transfer and (LMTD) is the mean temperature differences, in the form of a logarithmic function. Hence the mean temperature difference is denoted as Logarithmic Mean Temperature Difference (LMTD).

Parallel Flow Heat Exchanger



$$q = C_h[T_{hi} - T_{ho}] = C_C[T_{C,o} - T_{C,i}]$$

Now $\quad dq = -C_h\, dt_h \; [dt_h < 0]$

$$dq = C_C \cdot dt_h \; [dt_C > 0]$$

$$d[T_h - T_C] = dT_h - dT_C = -\frac{dq}{C_h} - \frac{dq}{C_C}$$

$$= -dq\left[\frac{1}{C_h} + \frac{1}{C_c}\right]$$

$$= -U \cdot dA_s(T_h - T_c)\left[\frac{1}{C_h} + \frac{1}{C_c}\right]$$

$$\frac{d(T_h - T_c)}{(T_h - T_c)} = -U\left[\frac{T_{hi} - T_{ho}}{q} + \frac{T_{co} - T_{ci}}{q}\right] \cdot dA_s$$

$$-\int_{\text{start}}^{\text{end}} \frac{d(T_h - T_c)}{(T_h - T_c)} = \frac{U}{q}[\theta_1 - \theta_2]\int_{\text{start}}^{\text{end}} dA_s$$

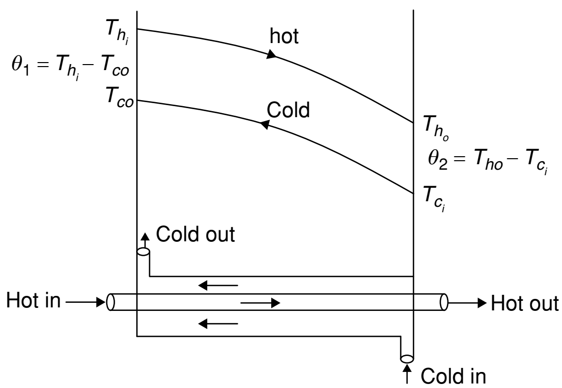
$$-\ln\left[\frac{T_{ho} - T_{co}}{T_{hi} - T_{ci}}\right] = \frac{U \cdot A_s}{q}[\theta_1 - \theta_2]$$

$$\therefore \qquad q = U \cdot A_s \cdot \frac{\theta_1 - \theta_2}{\ln\left(\frac{\theta_1}{\theta_2}\right)}$$

Here, $\text{LMTD} = \dfrac{\theta_1 - \theta_2}{\ln\left(\frac{\theta_1}{\theta_2}\right)}$ and $q = U \cdot A_s \cdot (\text{LMTD})$

The average temperature difference is $\dfrac{\Delta T_1 + \Delta T_2}{2}$

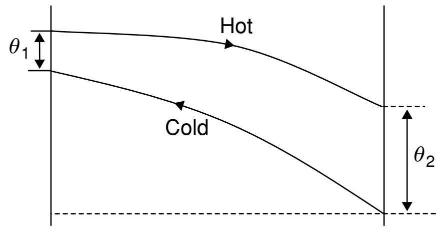
Counter flow



$$q = U \cdot A_s \cdot \frac{\theta_1 - \theta_2}{\ln\left(\frac{\theta_1}{\theta_2}\right)}$$

Case 1: when, $C_h > C_c$

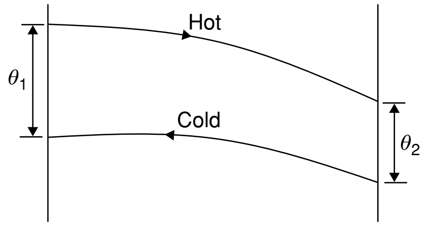
C_h = specific heat of hot fluid
C_c = specific heat of cold fluid



Here $\theta_1 < \theta_2$

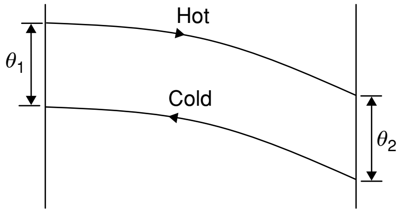
$$\text{LMTD} = \frac{\theta_1 - \theta_2}{\ln\left(\frac{\theta_1}{\theta_2}\right)}$$

Case 2: when $C_c > C_h$



Here $\theta_1 > \theta_2$

Case 3: if $C_c = C_h$



Here $\theta_1 = \theta_2$

$$\text{LMTD} = \frac{\theta_1 - \theta_2}{\ln\left(\frac{\theta_1}{\theta_2}\right)} = \frac{0}{0}$$

Now here, Let $\frac{\theta_1}{\theta_2} = x = 1$

$$\therefore \quad \text{LMTD} = \frac{\theta_2(x-1)}{\text{Ln}(x)}$$

Differentiating (L – Hospital rule)

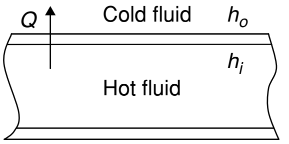
$$\text{LMTD} = \frac{\theta_2(1-0)}{\frac{1}{x}} = x\theta_2 = 1 \cdot \theta_2$$

$\therefore$ LMTD $= \theta_1 = \theta_2$

The value of 'U' – the overall heat transfer coefficient is not affected by flow direction but it depends on the flow velocity.

Heat transfer $Q = UA$ (LMTD).

In heat exchangers the overall heat transfer coefficient across the tube is given by $\frac{1}{U} = \frac{1}{h_i} + \frac{\delta}{k} + \frac{1}{h_o}$



Where h_i is the convective heat transfer coefficient (film coefficient) at the inside of wall and h_o is the heat transfer coefficient at the outside of the wall of the pipe and 'δ' the thickness of the pipe and 'K' the coefficient of thermal conductivity of the material.

Boiling and Condensation

Corresponding to a pressure, for a liquid there is a saturation temperature. Keeping the pressure constant if we raise the temperature of the liquid to the saturation temperature then the liquid boils.

Similarly when temperature of a vapour is lowered to the saturation temperature maintaining the pressure constant, the liquid condenses.

The heat transfer during these two processes is considered to be convection heat transfer; because the processes are associated with fluid motion.

In fact boiling and condensation differ from other forms of convection. Because it depends on the latent heat of vapourisation and the liquid vapour interface, surface tension. At equilibrium condition temperature remains constant during phase change. Huge amount of heat; latent heat, is transferred (absorbed or released) during boiling and condensation.

The convective heat transfer coefficient 'h' is much higher, associated with boiling and condensation than in other forms of convection heat transfer.

Boiling

Boiling is a 'liquid to vapour phase transformation' like evaporation. But there is significant difference between these two. Evaporation occurs when the vapour pressure is less than the saturation pressure at that temperature. Drying of clothes, evaporation of sweat from human body etc are examples.

Boiling, on the other hand, occurs at a temperature when the vapour pressure exceeds the saturation pressure. In atmospheric conditions, when the vapour pressure of the liquid exceeds the atmospheric pressure, the liquid boils atmospheric pressure is nothing but the weight of the atmosphere acting per unit area of the surface of the earth. When we heat a liquid the molecules of the liquid attain more kinetic energy and at a particular temperature the kinetic energy is sufficient to overcome the pressure exerted by the atmosphere and boiling starts.

Process of boiling is characterised by the formation of vapour bubbles at the heat transfer surface. Then the bubble rise to the free surface of the liquid.

Existence of bubbles is due to the surface tension of liquid. When temperature increases surface tension decreases. At the critical temperature surface tension becomes zero. That is why no bubbles are formed during boiling at super critical temperature.

Boiling is broadly classified in to two

1. Pool boiling
2. Flow boiling

Depending on the presence of bulk fluid motion. Pool boiling is one in which there is no bulk fluid motion.

Flow boiling is one in which bulk liquid flow occurs (it is also known as forced flow boiling).

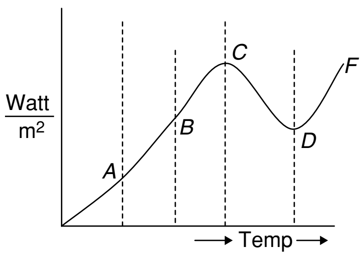
In Pool boiling the fluid body is stationary and any motion of the fluid is due to the natural convection current.

In flow boiling, the fluid is forced to move by external means such as pump.

Boiling Curve

In the boiling curve four different boiling regimes are indicated. They are.

1. Natural Convection boiling
2. Nucleate boiling
3. Transition boiling
4. Film boiling



Natural Convection Boiling

The region *A* and *B* indicate natural convection boiling. Bubble formation starts when the liquid is heated 2 to 3^0 *C* above the saturation temperature. In this type of boiling the fluid motion is governed by natural convection current.

The region *A* to *C* shall be nucleate boiling. It has two separate regions. In the region of '*A B*' very few numbers of bubbles may be formed that too isolated. These bubbles are dissipated soon after they get separated from the heating surface. The space vacated by the bubbles is filled by the fluid in the vicinity. This movement in fluid improves the convection heat transfer coefficient.

In the region '*BC*' the heating temperature is further increased. The rate of bubble formation is much high and numerous. Vapor columns are generated in the liquid. These bubble all the way move up to the free surface of the liquid and release the vapour. The vapour bubble cluster on the bottom surface blocking slightly to the rate of heat transfer and it reaches the maximum point '*C*'. The heat flux at '*C*' is known as the critical heat flux.

Transition Boiling

This is indicated by the region *CD*. As the temperature is increased beyond '*C*', the heat flux decreases. This is because a large portion of the heater surface is covered by bubbles and vapour film. This will act as an insulator. At the point '*C*' it is nucleate boiling and at '*D*' it is completely transferred to film boiling. Transition boiling is actually the region in between nucleate and film boiling.

Film Boiling

The region beyond the point '*D*' indicates film boiling. '*D*' is the point when heat flux is minimum. This is because the heater surface is covered by bubbles and vapour and it prevents heat influx. But if the temperature of the heater surface is further increased, the heat transfer rate increases. This is because of radiation heat transfer from the heated vapour film. At high temperature, the radiation effect is significant. Therefore from '*D*' heat transfer further increases as shown by curve *DE*.

Condensation Heat Transfer

A vapour condenses when its temperature is brought below the saturation temperature when the vapour comes in contact with a surface which is at a temperature below the saturation temperature, then condensation of the vapour begins. It can occur, on the free surface of a liquid or on a body of gas mass, if they are at temperature below the saturation temperature and the vapour is exposed to them. In the case of the gas the condensed liquid droplets suspended in the gas form a fog.

There are two forms of condensation. They are

1. Film wise condensation
2. Drop Wise condensation

Film wise condensation Film wise condensation is one in which the condensate form a liquid film over the surface. The plate will be completely wet and the condensate flows down along the plate under gravity. Also more condensation occurs on the film. The condensate film thickness over the plate increases along the direction of flow.

In drop wise condensation the condensate vapour forms droplets on the plate instead of a continuous film as in the case of film wise condensation. The surface of the plate will be covered by numerous droplets of varying diameter.

Drop wise condensation Drop wise condensation is more desirable. In film wise condensation, a condensate film is formed which obstructs the easy flow of heat. The heat transfer coefficient is the case of drop wise condensation is 10 times more that for film wise condensation. Even though drop wise condensation is the preferred mode of heat transfer, it is to be noted that drop wise condensation cannot be achieved for a long time. The droplets collapse and form big drops which will slide along the wall. After some time a liquid film will be formed at the surface. And the condition will becomes identical to that of film wise condensation.

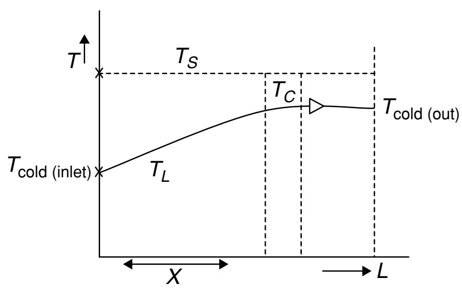
So it is a general practice to assume film wise condensation in the design of heat transfer equipment.

However it is being tried to achieve sustained drop wise condensation by using various vapour additions and surface coatings.

Condenser

Condenser is a heat exchanger in which a vapour condenses as a result of heat transfer, from it to a cold medium. In steam condenser high temperature steam is made to condense by circulating water. Similarly in refrigeration plant there are condensers. The condensation process is represented by the following diagram.

Condensation takes place at constant temperature T_s. The cold fluid gains temperature during heat transfer.



At any point the temperature of the cold fluid is given by

$$T_c = T_h - (T_h - T_{c\text{ inlet}})e^{\frac{-UA_x}{C_c}}$$

Where

T_h = The condensation temperature

$T_{c\text{ inlet}}$ = The cold fluid temperature at inlet

U = Overall heat transfer coefficient

A = Area of tube fro length x

C_c = Heat capacity of cold fluid ($m_c\, c_c$)

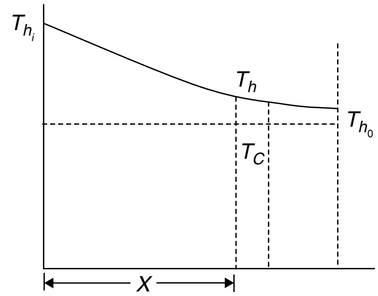
Heat flow is given by

$$Q = C_c(T_h - T_{c\text{ inlet}})\left[1 - e^{\frac{-UA_x}{C_c}}\right]$$

A_e = Total area of the tube. $A_e = \pi DL$

Evaporator

Evaporators are used for evaporating liquid in to vapour stage. A hot fluid is used to supply heat to the fluid which is to be evaporated. Evaporating liquid will be at a low temperature compared to the hot fluid. Evaporation takes place at constant temperature. The hot fluid loses some of its heat, during the process, and hence the temperature falls.



$$T_h = T_c + (Th_i - T_c)e^{\frac{-UA_e}{C_h}}$$

Heat flow $$Q = C_h(Th_i - T_c)\left[1 - e^{\frac{-UA_e}{C_h}}\right]$$

NTU Method of Effectiveness of Heat Exchangers

NTU means number of transfer units. Effectiveness of the heat exchanger is the ratio of actual heat transferred to the maximum possible heat that can be transferred

$$\varepsilon = \frac{\text{Actual heat transferred}}{\text{Maximum heat that can be transferred}}$$

Effectiveness depends on the dimensionless factor $\frac{UA}{C_{\min}}$.

This quantity is known as No: of Transfer Units (NTU) $\varepsilon \propto$ NTU

$$\varepsilon \propto \frac{UA}{C_{\min}}$$

For a given value of U and $C_{\min}$, ε is proportional to 'A', the heat transfer Area.

Therefore higher value for *NTU* means large size heat exchanger. Actually effectiveness is a function of *NTU* and capacity ratio. Capacity ratio is nothing but $\frac{C_{\min}}{C_{\max}} = C$.

$$\therefore \qquad \varepsilon = f\left(NTU, \frac{C_{\min}}{C_{\max}}\right) \varepsilon = f(NTU, C)$$

For parallel flow heat transfer $\varepsilon = \frac{1 - e^{-NTU(1+c)}}{1+c}$

Effectiveness is maximum when $NTU = \infty$

$$\varepsilon_{\max} = \frac{1}{1+c}.$$

For boilers and Condensers

$$\frac{C_{\min}}{C_{\max}} = 0$$

$\therefore\ e = 1 - e^{-NTU}$

For gas turbines $\dfrac{C_{min}}{C_{max}} = 1$

$$\therefore \qquad \varepsilon = \frac{1}{2}[1 - e^{-2NTU}$$

For counter flow heat exchangers

$$\varepsilon = \frac{1 - e^{-NTU(1-c)}}{1 - ce^{-NTU(1-c}}$$

When NTU = ∞, $\varepsilon_{max} = 1$

For boilers and condensers $\dfrac{C_{min}}{C_{max}} = 0$

$$\varepsilon = \frac{1 - e^{-NTU}}{1 - o \times e^{-NTU}} = 1 - e^{-NT}$$

For gas turbines $\dfrac{C_{min}}{C_{max}} = 1$

$$\varepsilon = \frac{1 - e^{o}}{1 - 1e^{o}} = \text{Limited to } \frac{NTU}{NTU + 1}$$

Effectiveness of Heat Exchanger

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

It is the ratio of actual heat transfer to the maximum heat transfer.

Now $q = C_h[T_{hi} - T_{ho}] = C_h[T_{co} - T_{ci}]$

$$\in = \frac{C_h[T_{hi} - T_{ho}]}{C_{min}[T_{hi} - T_{Ci}]} = \frac{C_c[T_{Co} - T_{Ci}]}{C_{min}[T_{hi} - T_{ci}}$$

Solved Example

Example 1: If the difference between temperature differences at the ends is 25°C and mean value of temperature difference over the whole length is 50°C, then find the value of LMTD

Solution:

$$\Delta T_1 - \Delta T_2 = 25°C \qquad (1)$$

$$\frac{\Delta T_1 + \Delta T_2}{2} = 50°C \qquad (2)$$

By solving $\Delta T_1 = 62.5$

$\Delta T_2 = 37.5$

$$\text{LMTD} = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\dfrac{\Delta T_1}{\Delta T_2}\right)} = \frac{62.5 - 37.5}{\ln\left(\dfrac{62.5}{37.5}\right)}$$

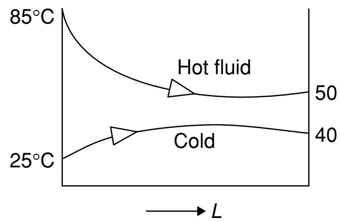
$$= \frac{25}{\ln 1.667} = 48.9°C.$$

Example 2: Hot water — $T = 85°C$, $T_0 = 50°C$; Cold water — $T_L = 25°C$, $T_0 = 40°C$

Calculate LMTD for parallel flow and counter flow.

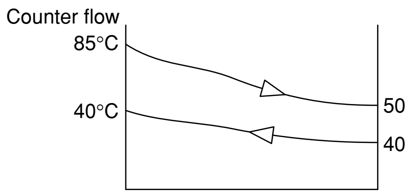
Solution:

$$\Delta T_1 = 85°C - 25C = 60°\ C$$
$$\Delta T_2 = (50°C - 40°C) = 10°C$$



$$\text{LMTD} = \frac{\Delta T_1 - \Delta T_2}{\ln \dfrac{\Delta T_1}{\Delta T_2}} = \frac{60 - 10}{\ln \dfrac{60}{10}}$$

$$(\Delta T_m)p = 27.9°C$$



$$\Delta T_1 = 85 - 40 = 45°C$$
$$50 - 25 = 25°C$$

$$\text{LMTD} = \frac{\Delta T_1 - \Delta T_2}{\ln \dfrac{\Delta T_1}{\Delta T_2}}$$

$$(\Delta Tm)C = \frac{45 - 25}{\ln \dfrac{45}{25}} = \frac{20}{\ln \dfrac{45}{25}} = 34°C$$

Example 3: The flow rates of hot and cold water streams running through a parallel flow heat exchanger are 0.3 kg and 0.6 kg/s respectively. The inlet temperatures on the hot and cold sides are 70°C and 20°C respectively. The exit temperature of hot water is 45°C. If the individual heat transfers coefficients on both sides are 650 W/m². Then the heat transfer area of the heat exchanger is

Solution:

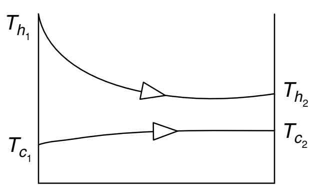
Given $mh = 0.3$ kg/s

$Mc = 0.6$ kg/s

$T_{h_1} = 70°C\ Th_2 = 45°C$

$T_{c_1} = 20°C,\ h_1 = h_0 = 650\ W/m^2°C$

The area of the heat exchanger is A



$$Q = mh \times C_p h \times (T_{h_1} - T_{h_2})$$
$$= 0.3 \times 4.187\ (70 - 45)$$
$$= 31.4 \text{ kJ/s}$$

Heat lost by hot water = Heat transfer across the heat exchanger.

$$31.4 = mc \times C_p c\ (T_{c_2} - T_0)$$
$$= 0.6 \times 4.187 \times (T_{c_2} - 20)$$
$$T_{c_2} - 20 = \frac{31.4}{0.6 \times 4.187} = 12.5°C$$
$$T_{c_2} = 32.5°C$$
$$\text{LMTD} = \Delta Tm = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)}$$

or

$$= \frac{(T_{h_1} - T_{c_1}) - (T_{h_2} - T_{c_2})}{\ln\left[\frac{(T_h - T_{c_1})}{T_{h_2} - T_{o_2}}\right]}$$
$$= \frac{(70-20)-(45-32.4)}{\ln\left[\frac{(70-20)}{12.5}\right]}$$
$$= \frac{50 - 12.5}{\ln \frac{50}{12.5}} = \frac{37.5}{\ln 4} = 27.05°C$$

As thickness of pipe is not given, we can use

$$\frac{1}{U} = \frac{1}{h_1} + \frac{1}{h_0} = \frac{1}{650} + \frac{1}{650}$$
$$u = 325 \text{ w/m}^2\text{k}$$
$$Q = uA \text{ (LMTD)},\ Q = 31.4 \text{ kJ/s}$$
$$\therefore \quad A = \frac{31.4 \times 1000}{325 \times 27.05} = 3.57 \text{ m}^2$$

Example 4: Steam enters a counter flow heat exchanger, dry saturated at 10 bar and leaves at 350°C. The mass flow of steam is 600 kg/min. The gas enters the heat exchanger at 650°C and mass flow rate is 1200 kg/min. If the tubes are 30 mm diameter and 3 m long. Determine the number of tubes required. Neglect the resistance offered by metallic tubes. Use the data

Tsat = 180°C (at 10 bar)
Cps = 2.71 kJ/kg°C
hs = 600 w/m^2°C
Cpg = 1 kJ/kg°C
hg = 250 w/m^{20}C

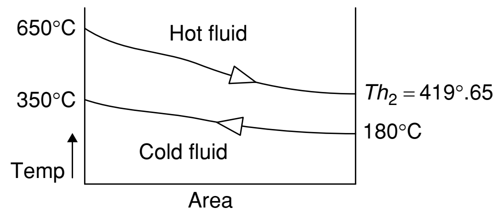
Solution:

Given
$$\dot{m}_s = \dot{m}_c = \frac{600}{60}$$
$$= 10 \text{ kg/S}$$
$$\dot{m}g = \dot{m}h = \frac{1200}{60} = 20 \text{ kg/S}$$

$$T_{h_1} = 650°C$$
$$T_{c_1} = (\text{Tsat}) = 180°C$$
$$T_{c_2} = 350°C$$
$$D = 30 \text{ mm} = 0.03 \text{ m}$$
$$L = 3 \text{ m}$$

Q = Heat loss by gases = Heat gained by steam

$$mh \times C_p h \times (T_{h_1} - T_{h_2})$$
$$= mc \times C_p h \times (T_{c_2} - T_{c_1})$$
$$= 20 \times 1 \times (650 - T_{h_2})$$
$$= 10 \times 2.71 \times (350 - 180) = 4607 \text{ kJ}$$
$$650 - T_{h_2} = \frac{4607}{20}$$
$$T_{h_2} = 650 - \frac{4607}{20}$$
$$= 419.65°C$$



Counter flow heat exchanger
Overall heat transfer co-efficient is as

$$L = \frac{18750 \text{ W}}{\pi \times \left(\frac{1}{100}\right) \times 96 \times 66.4 \times 37.4}$$
$$U = \frac{250 \times 600}{250 + 600} = 176.5 \text{ W/m}^2\text{°C}$$

Let number of tubes is n
Total heat transfer rate is given by

$$Q = U\,A\,\theta\text{m}$$
$$A = n \times (\pi\, d\, L)$$
$$A = \pi \times 0.03 \times 3\, n$$
$$= 0.2827 \text{ nm}^2$$
$$\theta_m = \frac{(\theta_1 - \theta_2)}{\ln\left(\frac{\theta_1}{\theta_2}\right)}$$
$$= \frac{(T_{h_1} - T_{c_1}) - (T_{h_2} - T_{c_1})}{\ln \frac{(T_{h_1} - T_{c_2})}{T_{h_2} - T_{c_1}}}$$
$$= \frac{(650 - 350)(419.5 - 180)}{\ln \frac{(650-350)}{(419-180)}}$$
$$= \frac{300 - 239.5}{\ln - \frac{300}{239.5}} = \frac{60.5}{\ln 1.25}$$
$$= 271.3°C$$

Substituting values

$$4607 \times 10^3 = 176.5 \times 0.2827n \times 271.3$$

$$n = \frac{4607 \times 10^3}{176.5 \times 0.2827 \times 271.3°}$$

$$= 340 \text{ tubes.}$$

Example 5: In a counter flow heat exchanger, the product of specific heat and mass flow rate is same for hot and cold fluids. If NTU is equal to 0.5, then the effectiveness of the heat exchanger is

(A) 1.0 (B) 0.5
(C) 0.33 (D) 0.2

Solution:

As .. $C_h = C_c$

$$R = \frac{C_{\min}}{C_{\max}} = 1$$

For counter flow

$$\in = \frac{1 - e^{-NTU(1-R)}}{1 - \mathrm{Re}^{NTU(1-R)}} = \frac{0}{0}$$

So apply L Hospital rule

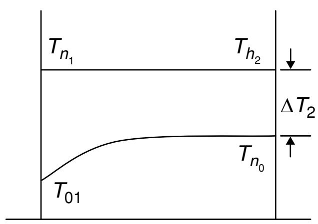
$$\lim_{R \to 0} = \frac{NTU}{1 + NTU} = \frac{0.5}{1.5} = \frac{1}{3}.$$

Example 6: A condenser is designed to condense 0.76 kg/minof steam with cooling water entering at 30°C and leaving at 55°C. Overall heat transfer coefficient = 3400 W/m^{2}K. The surface area required for this heat exchanger is (saturation temp of steam) = 95.6°h_{fg} of steam = 2300 kJ/kg

(A) 60 (B) 40 (C) 50 (D) 80°C

Solution:

Applying energy balance



Heat lost by steam = Heat gained by cooling water

= Heat transfer across the system

$$Q = m_h h_{fg} = m_c C_{pc}(T_{c_2} - T_{c_1})$$

$$UA\,\Delta\,Tm \qquad (1)$$

Calculation for LMTD

$$\Delta T_1 = T_{h_1} - T_{c_1} = 65.6°\text{C}$$

$$\Delta T_2 = T_{h_2} - T_{c_2} = 40°.6$$

$$\Delta T_m = \frac{\Delta T_1 - \Delta T_2}{\ln \frac{\Delta T_1}{\Delta T_2}} = 52.1$$

From equation (1)

$$Q = UA(\Delta T_m) = m_h h_{fg}$$

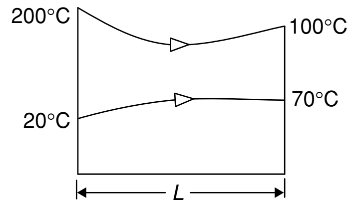
$$A = \frac{0.76 \times 2300 \times 10^3}{60 \times 52.1 \times 3400} = 0.16 \text{ m}^2$$

Example 7: In a parallel flow double pipe heat exchanger, water flows through the inner pipe and is heated from 20°C to 70°C. Oil flowing through the annulus is cooled from 200°C to 100°C. It is desired to cool the oil to a lower exit temperature by increasing the length of heat exchanger. The minimum temperature to which the oil may be cooled is

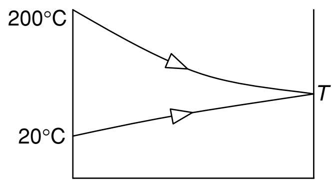
(A) 60°C (B) 85°C
(C) 70°C (D) 80°C

Solution:

Initial case



Required case: Exit temperature of oil can be lowered up to the point where it will be equal to exit temperature of cold fluid because after both fluids attain the same temperature no heat transfer will take place between them as ($\Delta T = 0$).
Applying energy balance equation in initial case



$$Q = C_h (T_{h_1} - T_{h_2})$$
$$= C_c (T_{c_2} - T_{c_1})$$
$$= C_h (200 - 100)$$
$$= C_c (70 - 20)$$
$$\frac{C_h}{C_c} = 0.5$$

Now in required case

$$Q = C_h (T_{h_1} - T)$$
$$= C_c (T - T_{c_1})$$
$$\frac{C_h}{C_c}(200 - T) = T - 20$$
$$T = 80°\text{C}.$$

Example 8: Find the length of the tube required for the following heat transfer where air is heated by exhaust gases. Q (heat transfer) = 5000 watts. Inside diameter (d_1) and outside diameter (d_o) of the tube are 5 cm and 6 cm respectively – h_i (Inside heat transfer coefficient, Air inside) = 100 w/m^2 k h_o (Outside heat transfer coefficient gas side) = 160 W/m^{2}K.

$T_{h_1} = 350°C$ $T_{h_o} = 150°C$
$T_{c_1} = 50°C$ $T_{c_0} = 100°C$
Neglect the tube resistance and assume flow arrangement is parallel.

(A) 3.5 m (B) 4.8 m
(C) 5.2 m (D) 4.75 m

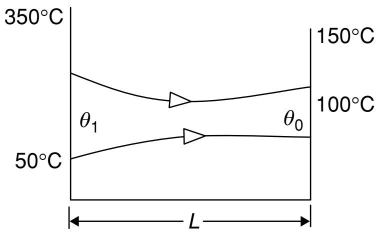
Solution:

$$LMTD = \frac{\theta_1 - \theta_O°}{\log\left(\frac{\theta_1}{\theta_O}\right)} = \frac{(350-50)-(150-100)}{\log\left(\frac{300}{50}\right)}$$

$$= \frac{300-50}{\log\left(\frac{300}{50}\right)} = \frac{250}{\log 6} = 139.52$$

The overall heat transfer coefficient referred to the outer surface of the tube is given by

$$\frac{1}{u_0} = \frac{d_0}{d_i}\cdot\frac{1}{h_i} + \frac{1}{h_o} = \frac{6}{5}\frac{1}{100} + \frac{1}{160}$$



$U_o = 54.8$ W/m^2-K

$$Q = A.\ U_0\,(\text{LMTD}) = (\pi d_0 L)\ U_0\,(\text{LMTD})$$

$$5000 = \pi \times \frac{6}{100} \times L \times 54.8 \times 139.52$$

$$L = 3.469 \approx 3.5 \text{ m}$$

Example 9: A parallel flow intercooler on a two stage air compressor takes in air at 6 bar and 180°C and passes to the next stage at 30°C and at the equivalent rate of 6 m^3 of free air per/ minute. The cooling water passes over the tubes which are 10 mm OD and 1.2 mm thick. The inlet and outlet water temperature are 12°C and 28°C respectively and air velocity through the tube is limited to 6 m/sec. Atmospheric pressure and temperature are 1.03 atm and 15°C. Take following data C_p(air) = 1000 J/kg K, R (gas constant) = 287 Nm/kg K, ha(air side) = 90 W/m^{2}K, h_w (water side) = = 1800 W/m^{2}K.

Find the number of tubes and length of each tube required.

(A) 96, 3.2 m (B) 88, 3 m
(C) 84, 4.3 m (D) 99, 2.44 m

Solution:

The LMTD for the arrangement is given by LMTD

$$\text{LMTD} = \frac{\theta_1 - \theta_0}{\log\frac{\theta_1}{\theta_0}} = \frac{168-2}{\log_e\frac{168}{2}}$$

$$= 37.4°$$

The overall heat transfer coefficient is given by

$$\frac{1}{U_0} = \frac{1}{h_1}\cdot\frac{d_0}{d_1} + \frac{1}{h_0} = \frac{1}{90}\cdot\frac{10}{7.6} + \frac{1}{1800}$$

$U_o = 65.9$ /mK

Volume of air at the inlet condition of the cooler is calculated by using

$$\frac{P_1V_1}{T_1} = \frac{PV}{T}$$

Where P_1, V_1 and T_1 represent the condition of the air at the inlet of cooler and P, V, T represent the condition at the inlet of the first stage of compressor.

$$V_1 = 6 \times \frac{1.03}{6} \times \frac{453}{288}$$

$$= 1.62 \text{ m}^3\text{/min}$$

If n = the number of tubes assumed. Then $A_1\ Vh = V_1$.
Where A_1 is the inside cross sectional area of the tube;

$$\frac{\pi}{4}\left(\frac{0.76}{100}\right)^2 \times 6 \times n = \frac{1.62}{60}$$

$\therefore$ $n = 99$

The mass of air passing through the tube is given by

$$M_a = \frac{PV}{RT} = \frac{1.03\times 10^5 \times 6}{287 \times 288}$$

$$= 7.5 \text{ kg/min}$$

The heat lost by air per sec and given to water is calculated as follows.

$$Q = m_a C_{pa}\,(\Delta T) =$$

$$\left(\frac{7.5}{60}\right)\times 1000(180-30)$$

$$= 18750 \text{ W.}$$

We can also write down

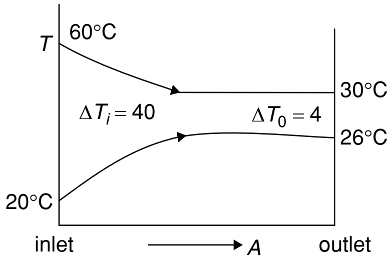
$$Q = (\pi d_o L) n\ U_o\,(\text{LMTD})$$

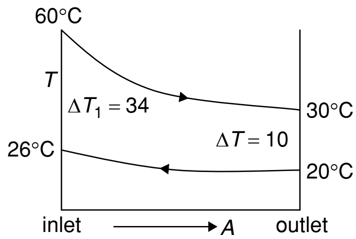
$$L = \frac{18750 \text{ W}}{\pi \times \left(\frac{1}{100}\right) \times 99 \times 65.9 \times 37.4}$$

$$= 2.44 \text{ M}$$

Example 10: A heat exchanger is used to cool oil of specific heat 2200 J/kgK from 60°C to 30°C using water available at 20°C. The increase in water temperature during the cooling process of oil is 6°C. The flow rate of oil is 10 kg/s. Take the overall heat transfer coefficient as 300 W/m^{2}K. The heat exchanger is a parallel flow type. The percentage reduction in the heat transfer area when the heat exchanger happens to be a counter type (maintaining the same end temperature values) is

(A) 18% (B) 20%
(C) 32% (D) 42%





Solution:

$$Q = m_h\, C_h\,(T_{h_1} - T_{h_0})$$

$$= 10 \times 2200\,(60 - 30)\text{J/s}$$

$$= 660000 \text{ W}$$

$$Q = UA\,(\text{LMTD}),$$

$$\text{LMTD} = \frac{40 - 4}{\ln \frac{40}{4}} = 15.635°\text{C}$$

$$660000 = 300 \times A \times 15.635$$

$$A = 140.71 \text{ m}^2$$

For counter flow $\text{LMTD} = \dfrac{34 - 10}{\ln \dfrac{34}{10}}$

$$= 19.611°\text{C}$$

$$660000 = 300 \times \text{A} \times 19.611°\text{C}$$

$$A = 112.18 \text{ m}^2$$

Difference in area of parallel flow to counter flow = 140.71 – 112.18

$$= 28.53 \text{ m}^2 = 20\%$$

$$\left\{\begin{array}{l}\text{The flow rate of water can also bedetermined} \\ \text{as it will be a necessary data } Q = m_c C_c (T_{C_0} - T_{C_1}) \\ 660000 = m_c \times 4180\,(26 - 20\; m_c = 26.32 \text{ kg/s}\end{array}\right\}$$

NOTES

1. LMTD method of analysis is suitable when all four temperatures are known.
2. When inlet flow rates and temperatures for a heat exchanger are specified the easier method of analysis is NTU method.
3. For the performance evaluation over the whole operating range of heat exchanger of effectiveness NTU method is suitable.
4. When heat capacity ratio is zero effectiveness is equal to $1 - e^{-NTU.}$
5. For a condenser/evaporator the effectiveness is $1 - e^{-NTU}$.
6. If heat capacities are equal for the parallel flow type effectiveness is $\dfrac{(1 - e^{-2N})}{2}$.
7. Effectiveness of a heat exchanger is the ratio of actual heat flow / max possible heat flow.
8. For a given heat exchanger if the heat capacity ratio $\dfrac{C_{\min}}{C_{\max}}$ increases, the effectiveness will decrease.
9. When effectiveness increases, the total heat flow need not increase.
10. Storage type heat exchanger is also called regenerative heat exchanger.
11. Air preheaters in large thermal plants use regenerative type heat exchangers.
12. The overall heat transfer coefficient will generally be minimum in the case of gas to gas heat exchangers.
13. In a condenser the controlling resistance will be on the cold fluid side.
14. In an evaporator the controlling resistance will be on the hot fluid side.

Exercises

Practice Problems I

Direction for questions 1 to 20: Select the correct alternative from the given choices.

Direction for questions 1, 2 and 3: A process industry employs a counter flow heat exchanger to cool 0.8 kg/s of oil (C_p = 2.5 kj/kgK) from 120°C to 40°C by the use of water entering at 20°C. The overall heat transfer co-efficient is estimated to be 1600 W/m^{2}K. It is assumed that the exit temperature of water will not exceed 80°C NTU is taken as 4

1. Mass flow rate of water is
   (A) 0.545 kg/s (B) .638 kg/s
   (C) .876 kg/s (D) .712 kg/s

2. Surface area required is
   (A) 5 m^2 (B) 6 m^2
   (C) 8 m^2 (D) 7 m^2

3. Effective of exchanger is
   (A) .6 (B) .8
   (C) .7 (D) .5

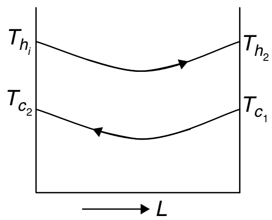
Direction for questions 4, 5 and 6: Hot water at 2.5 kg/s and 100°C enters a concentric tube counter flow heat exchanger having total area of 23 m^2 cold water at 20°C enters at 5 kg/s and overall heat transfer co-efficient is 1000 W/m^{2}K.

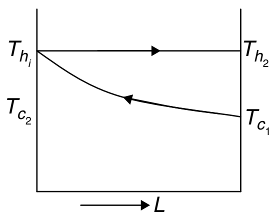
4. Find the total heat transfer rate
(A) 672 kW (B) 950 kW
(C) 788 kW (D) 1010 kW

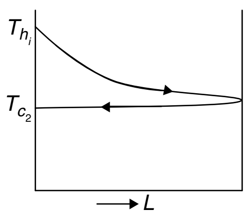
5. Find the outlet temperature of hot water
(A) 35°C (B) 36°C
(C) 40°C (D) 52°C

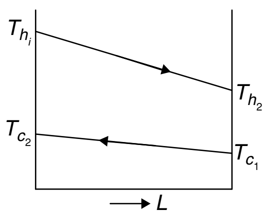
6. Find the outlet temperature
(A) 59°C (B) 60°C
(C) 48°C (D) 52°C

7. In a double pipe counter flow heat exchanger, if $C_h = C_c$ then temperature profiles of two fluids along the length will be

(A)


(B)


(C)


(D)


8. A counter flow shell and tube exchanger is used to heat water with hot exhaust gases. The water (C = 4180 J/kg°C) flows at a rate of 2 kg/s. While the exhaust gas (1030 J/kgC) flows at the rate of 5.25 kg/s. If the heat transfer surface area is 32.5 m^2, and the overall heat transfer coefficient is 200 W/m^2. What is NTU for the heat exchanger?
(A) 1.2 (B) 2.4
(C) 4.5 (D) 8.6

Direction for questions 9 and 10: A chemical having specific heat of 3.3 kJ/kgK flowing at the rate of 20000 kg/h enter a parallel flow heat exchanger at 100°C. The flow rate of cooling water is 50000 kg/h with as inlet temperature of 30°C. The heat transfer area is 10 m^2 and overall heat transfer coefficient is 1050 W/m^{2}K. Take for water, specific heat = 4.186 kJ/kg

9. Effectiveness of the heat exchanger will be
(A) 0.2 (B) 0.3
(C) 0.4 (D) 0.6

10. The outlet temperature of chemical will be
(A) 71.8°C (B) 95°C
(C) 80°C (D) 82°C

Direction for questions 11 and 12: Engine oil at 150°C is cooled to 80°C in a parallel flow heat exchanger by water entering at 25°C and leaving at 60°C

11. The exchanger effectiveness will be
(A) 0.36 (B) 0.46
(C) 0.56 (D) 0.64

12. The number of transfer units will be
(A) 1.5 (B) 1.2 (C) 1.6 (D) 2.0

13. Air is heated using the exhaust flue gas from a boiler. During the process of heating, air temperatures increases from 40°C to 100°C and flue gas cools down from 300°C to 150°C. Air flows inside a tube and flue gas flows outside. The convection heat transfer coefficients inside and outside are 100 W/m^{2}K and 160 W/m^{2}K inside and outside diameters of the tubes are 5 cm and 6 cm respectively. For a heat transfer ratio of 3000 kJ/h length of the tube is (assume parallel flow)
(A) 0.82 m (B) 0.721m
(C) 0.95 m (D) 0.633 m

14. A parallel flow heat exchanger handles hot and cold water streams in it. The flow rates of hot and cold water are respectively 10 kg/min and 25 kg/min. Specific heat may be taken as 4.18 kJ/kgK for both the streams. Hot water enters at 70°C and leaves at 50°C cold water enters the exchanger at 25°C. If the convective heat transfer coefficient inside and outside the tubes can be taken as 60 w/m^{2}K, the heat transfer area is
(A) 30 m^2 (B) 16.1 m^2
(C) 21.5 m^2 (D) 40.2 m^2

15. A counter flow heat exchanger has NTU of 2.5 and the ratio of $\dfrac{C_{\min}}{C_{\max}} = 0.25$, the effectiveness of this exchanger is
(A) 0.55 (B) 8.66
(C) 0.77 (D) 0.88

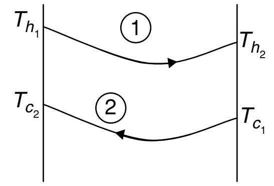
16. Air enters a counter flow heat exchanger at 70°C and leaves at 40°C. Water enters at 30°C and leaves at 50°C, LMTD is
(A) 5.65°C (B) 14.43°C
(C) 19.52°C (D) 20.17°C

17. Heat exchanger are used in
(A) Condensers and boilers in steam power plants
(B) Radiators

(C) Inter coolers and pro heaters
(D) All of these

18. AMTD (Arithmetic Mean Temperature Difference) will be 5% lighter than LMTD (Log Mean Temperature Difference) for a parallel heat flow heat exchanger.
When $\frac{\Delta T_1}{\Delta T_2}$ is equal to
(ΔT_1 ΔT_2 being the differences at the inlet and outlet of the heat exchanger)
(A) 3.2 (B) 2.2
(C) 2.0 (D) 3.0

Direction for questions 19 and 20: For a given counter flow heat exchanger gives $m_1 = m_2 = 1$ kg/s



$T_{hi} = 420°C$, $T_{ci} = 20°C$
$C_1 = 1$ kJ/kg-K, $C_2 = 4$ kJ/kg-K

19. If effectiveness is 0.75 then heat transfer rate is in (kJ)
(A) 325 (B) 300
(C) 350 (D) 270

20. Exit temperature T_{o_2} of fluid 2 in equal to
(A) 85°C (B) 95°C
(C) 190°C (D) 105°C

Practice Problems 2

Direction for questions 1 to 30: Select the correct alternative from the given choices.

1. In a certain heat exchanger both the fluids have identical mass flow rate specific heat product. The hot fluid enters at 75°C and leaves at 45°C and cold fluid entering 25°C and leaves at 56°C. The effectiveness of the heat exchanger is
(A) 0.58 (B) 0.62
(C) .53 (D) .48

Direction for questions 2 and 3: Two fluids *A* and *B* exchange heat in a counter-current heat exchanger. Fluid *A* enters at 420°C and has a mass flow rate of 1 kg/s. Fluid *B* also having mass fluid rate 1 kg/s and enters at 20°C. Effectiveness of heat exchanger is 0.75. Specific heat of fluid *A* is 1 kJ/kgK and that of fluid *B* is 4 kJ/kgK

2. Exit temperature of fluid *B* will be
(A) 89.2 (B) 95°C
(C) 85 (D) 75.2°C

3. Heat transfer rate will be
(A) 326 kW (B) 300 kW
(C) 296 kW (D) 286 kW

Direction for questions 4 and 5: In a certain double pipe parallel heat exchanger hot water flows at a rate of 40,000 kg/h and gets cooled from 95° to 65°. At the same time 40000 kg/s cooling water at 30°C enters heat exchanger. Assume C_p = 4.2 kJ/kgK and overall heat transfer coefficient = 2270

4. LMTD will be
(A) 25 (B) 234
(C) 22.8 (D) 26.7

5. Heat transfer area required will be
(A) 28.3 m (B) 39 m^2
(C) 26.3 m^2 (D) 35 m^2

Direction for questions 6 and 7: A counter flow heat exchanger is to heat air entering at 400°C with a flow rate of 6 kg/s by the exhaust gas entering at 850°C with a flow rate of 4 kg/s. The overall heat transfer coefficient is 100 W/m^2K and the outlet temperature of the air is 500°C. Specific heat at constant pressure for both air and the exhaust gas can be taken as 1100 J kg/K.

6. The heat transfer area needed will be
(A) 18.8 m^2 (B) 20.33 m^2
(C) 13.3 m^2 (D) 19.5 m^2

7. The number of transfer units will be
(A) 0.462 (B) 1.12
(C) 0.83 (D) .54

Direction for questions 8 and 9: A counter flow heat exchanger is used to cool 2000 kg/h of oil (C_p = 2.5 kJ/kg K) from 105°C to 30°C by the use of water entering at 20°C and leaving at 70°C. If the overall heat transfers coefficient is expected to be 1.5 kW/m^2 K, then for the water flow rate,

8. What is the effectiveness of heat exchanger provided that the exit temperature of the water is not to exceed 80°C. Use NTU effective approach?
(A) .75 (B) .833
(C) .90 (D) .83

9. The surface area required will be
(A) 4.3 m^2 (B) 2.5 m^2
(C) 3.2 m^2 (D) 1.9 m^2

Direction for questions 10, 11 and 12: Air is heated in a heat exchanger by using the exhaust gas from a furnace. The total heat transfer rate is found to be 8000 watts. Flue gas flows inside a pipe of 5 cm CD and 6 cm OD. Air flows outside the pipe. Inside and outside heat transfer coefficient are respectively 100 W/m^2K and 160 W/m^2K. Inlet and outlet temperatures of flue gas are 350°C and 150°C respectively. Air gets heated from 50°C to 100°C assuming parallel flow.

10. LMTD is
(A) 140°C (B) 150°C
(C) 160°C (D) 170°C

11. Overall heat transfer coefficient referred out outside pipe diameter is
(A) 55.2 W/m^{2}K (B) 47.6 W/m^{2}K
(C) 62.5 W/m^{2}K (D) 54 W/m^{2}K

12. The length of pipe required is
(A) 4.6 m (B) 5.2 m
(C) 5.5 m (D) 6.2 m

13. If the heat exchanger is a counter flow type, the length of the pipe required for the same heat load is
(A) 5.2 m (B) 4.7 m
(C) 5.8 m (D) 4.2 m

14. What is the maximum possible effectiveness for parallel flow?
(A) 0.369 (B) .454
(C) .545 (D) 0.639

15. What is the maximum possible effectiveness of the arrangement of heat exchanger in counter flow
(A) 4 (B) 3
(C) 2 (D) 1

16. A counter flow heat exchanger of 8 m^2 surface area is used for heating the cold. Liquid at 300°C flowing at the rate of 3 kg/s. Using hot fluid at 365°C flowing at the rate of 1 kgs. Overall heat transfer coefficient is 450 W/m^{2}K. Find the capacity ratio of heat flow and NTV of the system. $C_p = 2.1$ kJ/kg/K C_{ph} 4.2 kJ/kg/K.
(A) 0.67, 0.285 (B) 0.451, 0.52
(C) 0.85, 0.285 (D) 0.67, 0.857

17. Based on the effectiveness, the outlet temperatures f the cold fluid is
(A) 321°C (B) 327°C
(C) 330°C (D) 333°C

18. A liquid of density 10,000 kg/m^3 and specific heat 0.14 kJ/kg°. K is flowing through a long pipe of ID 3 cm. The flow velocity is 1.5 m/s. The viscosity of the fluid is given as 0.0011 Ns/m^2. The thermal conductivity of the fluid is 10w/m^{2}k. The heat transfer coefficient for the wall temperature at which the above properties are specified is (given $N_u = 0.023\, R_e^{0.8}\, (P_r)^{0.33}$
(A) 67.39 kW/m^{2}K (B) 52.34 kW/m^{2}K
(C) 46.54 kW/m^{2}K (D) 42.11 kW/m^{2}K

Direction for questions 19, 20 and 21: A flat plate is 20 cm wide and 40 cm long, and is at a temperature of 90°C. Air at 30°C is flowing parallel to the side 40 cm with a velocity of 3 m/s. The properties of air at 60°C are Kinematic viscosity 19$10^{-6}$ m^2/s, thermal conductivity 0.025 W/mK. Prandtl No = 0.7. Convective happen according to the relation $N_u = 0.664\, R_e^{1/2} \cdot P_r^{1/3}$

19. The convective heat transfer coefficient is
(A) 12.52 W/m^{2}K (B) 11.5 W/m^{2}K
(C) 9.3 W/m^2 K (D) 7.6 W/m^{2}K

20. The heat loss per second from the plate is
(A) 57 W (B) 54.5 W
(C) 48.6 W (D) 44.5 W

21. If the air flow is parallel to the 20 cm side, the heat loss per second is
(A) 52 W (B) 63 W
(C) 69 W (D) 74 W

22. The ratio of the thickness of hydrodynamic boundary layer to thermal boundary layer is (Prandtl No)^n where 'n' is
(A) $\frac{1}{2}$ (B) $\frac{-1}{2}$
(C) $\frac{1}{3}$ (D) $\frac{-1}{3}$

23. Water flows through a tube of id 2 cm at a rate of 1.5 kg/min. Kinematic viscosity of water is 10^{-6} m^2/s. Thermal conductivity of water at the flowing temperature is 0.45 W/mK. Prandtl number is 6. If the equation of heat transfer is $N_u = 0.664\, R_e^{1/2}\, P_r^{1/3}$, the convective heat transfer coefficient is
(A) 1073 W/m^{2}K (B) 1082 W/m^{2}K
(C) 1118 W/m^{2}K (D) 1372 W/m^{2}K

24. Water enters a 2.5 cm id thin copper tube of a heat exchanger at 15°C at a rate of 0.3 kg/s and is heated by condensing steam at 120°C outside the tubes. The average heat transfer coefficient is 800 W/m^{2}K. In order to heat water to 115°C, the length of the tube required is
(A) 61 m (B) 55 m
(C) 68 m (D) 48 m

Direction for questions 25 and 26: A stainless tube of diameter 6 cms has temperature at its surface. An air stream of temperature 25°C flows past the tube at a velocity 2.5 m/s such that the tube is normal to the air steam. The equation for heat transfer is given as $N_u = 0.024\, R_e^{0.8}$. The properties of air at mean temperature are: density 1.13 kg/m^3, C_p = 1000 J/kgK, K = 0.0275 W/mK, kinematic viscosity = 17 × 10^{-6} m^{2}K

25. The convective heat transfer coefficient is
(A) 20.32 W/m^{2}K (B) 18.45 W/m^{2}K
(C) 15.76 W/m^{2}K (D) 14.11 W/m^{2}K

26. The heat lost per meter length is
(A) 68.42 W (B) 73.42 W
(C) 81.65 W (D) 89.12 W

Direction for questions 27, 28 and 29: Saturated steam at a temperature of 80°C has latent heat 2325 kJ/kg. Stream just condenses over the tubes of a condenser which carry water. The flow rate of water is 600 kg/mt. The temperature of water at the inlet and the outlet of tube are 25°C and 50°C respectively. The inside diameter of tube is 2.5 cm. There are 12 tubes each of 10 m length. Specific heat of water may be taken as 4.18 kJ/kgK.

27. The rate of steam consumption is kJ/mt is
(A) 27 kg/mt (B) 33 kg/mt
(C) 38 kg/mt (D) 42 kg/mt

28. The overall heat transfer coefficient is kW/m^{2}K is
(A) 4.8 kW/m^{2}K (B) 3.82 kW/m^{2}K
(C) 3.12 kW/m^{2}K (D) 2.7 kW/m^{2}K

29. Effectiveness of the condenser is
(A) 0.456 (B) 0.583
(C) 0.622 (D) 0.832

30. 'Fouling factor' is used in heat exchanger design for
(A) Compensating the directional changes in the fluid flow.
(B) Compensating the for loss of heat transfer due to scale formation.
(C) Compensating for the head loss due to friction within the tubes.
(D) Compensating for the coolant contamination.

Previous Years' Questions

1. In a condenser, water enters a 30°C and flows at the rate 1500 kg/h. The condensing steam is at a temperature of 120°C and cooling water leaves that condenser at 80°C. Specific heat of water is 4.187 kJ/kgK. If the overall heat transfer coefficient is 2000 W/m^{2}K, the heat transfer area is **[2004]**
(A) 0.707 m^2 (B) 7.07 m^2
(C) 70.7 m^2 (D) 141.4 m^2

2. Hot oil is cooled from 80 to 50°C in an oil cooler which uses air as the coolant. The air temperature rises from 30 to 40°C. The designer uses a LMTD value of 26°C, the type of heat exchanger is **[2005]**
(A) Parallel flow (B) Double pipe
(C) Counter flow (D) Cross flow

3. In a counter flow heat exchanger, hot fluid enters at 60°C and cold fluid leaves at 30°C. Mass flow rate of the hot fluid is 1 kg/s and that of the cold fluid is 2 kg/s. Specific heat of the hot fluid is 10 kJ/kgK and that of the cold fluid is 5 kJ/kgK. The Log Mean Temperature Difference (LMTD) for the heat exchanger is °C is **[2007]**
(A) 15 (B) 30
(C) 35 (D) 45

4. A building has to be maintained at 21°C (dry bulb) and 14.5°C (wet bulb). The dew point temperature under these conditions is 10.17°C. The outside temperature is –23°C (dry bulb) and the internal and external surface heat transfer coefficients are 8 W/m^{2}K and 23 W/m^{2}K respectively. If the building wall has a thermal conductivity of 1.2 W/mK, the minimum thickness (in m) of the wall required to prevent condensation is **[2007]**
(A) 0.471 (B) 0.407
(C) 0.321 (D) 0.125

5. The logarithmic mean temperature difference (LMTD) of a counter flow heat exchanger is 20°C. The cold fluid enters at 20°C and the hot fluid enters at 100°C. Mass flow rate of the cold fluid is twice that of the hot fluid. Specific heat at constant pressure of the hot fluid is twice that of the cold fluid. **[2008]**
The exit temperature of the cold fluid is;
(A) is 40°C
(B) is 60°C
(C) is 80°C
(D) Cannot be determined

6. In a parallel flow heat exchanger operating under steady state, the heat capacity rates (product of specific heat at constant pressure and mass flow rate) of the hot and cold fluid are equal. The hot fluid, flowing at 1 kg/s with $C_p = 4$ kJ/kgK, enters the heat exchanger at 102°C while the cold fluid has an inlet temperature of 15°C. The overall heat transfer coefficient for the heat exchanger is estimated to be 1 kW/m^{2}K and the corresponding heat transfer surface area is 5 m^2. Neglect heat transfer between the heat exchanger and the ambient. The heat exchanger is characterized by the following relation:

$2\varepsilon = 1 - exp(-2\text{NTU})$.

The exit temperature (in°C) for the cold fluid is **[2009]**
(A) 45 (B) 55
(C) 65 (D) 75

7. In a condenser of a power plant, the steam condenses at a temperature of 60°C. The cooling water enters at 30°C and leaves at 45°C. The logarithmic mean temperature difference (LMTD) of the condenser is **[2011]**
(A) 16.2°C (B) 21.6°C
(C) 30°C (D) 37.5°C

8. Water (C_p = 4.18 kJ/kgK) at 80°C enters a counter flow heat exchanger with a mass flow rate of 0.5 kg/s. Air (C_p = 1 kJ/kgK) enters at 30°C with a mass flow rate of 2.09 kg/s. If the effectiveness of the heat exchanger is 0.8, the LMTD (in °C) is **[2012]**
(A) 40 (B) 20
(C) 10 (D) 5

9. In a heat exchanger, it is observed that $\Delta T_1 = \Delta T_2$, where ΔT_1 is the temperature difference between the

two single phase fluid streams at one and ΔT_2 is the temperature difference at the other end. This heat exchanger is **[2014]**
(A) A condenser
(B) An evaporator
(C) A counter flow heat exchanger
(D) A parallel flow heat exchanger

10. In a concentric counter flow heat exchanger, water flows through the inner tube at 25°C and leaves at 42°C. The engine oil enters at 100°C and flows in the annular flow passage. The exit temperature of the engine oil is 50°C. Mass flow rate of water and the engine oil are 1.5 kg/s and 1 kg/s respectively. The specific heat of water and oil are 4178 J/kgK and 2130 J/kgK, respectively. The effectiveness of this heat exchanger is ____. **[2014]**

11. A double pipe counter flow heat exchanger transfers heat between two water streams. Tube side water at 19 liter/s is heated from 10°C to 38°C. Shell side water at 25 liter/s is entering at 46°C. Assume constant properties of water; density is 1000 kg/m^3 and specific heat is 4186 J/kgK. The LMTD(in°C) is _____. **[2014]**

12. A hollow shaft ($d_o = 2d_i$ where d_o and d_i are the outer and inner diameters respectively) needs to transmit 20 kW power at 3000 RPM. If the maximum permissible shear stress is 30 MPa, d_o is: **[2015]**
(A) 11.29 mm (B) 22.58 mm
(C) 33.87 mm (D) 45.16 mm

13. A balanced counter flow heat exchanger has a surface area of 20 m^2 and overall heat transfer coefficient of 20 W/m^2-K. Air (C_p = 1000 J/kg-K) entering at 0.4 kg/s and 280 K is to be preheated by the air leaving the system at 0.4 kg/s and 300 K. The outlet temperature (in K) of the preheated air is: **[2015]**
(A) 290 (B) 300
(C) 320 (D) 350

14. Saturated vapor is condensed to saturated liquid in a condenser. The heat capacity ratio if $C_r = \frac{C_{min}}{C_{max}}$ .The effectiveness (ε) of the condenser is: **[2015]**
(A) $\frac{1-\exp[-NTU(1+C_r)]}{1+C_r}$
(B) $\frac{1-\exp[-NTU(1-C_r)]}{1-C_r\exp[-NTU(1-C_r)]}$
(C) $\frac{NTU}{1+NTU}$
(D) 1 – exp(–NTU)

15. Consider a parallel-flow heat exchanger with area A_p and a counter-flow heat exchanger with area A_c. In both the heat exchangers, the hot stream flowing at 1 kg/s cools from 80°C to 50°C. For the cold stream in both the heat exchangers, the flow rate and the inlet temperature are 2 kg/s and 10ºC, respectively. The hot and cold streams in both the heat exchanges are of the same fluid. Also, both the heat exchangers have the same overall heat transfer coefficient. The ratio A_c/A_p is ___________. **[2016]**

16. For a heat exchanger, ΔT_{max} is the maximum temperature difference and ΔT_{min} is the minimum temperature difference between the two fluids. *LMTD* is the log mean temperature difference. C_{min} and C_{max} are the minimum and the maximum heat capacity rates. The maximum possible heat transfer (Q_{max}) between the two fluids is: **[2016]**
(A) $C_{min}\,LMTD$ (B) $C_{min}\,\Delta T_{max}$
(C) $C_{max}\,\Delta T_{max}$ (D) $C_{max}\,\Delta T_{min}$

Answer Keys

Exercises

Practice Problems 1

1. B	**2.** A	**3.** B	**4.** A	**5.** B	**6.** D	**7.** D	**8.** A	**9.** C	**10.** A
11. C	**12.** B	**13.** D	**14.** B	**15.** D	**16.** B	**17.** D	**18.** B	**19.** B	**20.** B

Practice Problems 2

1. B	**2.** B	**3.** B	**4.** B	**5.** C	**6.** B	**7.** A	**8.** B	**9.** B	**10.** A
11. D	**12.** C	**13.** B	**14.** C	**15.** D	**16.** D	**17.** A	**18.** A	**19.** C	**20.** D
21. B	**22.** C	**23.** A	**24.** A	**25.** C	**26.** D	**27.** A	**28.** D	**29.** A	**30.** B

Previous Years' Questions

1. A **2.** D **3.** B **4.** B **5.** C **6.** B **7.** B **8.** C **9.** C
10. 0.65 to 0.67 **11.** 10.8 to 11.2 **12.** B **13.** A **14.** D
15. 0.91 to 0.95 **16.** B

Test

Heat Transfer

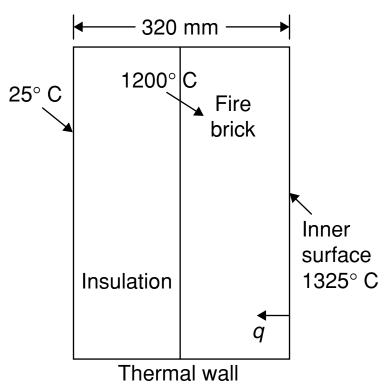
Time: 60 Minutes

1. Biot number is defined as
   (A) $\frac{\alpha t}{L^2}$ (B) $\frac{\alpha t^2}{L^2}$
   (C) $\frac{hk}{L}$ (D) $\frac{hL}{k}$
2. Heat transfer by convection is described by
   (A) Fick's law
   (B) Fourier's law
   (C) Newton's law of cooling
   (D) Stefan–Boltzman law
3. An increase in convective co-efficient over a fin effectiveness
   (A) Decreases (B) Increases
   (C) Does not influence (D) None of the above
4. The Nusselt number, in case of natural convection, is a function of
   (A) Grashoff's and Prandtl numbers
   (B) Reynold's number
   (C) Reynold's and Prandtl numbers
   (D) Weber and Mach number
5. Match List-1 with List-II and select correct answer using codes given below the list.

List-I	List-II
a. Stephen Boltzman Law	**1.** $q = hA\,(T_1 - T_2)$
b. Newtons law of cooling	**2.** $E = \alpha\,Eb$
c. Fouriers law	**3.** $q\frac{KA}{L}(T_1 - T_2)$
d. Kirchoff's law	**4.** $q = \sigma A\,(T_1^{\,4} - T_2^{\,4})$
	5. $Q = KA\,(T_1 - T_2)$

Codes:	A	B	C	D
a	4	1	3	2
b	4	5	1	2
c	2	1	3	4
d	2	5	1	4

6. A case of natural convection is given by:
   (A) Cooling of billets in atmosphere
   (B) Cooling of IC engines
   (C) Flow of water inside condensers
   (D) Cooling of a hot plate in a stream of cold water.
7. If h = coefficient of convective heat transfer, K is the coefficient of thermal conductivity, of fluid, l = characteristic linear dimension, then the term $\frac{hl}{k}$ is called
   (A) Reynold's number (B) Nusselt number
   (C) Prandtl number (D) Biot number
8. The rate of radial heat flow per unit length through the wall of a hollow cylinder of inner radius r_1, outer radius r_2, inner temperature t_1 and outer temperature t_2 is given by
   (A) $2\pi k(t_1 + t_2)/\log(r_1/r_2)$
   (B) $2\pi(t_1 + t_2)/k \log(r_2/r_1)$
   (C) $2\pi k(t_1 - t_2)/\log(r_2/r_1)$
   (D) $\log(r_2/r_1)/2\pi\, k\,(t_1 - t_2)$
9. For forced convection, Nusselt number is a function of
   (A) Prandtl number and Grashoff's number
   (B) Grashoff's number only
   (C) Reynold and Grashoff's numbers
   (D) Reynold and Prandtl numbers
10. The heat dissipated from a infinite long fin is given by
   (A) $\sqrt{PhKA}(t_s - t_a)$
   (B) $PhI\,(t_s - t_a)$
   (C) $\sqrt{PhKA}(t_s - t_a)\tanh(ml)$
   (D) $\sqrt{PhKA}(t_s - t_a)\times\left[\frac{\tanh(ml) + hlmK}{1 + hlmK}\right]$
11. A brick wall is of length 6 m, height 5 m and thickness 0.3 m. Temperature of the inner surface is 100°C and outer surface is 40°. The thermal conductivity of the brick wall 0.7 W/mk. If heat flows across the thickness, the temperature at an interior point in the wall 20 cm away from inner side is
   (A) 60°C (B) 35°C
   (C) 48°C (D) 55°C
12. A furnace wall of 1 m length and 1 m height is composed a brick lining of coefficient of thermal conductivity 0.84 W/mK in side and over it another insulation of coefficient of thermal conductivity 0.16 W/mK exposed to atmosphere. Thickness of the wall is 320 mm and that of brick lining is a mm. Under steady condition the value of 'a' is (neglect convective heat transfer)



(A) 138.7 (B) 114.7
(C) 141.2 (D) 152.8

Direction for questions 13 to 15: A steel pipe 34 mm OD 30 mm ID is carrying steam at 120°C. The pipe is insulated with asbestos ($K = 0.3$ W/m°C) to prevent condensation. Ambient temperature is 25°C. Surface conductance on air side and steam side are 13 W/m^2°C and 500 W/m^2°C respectively. h_{fg} at 120°C = 2300 kJ/kg; k for steel pipe = 72 W/m°C).

13. The rate of steam condensation when the pipe is uninsulated.
(A) 128.09 W/m (B) 144.7 W/m
(C) 130 W/m (D) 131.5 W/m

14. Rate of condensation with insulation 13.5 mm
(A) 127 W/m (B) 114.7 W/m
(C) 130 W/m (D) 140 W/m

15. The mass flow rate of condensation when the above insulation is not provided
(A) 0.0448 kg/h (B) 0.2 kg/h
(C) 0.33 kg/h (D) 0.683 kg/h

Direction for questions 16 to 19: A thin walled copper tube with OD = .02 m carries steam at 400 K. The surrounding temperature is 300 K. The tube is insulated with material of K 0.07 W/m-K

16. What is the critical thickness of insulation for an external convective heat transfer coefficient $h = 4.0$ W/m^2-K (conduction resistance of tube is nil)
(A) 0.88 cm (B) 0.9 cm
(C) 0.6 cm (D) 0.75 cm

17. The rate of heat transfer per meter of tube for an insulation 0.002 m thick
(A) 23.2 W/m (B) 26.8 W/m
(C) 21.1 W/m (D) 35.6 W/m

18. For critical thickness insulation, the heat flow is
(A) 28.2 W/m (B) 35 W/m
(C) 25 W/m (D) 50 W/m

19. Overall heat transfer coefficient with .05 m thick insulation
(A) 0.56 W/m^{2}K (B) 0.67 W/m^{2}K
(C) 0.27 W/m^{2}K (D) 0.70 W/m^{2}K

20. A copper thermo couple initially at 25°C, when placed in a gas stream of 200°C measures a temperature of 198°C in 5 sec. For copper $\rho = 8940$ kg/m^3,
$C = 384$ J/kg-K, $k = 390$ W/mK, $h = 400$ W/m^{2}K. The junction diameter is
(A) 0.78 mm (B) 0.88 m
(C) 1 mm (D) 0.9 mm

Direction for questions 21 and 22: A iron fin of length 50 mm, width 100 mm and thickness 5 mm ($k = 210$ kJ/mh°C and $h = 42$ kJ/m^{2}h°C for the material of the fin) Temperature at the base of the fin is 80°C. Atmospheric temperature is 20°C.

21. The amount of heat transferred is
(A) 20.13 kJ/h (B) 24.75 kJ/h
(C) 31.2 kJ/h (D) 40.2 kJ/h

22. The tip temperature of the fin if atmosphere temperature is 20°C is
(A) 40.2°C (B) 56.8°C
(C) 38.3°C (D) 74.2°C

Direction for questions 23 to 27: Air at 20°C at a pressure of 1 bar is flowing over a plate at a velocity of 3 m/s. The plate is 280 mm wide and at 56°C. Properties of air at mean temperature of 38°C are $\rho = 1.1374$ kg/m^3. Properties of air at 38°C are
$k = 0.02732$ W/m°C, $Cp = 1.005$ kJ/kg°K,
$n = 16.768 \times 10^{-6}$ m^2/sec, $P_r = 0.7$.
At $x = 280$ mm

23. The boundary layer thickness d is
(A) 6.26 mm (B) 5.88 mm
(C) 4.3 mm (D) 7.35 mm

24. Thickness of thermal boundary layer δth is
(A) 3 mm (B) 4 mm
(C) 6 mm (D) 7 mm

25. Local convective heat transfer h_x is
(A) 8.56 W/m^2°C (B) 6.43 W/m^2°C
(C) 7.2 W/m^2°C (D) 9.35 W/m^2°C

26. Average convective heat transfer $\overline{h}$ is
(A) 12.8 W/m^2°C (B) 13.6W/m^2°C
(C) 18.8 W/m^2°C (D) 40.2W/m^2°C

27. Rate of heat transfer is
(A) 56.2 W (B) 51.3 W
(C) 36.3 W (D) 40.2 W

Direction for questions 28 and 29: A bulb of 60 watt at 120°C is used in quiescent air at 30°C. The bulb can be approximated to 50 mm diameter sphere (free convection coefficient is $Nu = 0.60\,(G_rP_r)^{0.25}$ (properties of air at $t_f = 348$ k)
$P_r = 0.697$, $v = 20.76 \times 10^{-6}$ m^2/s,
$K = 0.03$ W/mK

28. The heat transfer from the bulb is
(A) 4.32 W (B) 6.81 W
(C) 5.5 W (D) 8.3 W

29. Power lost by free convection (%) is
(A) 11.35% (B) 18%
(C) 19.5% (D) 25%

30. A vertical plate of 500 mm high and width 1 m is maintained at 30°C and is exposed to steam at atmosphere pressure
Properties of water film at mean temperature are
$\rho = 980.3$ kg/m^3
$k = 66.4 \times 10^{-2}$ J/sm°C
$\mu = 434 \times 10^{-6}$ kg/ms
$h_{fg} = 2257$ kJ/kg
The rate of heat transfer
(A) 567×10^3 kJ/h (B) 280 kJ/h
(C) 300 kJ/h (D) 310 kJ/h

Answer Keys

1. D	**2.** C	**3.** A	**4.** A	**5.** A	**6.** A	**7.** B	**8.** C	**9.** D	**10.** A
11. A	**12.** B	**13.** A	**14.** A	**15.** B	**16.** D	**17.** B	**18.** A	**19.** A	**20.** A
21. B	**22.** D	**23.** A	**24.** D	**25.** B	**26.** A	**27.** C	**28.** B	**29.** A	**30.** A