

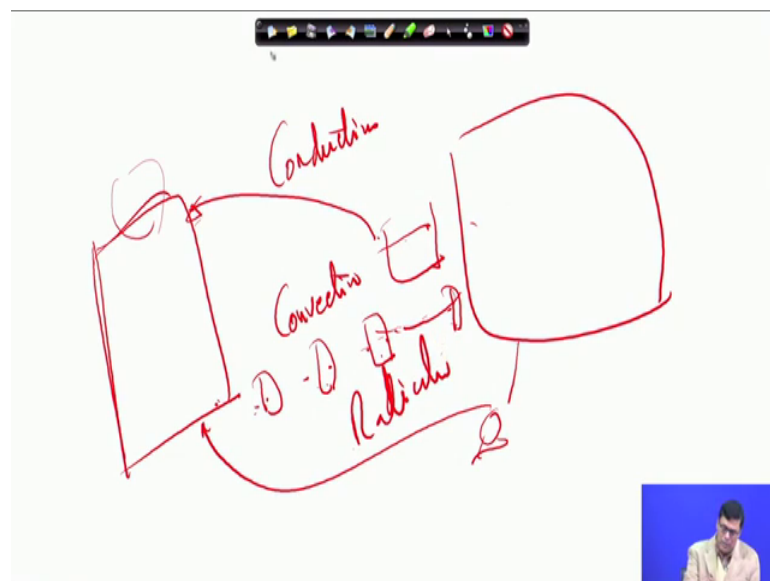
Aspects of Biochemical Engineering
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Lecture – 49
Transport Phenomenon in Bioprocess III

Welcome back to my course Aspects of Biochemical Engineering. I think in the last two lectures I try to discuss both momentum transfer transport and also mixing time in that in the bioreactors. And today I at this lecture I am going to discuss the very important topic that is heat transfer.

Now, you can remember that in the in the last in previously I try to discuss the how you can explain this conduction, convection, and radiation. Because I have given the example that if you look at look at you know that one place this here some kind of fire that has been created and we want to extinguish this fire.

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Then there are 3 different approaches we have suppose there is a pond here and in this pond I can with the help of bucket I can take the water, one percent can take the water and put the water in this for the fire extinguishing purpose.

The another approach is that one person you can take this bucket of water give it to the at the one person standing here, one person standing here, one person standing here. And so

the he handed over the bucket here, he hand over the bucket here, he now handed over the bucket here.

And here so here what is happening? If you if you look at first case that both the water and the man is on our movement, but here that the water movement is there, but medium is not moving because all the person they are standing here am I right.

And another way we can do that we can use some kind of pump and we can we can we can we can we can spray these pump on the surface of the, this fire, so that extinguish the fire thickness.

So three different mechanisms we have now this is we call is conduction, this is the person who is carrying the liquid and that for just to subside the fire, and this is this is where the medium is not move and liquid is going, but the that medium is not moving that is we convection, and this we call it radiation.

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Heat transfer

- ✓ Heat transfer deals with the **transport of different forms of energy in term of temperature.**
- ✓ **Application:** temperature controlling in a reactor, sterilization, insulation of process flow pipe

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So, this is three mechanism and which is largely a apply in case of heat transfer. Now let us see that heat transfer deals with the transfer transport of different form of energy in the form of temperature, so this we understand.

Now where so biochemical industries largely applied the reason is that reason is that that we required the temperature control in case of reactor, because we I told you that organism they required a particular temperature for their growth and metabolism, then

for sterilization because sterilization is the very important part of fermentation industry because we shall have to kill the other organism that present in the system. So, that our desired organism can grow and insulation of the process by flow line the, that also very much you required.

Suppose you want to particularly in case of sterilizer we have we have this pipe after the heat exchanger there should be totally insulated, so that we can maintain the temperature in the pipe line for the sterility of the liquid.

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Molecular heat transfer/Conductive heat transfer (Fourier's law)

- ✓ Heat flow through material medium without actual migration of particles of the medium, from region of higher temperature to a region of lower temperature.
- ✓ The phenomena can be explained by **Fourier's law**

$$Q \propto A \left[\frac{dT}{dx} \right]$$
$$Q = -kA \left[\frac{dT}{dx} \right]$$

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So, so these are the now, question comes that how you do the analysis of this heat transfer first is the molecular. If you look at molecular heat transfer or conductive heat transfer how you can express?

The heat flows through the material media without actual migration of the particle of the media region, that highly temperature is that is the lower temperature high temperature to the low temperature. This is this how you can take place Q equal to A into d A to the power d x am I right.

Now, d A is the d T is the temperature difference, and d x is the thickness of that particular medium and A is the area that we have. So, we can write this is k is the proportionality constant.

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Molecular heat transfer/Conductive heat transfer (Fourier's law)

- ✓ Q is the rate of heat transfer in watts (W),
- ✓ A is the area normal to direction of heat flow in m^2 , T is the temperature (K),
- ✓ x is the length of conduction path along the heat flow in (m),
- ✓ $\frac{dT}{dx}$ is the rate of change of temperature with distance measured in the direction of heat flow (called temperature gradient) in K/m ,
- ✓ k is the proportionality constant and is called thermal conductivity.

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Now Q is the heat transfer that I told you heat transfer in the watt, and A is the area, x is the length of the conductive path. And $d T$ by $d x$ is the rate of change of temperature with distance measured in the direction of the heat flow, and k is the proportionality constant.

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Molecular heat transfer/Conductive heat transfer (Fourier's law)

✓ (-) sign in the equation because with increase in x there is decrease in T (i.e. temperature decrease in direction of heat flow) and it makes a heat flow positive in direction of heat flow.

$$Q = -kA \frac{dT}{dx}$$
$$\frac{Q}{A} = q_x = -k \frac{dT}{dx}$$

Where q is the heat flux i.e. Rate of heat flow per unit area in W/m^2 in x direction.

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Now, this is the Q equal to this we can write, so this we can write Q by A equal to $k x$ you can write this form.

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Molecular heat transfer/Conductive heat transfer (Fourier's law)

✓ **Fourier's law** can also be used in macroscopic conduction

The macroscopic form of Fourier's law as follows

Rate of heat transfer

$$Q = kA \frac{(-\Delta T)}{\Delta x} = \frac{(-\Delta T)}{\Delta x/Ak} = \frac{(-\Delta T)}{R} = \frac{\text{driving force}}{\text{resistance}}$$

Minus sign before ΔT indicates heat is transferring higher temperature to lower temperature

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And so Q equal to Q A in to dx by d T, the now this is initially you can remember we asks any kind of transfer is equal to driving force where resistance.

So, we want to write it the this express the equation in that same form that Q equal to del T by R, R is the resistance and this resistance is nothing, but del x A into k that is the resistance. So, driving force is the temperature difference and resistance is nothing, but del x by A into A k.

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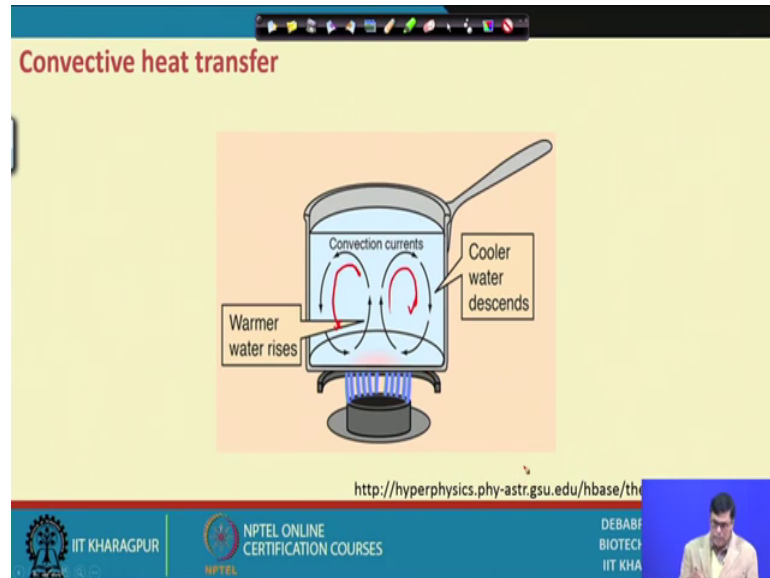
Convective heat transfer

- ✓ Convection is **heat transfer by mass motion of a fluid such as air or water**
- ✓ Convection above a hot surface occurs because hot air expands, becomes less dense, and rises. Hot water is likewise less dense than cold water and rises, causing convection currents which transport energy.

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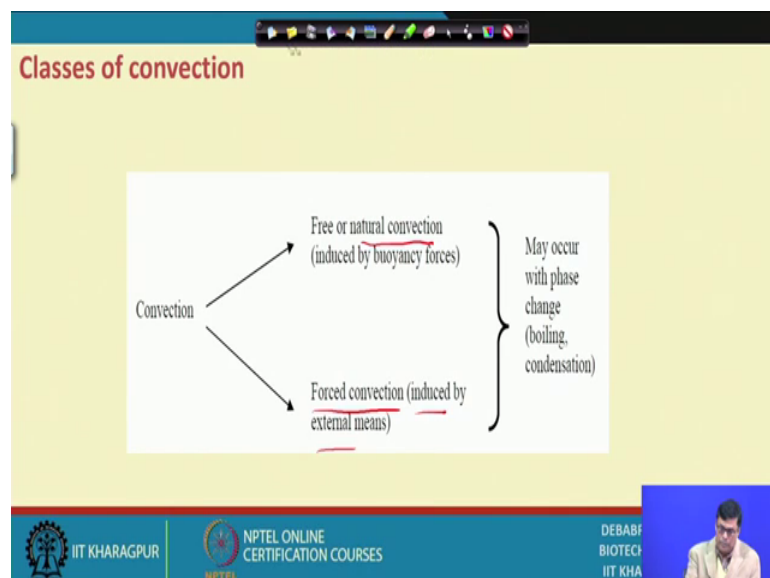
Now, next is the convective convective heat transfer and convection of the heat transfer by the mass motion of the fluid in such air, or water. And convection amount of the hot surface occurred because of the hot air expands.

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And between because let me give the example like this. It is the hot surface with the close at the bottom you can see that your hot surface. So, it is going like and it will go rise, it will it will go rise, and it will come back like this it will go rise, and come back like this.

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So, this is the cooler water descends and this is the warmer water rise, this is this is this is this is the phenomena, this is going on reusing convection process. So, convection may be of two types one is called natural convection, or free convection. Another is force convection we induced by the external means.

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Classes of convection

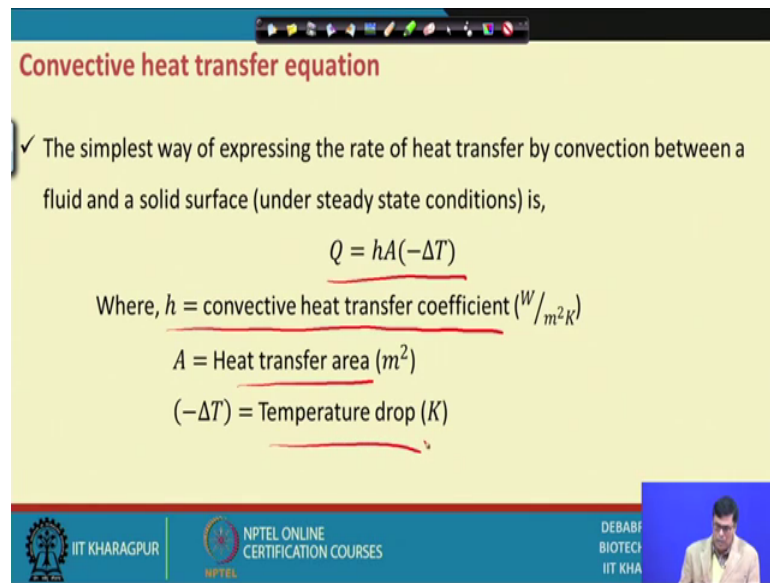
- ✓ In natural convection, the flow is induced by the differences between fluid densities which result due to temperature changes.
- ✓ Forced convection uses externally induced flow, such as wind.

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Now, the natural convection the flow induced by the different differences between the fluid density I have with the result due to temperature changes. Now we understand that as we increase the temperature the density is reduced am I right, so that results a temperature changes.

The forces of force convection externally induced flow with the such as wind we use the kind of flow pattern. So, that you know flows convection that takes place.

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Convective heat transfer equation

✓ The simplest way of expressing the rate of heat transfer by convection between a fluid and a solid surface (under steady state conditions) is,

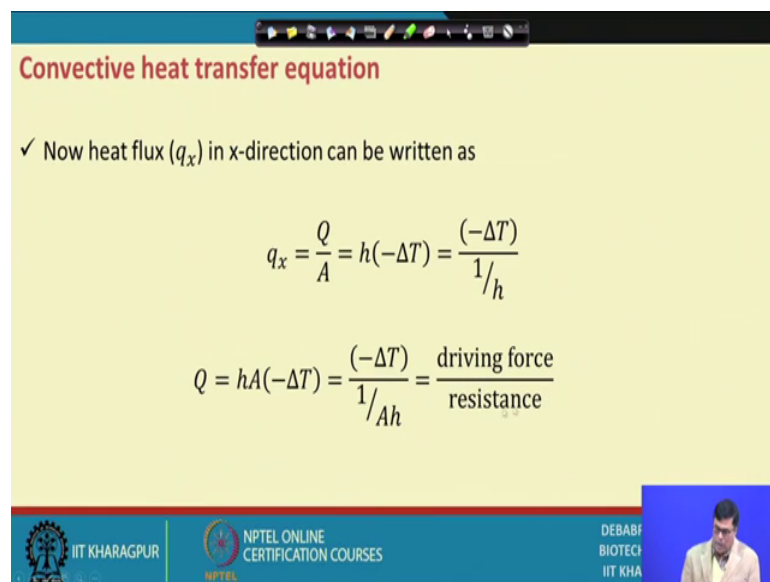
$$Q = hA(-\Delta T)$$

Where, h = convective heat transfer coefficient (W/m^2K)
 A = Heat transfer area (m^2)
 $(-\Delta T)$ = Temperature drop (K)

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So, here the rate of heat transfer can be expressed like this that Q equal to A into h into A del T, where h is the convective heat transfer coefficient, A is the heat transfer area, and del T is the temperature drop.

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Convective heat transfer equation

✓ Now heat flux (q_x) in x-direction can be written as

$$q_x = \frac{Q}{A} = h(-\Delta T) = \frac{(-\Delta T)}{1/h}$$
$$Q = hA(-\Delta T) = \frac{(-\Delta T)}{1/Ah} = \frac{\text{driving force}}{\text{resistance}}$$

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Now this is equal to I can similarly we can as we did in case of conduction we can write in the same form, driving force by resistance and this will be 1 by A h.

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Newton's cooling law

✓ Suppose heat is transferring from hot liquid (T_h) to cold liquid (T_c) by natural convection, therefore heat flux as follows

$$q = h(T_h - T_c)$$

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Now, Newton's law of cooling is that when the heat that hot liquid temperature is T_h , and cool liquid T_c , then natural convection heat flux equal to $q = h(T_h - T_c)$.

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Shell energy balances

✓ The governing equation

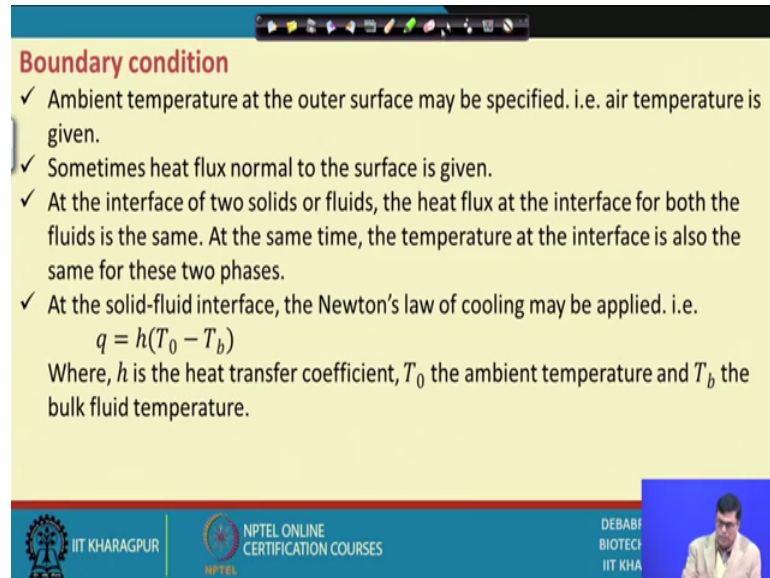
Rate of "energy in" by molecular transport - Rate of "energy out" by molecular transport + Rate of "energy in" by convective transport - Rate of "energy out" by convective transport + Rate work done on the system + Rate of work done on the system by external forces + Rate of energy production = 0

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Now the cell energy balance the governing equation we can explain like this. The rate of energy by molecular rate of energy by molecular transport minus rate of energy by molecular energy out by molecular transport, rate of energy by convective transport, rate of energy out by convective transport.

And rate of work done on the system, rate of work done on the system by the external force, and rate of energy production all because there should be equal to 0, this is the governing equation.

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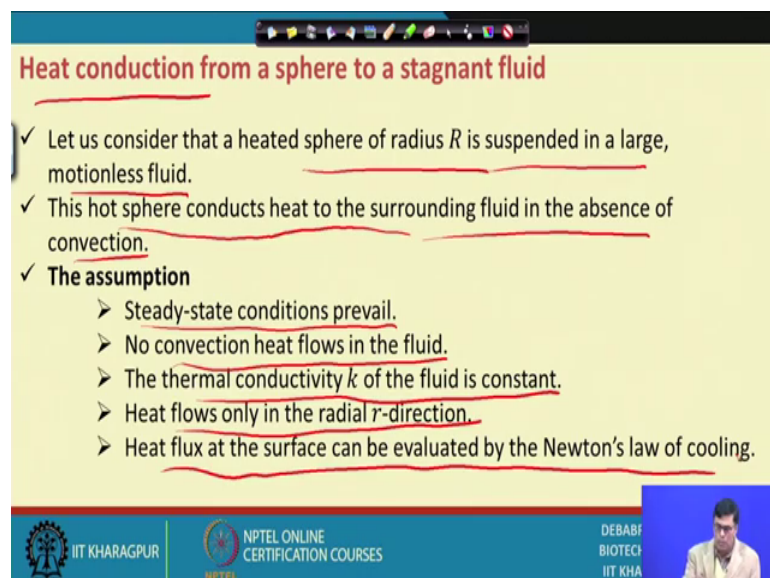
Boundary condition

- ✓ Ambient temperature at the outer surface may be specified. i.e. air temperature is given.
- ✓ Sometimes heat flux normal to the surface is given.
- ✓ At the interface of two solids or fluids, the heat flux at the interface for both the fluids is the same. At the same time, the temperature at the interface is also the same for these two phases.
- ✓ At the solid-fluid interface, the Newton's law of cooling may be applied. i.e.
$$q = h(T_0 - T_b)$$
Where, h is the heat transfer coefficient, T_0 the ambient temperature and T_b the bulk fluid temperature.

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Now, this is the boundary conditions we have. The ambient temperature of the other surface may be specified at air temperature, is the given sometime heat flux normal to the surface is given. So, these are given I am not going through any details you can easily very easily find out.

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Heat conduction from a sphere to a stagnant fluid

- ✓ Let us consider that a heated sphere of radius R is suspended in a large, motionless fluid.
- ✓ This hot sphere conducts heat to the surrounding fluid in the absence of convection.
- ✓ **The assumption**
 - Steady-state conditions prevail.
 - No convection heat flows in the fluid.
 - The thermal conductivity k of the fluid is constant.
 - Heat flows only in the radial r -direction.
 - Heat flux at the surface can be evaluated by the Newton's law of cooling.

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Heat of conduction from a sphere, now people that we discuss about the, that in case of the convection now heat of conduction from sphere of a stagnant fluid this can be the let us consider the heat of sphere of radius R is suspended in a large motion, less fluid. And hot sphere hot sphere conducts heat to their surrounding fluid in the absence of convections.

Now, the following assumptions are maintain that steady state condition prevail, no convection heat flow in the fluid, the thermal conductivity k of the fluid is constant. Heat flow only in the radial r direction and heat flux at the surface can be evaluated by the Newton law of cooling.

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Heat conduction from a sphere to a stagnant fluid

✓ Heat flux = q_r

The diagram illustrates a sphere of radius R at temperature T_R surrounded by a fluid at temperature T_c . A radial distance r is shown from the center of the sphere to a fluid element of thickness Δr . The fluid element is shown as a curved layer with a thickness Δr and a temperature T_c . The sphere is labeled 'Sphere' and the fluid is labeled 'Fluid'. The temperature at the surface of the sphere is T_R .

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So, this was how we can do that this is the this is the sphere, and this is the sphere and this is the fluid that we have, this is the r, and this is the T c, and this is the T R is the in difference.

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Heat conduction from a sphere to a stagnant fluid

✓ Rate of “heat in” at the spherical surface at r – Rate of “heat out” at the spherical surface at $r + \Delta r = 0$

i.e. $(4\pi r^2 q_r)|_r - (4\pi r^2 q_r)|_{r+\Delta r} = 0$

✓ Dividing both sides by $4\pi\Delta r$ and taking the limit $\Delta r \rightarrow 0$, we have

$$\frac{d(r^2 q_r)}{dr} = 0$$

Integrating the above eqn, we get $r^2 q_r = C_1$

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So, rate of the rate in the spherical surface r , and rate r in their or heat out at the spherical surface r plus r , there should be equal to 0. And which can be represented like this is the surface area am I right in this field, surface area of a sphere is $4\pi r^2$ into q_r , this is the r , and $4\pi r^2$ into $r + \Delta r$.

Now, this if you divide by $4\pi\Delta r$ and Δr tends to 0, we can write this equation in this form and this we can integrate it we can write $r^2 q_r = C_1$, C_1 is a constant.

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Heat conduction from a sphere to a stagnant fluid

✓ Now applying the Fourier's law of heat conduction, i.e.

$$q_r = -k \frac{dT}{dr}$$

We get

$$\frac{dT}{dr} = -\frac{C_1}{kr^2}$$

Integrating the above equation, we obtain

$$T = \frac{C_1}{kr} + C_2$$

✓ Now C_1 and C_2 are evaluated from the boundary conditions.

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Now, then by applying the Fourier's law of heat of conduction we can write $q = -k \frac{dT}{dr}$ and then we can write $dT = -\frac{q}{k} dr$.

This we can write in this form, we have seen before also. This we can write it here and then we have finally, equation will be getting this is equal to $T = -\frac{q}{k} r + C_1$ and that $C_1 = kR(T_R - T_C)$.

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Heat conduction from a sphere to a stagnant fluid

- ✓ Boundary condition 1: $T = T_R$
At $r = R$
- ✓ Boundary condition 2: $T = T_C$
At $r = \infty$,

Now, $T_R = \frac{C_1}{kR} + C_2$
And $T_C = C_2$

Substitution the value of C_2 , we get
 $C_1 = (T_R - T_C)kR$

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Now, here the heat of combustion of sphere to a stagnant fluid the boundary condition $T = T_R$, where small r is equal to capital R and $T = T_C$, where r tends to a infinity. Then your equation will be $T_R = \frac{C_1}{kR} + C_2$ and $T_C = C_2$ then we can write in this form, $C_1 = (T_R - T_C)kR$.

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Heat conduction from a sphere to a stagnant fluid

Substituting the values of C_1 and C_2 in $T = \frac{C_1}{kr} + C_2$

we obtain

$$\frac{T - T_C}{T_R - T_C} = \frac{R}{r}$$

We can obtain the temperature profile in the radial direction using this equation

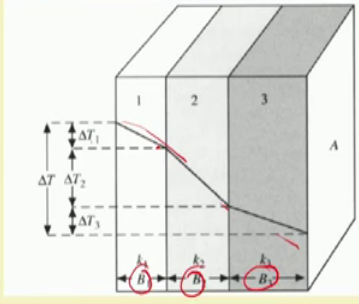
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Finally we can write this equation that T equal to C_1 into $k r$. And T_1 minus T_C by T_R minus T_C equal to capital R by small r .

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Combining thermal resistances in series

- ✓ When a system contains several different heat-transfer resistances in series, the **overall resistance** is equal to the **sum of the individual resistances**
- ✓ the **temperature change across the entire structure** is

$$\Delta T = \Delta T_1 + \Delta T_2 + \Delta T_3$$


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Now, this is the combining resistance because this is very important. This is a when a system contains the several heat transfer resistance in series, overall resistance is equal to sum of the individual resistance, and temperature changes the across the entire structure.

Now let us a let us have this 1 resistance, 2 resistance, 3 resistance, and how the temperature changing like this. There are different resistance that we have so that

temperature change the ΔT across this layer, and ΔT across this resistance, the ΔT across this resistance.

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Combining thermal resistances in series

✓ Rate of heat conduction in this system (under steady state) is given by

$$Q = \frac{(-\Delta T)}{R_w} = \frac{(-\Delta T)}{R_1 + R_2 + R_3}$$
$$R_1 = \frac{B_1}{k_1 A}$$
$$R_2 = \frac{B_2}{k_2 A}$$
$$R_3 = \frac{B_3}{k_3 A}$$

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Now the rate of heat conduction in the in the system under steady state condition governed by this equation, this is the driving force, and this is the resistance, a resistance is the R_1 , R_2 , R_3 , and R_1 can be expressed like this. We have shown than B_1 then this is the, this like this.

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Individual and overall heat transfer coefficient

✓ Assume a simple case in which hot fluid is flowing through a circular pipe and cold fluid flowing outside the pipe

✓ The overall resistance to heat flow from hot fluid to cold fluid is made of three resistance in series

- Resistance offered by film of hot fluid
- Resistance offered by metal wall
- Resistance offered by film of cold fluid

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Now, individual and overall heat transfer coefficient assume the, assume a simple case in which the hot fluid is flowing through a circular pipeline, and cold fluid is a flowing outside the pipe line.

So, it is a kind of annular things you know that we can write that this is like this, this is a the hot liquid is flowing through a circular pipeline cold fluid is a outside the pipeline. So, here might be a cold, and if you if you consider this heat hot liquid. So, cold liquid and hot liquid this is hot am I right.

So, the overall resistance of flow of the hot fluid to cold fluid is measured by 3 resistance, a resistance offered by the film of hot fluid, resistance offered by the metal wall, resistance offered by film of the.

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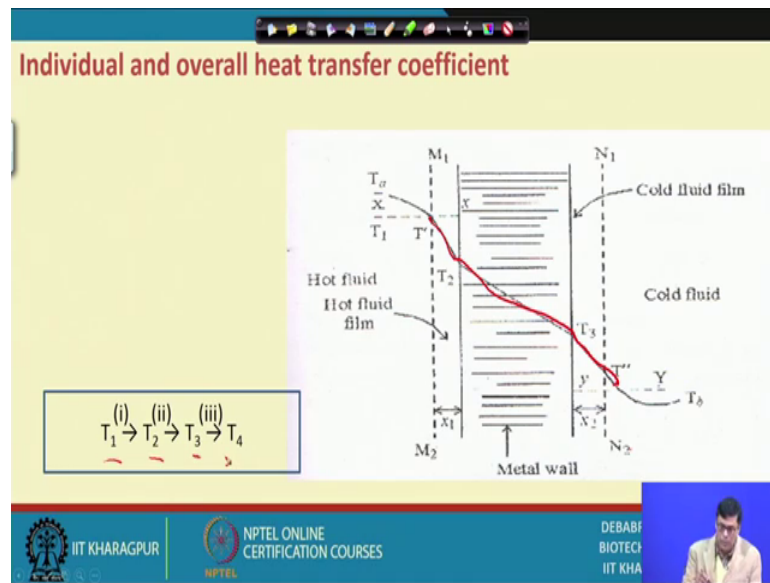
Individual and overall heat transfer coefficient

- ✓ Assume a simple case in which hot fluid is flowing through a circular pipe and cold fluid flowing outside the pipe
- ✓ The overall resistance to heat flow from hot fluid to cold fluid is made of three resistance in series
 - i. Resistance offered by film of hot fluid
 - ii. Resistance offered by metal wall
 - iii. Resistance offered by film of cold fluid

The slide includes a diagram of a pipe with red arrows indicating flow direction. The bottom of the slide features logos for IIT Kharagpur, NPTEL Online Certification Courses, and a small video inset of a presenter.

So, you have 3 different layers. So, I have shown you this like this. So, here what he is saying that resistance offered by whole fluid there will be, but this is hot the, this is they have the resistance. Then the wall has the resistance and this is the cold fluid, now cold film they have the resistance.

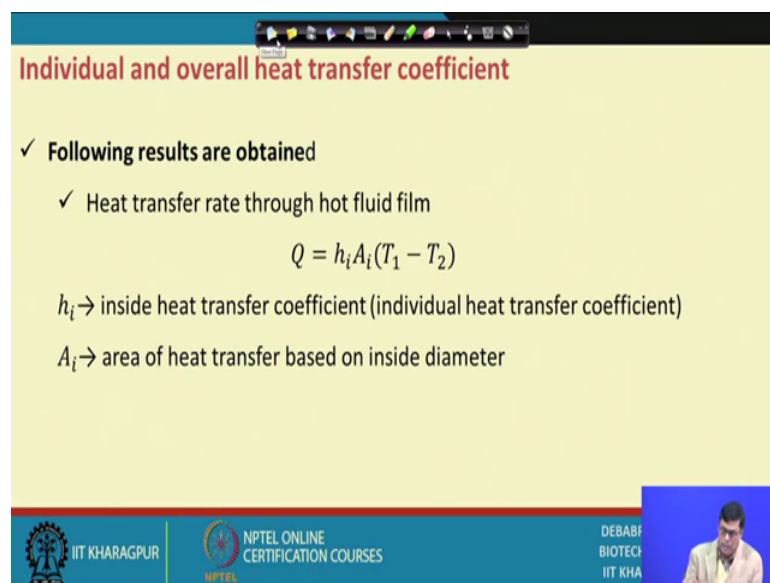
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Now this is how we can explain like this is a, this is different layered that we have. And different resistance we can we can measured at different places and this was 1, 2, 3, the difference situation that we have that this is different region that we have, that is cold film, and this is a and this is the hot side, and this is the metal surface metal wall is there.

So, this is how this comes like this. So, if the temperature is flowing like this and like this, so you can write T_1 to T_2 , T_2 to T_3 , T_3 to T_4 ok.

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So, here the heat transfer rate in the hot fluid can be expressed as $Q = h_i A_i (T_1 - T_2)$ am I right.

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Individual and overall heat transfer coefficient

✓ Rate of heat transfer through the metal wall

$$Q = \frac{kA_w(T_2 - T_3)}{x_w}$$

k → thermal conductivity of the pipe material
 x_w → pipe wall thickness
 A_w → heat transfer area

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So, in case of wall we can write what you can write $Q = k A_w (T_2 - T_3) / x_w$ then and A_w is equal to what? A_w is the surface area am I right.

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Individual and overall heat transfer coefficient

For cylinder

$$A_w = 2\pi r_m L$$

L → length of the cylindrical pipe
 r_m → log mean of inner and outer radius of the cylinder

For sphere

$$A_w = 4\pi r_m^2$$

r_m → geometric mean of inner and outer radius of the sphere

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So, twice pi r is the temperature in to length the. So, you can you cover all the surface area of the circular tube. And this is the, this for sphere we shall have to have the area is 4 pi R square.

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Individual and overall heat transfer coefficient

- ✓ Rate of heat transfer through the cold fluid film

$$Q = h_o A_o (T_3 - T_4)$$

$h_o \rightarrow$ outside heat transfer coefficient (individual heat transfer coefficient)
 $A_o \rightarrow$ area of heat transfer based on outside diameter
- In practical aspect it is difficult to measure ΔT in each layer. Hence, measurement of individual heat transfer coefficient is not easy. This problem is solved by introducing **overall heat transfer coefficient**

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And in case of rate of heat for the cold fluid, we can write Q equal to $h_o A_o (T_3 - T_4)$.

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Individual and overall heat transfer coefficient

- ✓ In terms of overall heat transfer coefficient

$$Q = U_o A_o (T_1 - T_4) = U_i A_i (T_1 - T_4)$$

$U_o \rightarrow$ overall heat transfer coefficient based on outside diameter
 $U_i \rightarrow$ overall heat transfer coefficient based on inside diameter
- Combining all the rate equation

$$\frac{1}{U_i A_i} = \frac{1}{U_o A_o} = \frac{1}{h_i A_i} + \frac{x_w}{k A_w} + \frac{1}{h_o A_o}$$

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So, when we the overall heat transfer that you have the Q into $U_o A_o (T_1 - T_4)$. Now you combine all the equations we will get in this form and I right

1 by $U_i A_i$ equal to 1 by $U_o A_o$ equal to this into this into this is the overall equation we will get.

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Individual and overall heat transfer coefficient

✓ For thin wall tubes or cylinder, the inside and outside radii are not much different from each other. Hence the combining equation can be modified as

$$\frac{1}{U_i} = \frac{1}{U_o} = \frac{1}{h_i} + \frac{x_w}{k} + \frac{1}{h_o}$$
$$\frac{1}{U} = \frac{1}{h_i} + \frac{x_w}{k} + \frac{1}{h_o}$$

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From that we can write this equation you can see that equation this one and from this we can easily find out this equation. This is for thin tubes of cylinder inside and outside radii radius are not much difference for the each other and hence there is a combined equation will be like that.

So, what we can see previously that you see that previously this equation was our equation. Now we consider this is same this more or less they are not changing.

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Fouling factor

- ✓ Due to continuous uses of heat-transfer equipment, dirt and scale deposit on one or both sides of the pipes, providing additional resistance to heat flow and reducing the overall heat-transfer coefficient.
- ✓ Each fouling layer has associated with it a heat transfer coefficient; for scale and dirt the coefficient is called a **fouling factor**.

Steam generator
Scale formation in boiler tubes

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Then what we can write we can write this equation in this form. This is the form we can write. So, fouling factor that is the, another important thing that we have in case of heat transfer; this is due to the continuous use of the heat surface equipment dirt, and scale deposit on one, or both side of the pipe providing additional resistance to the heat flow and reduce the overall heat transfer coefficient.

Now, I can give take the example in the steam generator, steam generator. Now in case of steam generator major problem is the scale formation in boiler tubes in then what is happening now?

If the scale formation they are in the boiler tubes then what will happen the heat will not transfer properly the conductivity of the metal that will be less conductivity of the solid surface will be will be less. So, heat transfer you require more heat that is the fouling factor. The each fouling layer are associated with the heat transfer coefficient for scale, and dirt coefficient is called fouling factors.

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Fouling factor

- ✓ Let h_{fh} be the fouling factor on the hot-fluid side, and h_{fc} be the fouling factor on the cold-fluid side.
- ✓ Overall all heat transfer equation can be modified as

$$\frac{1}{U} = \frac{1}{h_{fh}} + \frac{1}{h_i} + \frac{x_w}{k} + \frac{1}{h_o} + \frac{1}{h_{fc}}$$

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So, this is a if we consider that that heat hot surface and cold surface then we get the overall heat transfer equal to this is the, and there we can write like this.

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Heat exchanger

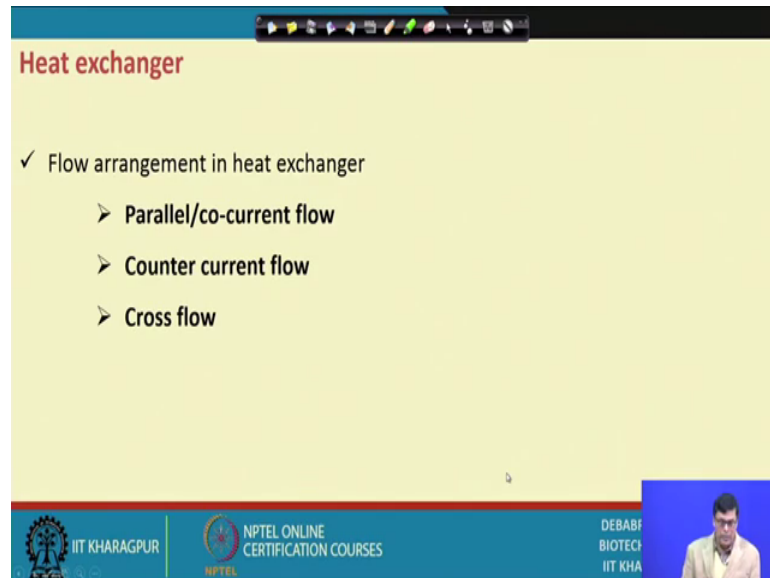
- ✓ The equipment involve heat energy transfer from hot liquid to cold liquid either by conduction-convection or by radiation.
- ✓ Heat transfer equipment can be divided as cooler, heater, condenser etc on the basis of functionality
- ✓ Some popular heat exchanger are double pipe heat exchanger, shell and tube heat exchanger, finned tube heat exchanger, plate type heat exchanger etc

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Though heat exchanger the equipment involve in a heat exchanger it is from hot liquid to cold or to cold fluid either by conduction, convection, or by radiation. Heat transfer equipments can be divided as cooler, heater, condenser etcetera on the basis of it is functionality.

Some popular heat exchanger are double pipe heat exchanger, because I work with this (Refer Time: 20:16) biochemical industry. We use the double pipe heat exchanger shell, and tube heat exchanger, mostly used in the different industry finned tube heat exchanger, are also used by the into the plate and frame heat exchanger, largely used in the fermentation industries.

(Refer Slide Time: 20:34)



The image shows a presentation slide with a yellow background and a red title bar. The title is "Heat exchanger" in red. Below the title, there is a list of flow arrangements in a heat exchanger, marked with a checkmark and bullet points. The list includes: "Parallel/co-current flow", "Counter current flow", and "Cross flow". At the bottom of the slide, there is a blue footer with logos for IIT KHARAGPUR, NPTEL ONLINE CERTIFICATION COURSES, and DEBABI BIOTECH IIT KHA. A small video inset of a person is visible in the bottom right corner.

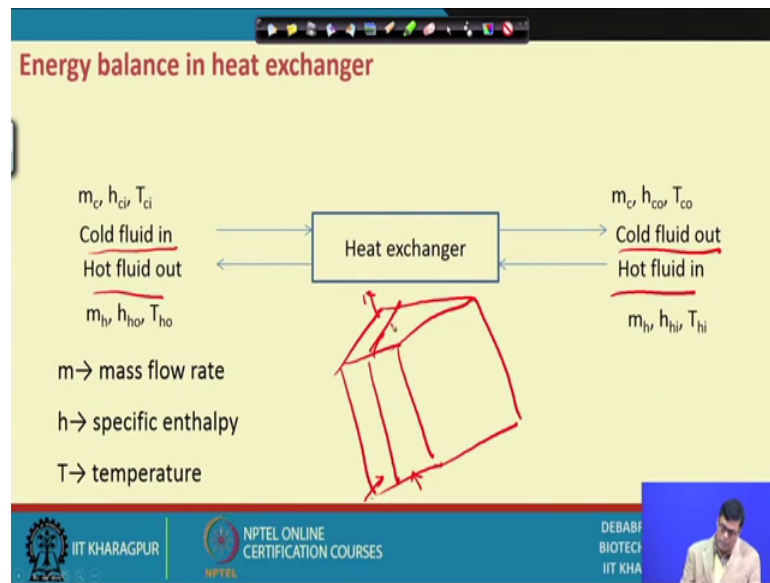
Heat exchanger

- ✓ Flow arrangement in heat exchanger
 - Parallel/co-current flow
 - Counter current flow
 - Cross flow

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So, there are a heat ratio exchange exchanger may be of different arrangement; one is parallel, or concurrent flow, counter current flow, and cross flow. So, this is the kind of energy balance, in the heat exchanger.

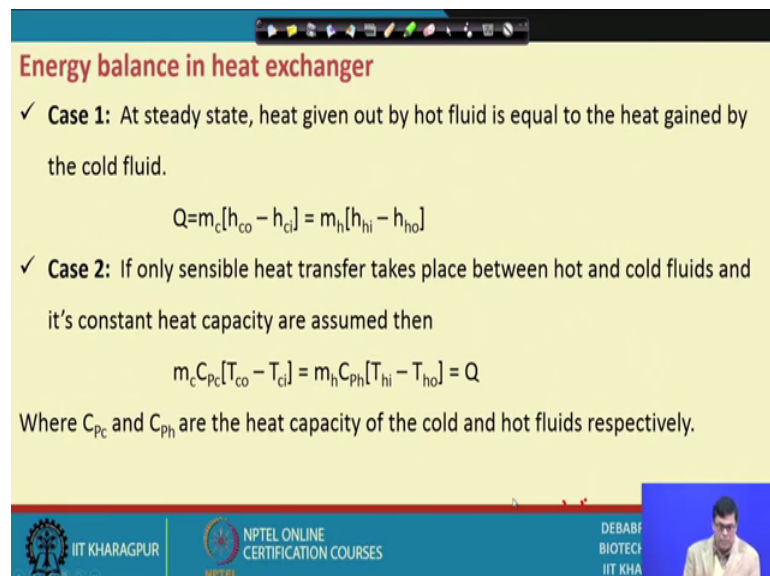
(Refer Slide Time: 20:43)



This is the cold or hot you know cold the, you can see this is the cold fluid in and the hot fluid out. And did the heat exchanger and cold fluid out and hot fluid in that is that is have.

So, if the here I can explain little bit suppose we have heat the plate, plate heat exchanger in case of plate heat exchanger we can have like this. So, one plate we can pass the hot liquid and take out the hot liquid another plate we can pass cold liquid and take out the cold liquid that is like this.

(Refer Slide Time: 21:28)



Now, this case one the steady state as steady state heat given out in the hot fluid is equal to the heat gained by the cold liquid. It can be express like this that $m_c c_{p,c} (T_{c0} - T_{ci}) = Q$. And similarly hot surface we can express.

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Energy balance in heat exchanger

✓ **Case 3:** For latent heat transfer (condensation of vapour) from condensing vapour to a coolant, the energy balanced will be

$$m_h \lambda = m_c C_{p,c} [T_{c0} - T_{ci}] = Q$$

When m_h = rate of condensation of vapour
 λ = latent heat of condensation of vapour.

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And the so if you if you look at that case 3 is the latent heat for the condenser surface of the coolant though it can be expressed at $m_h \lambda$ and $m_c C_{p,c} (T_{c0} - T_{ci}) = Q$. You may choose the a rate of condensation of vapor and λ is the latent heat of condensation of vapor.

(Refer Slide Time: 22:19)

Energy balance in heat exchanger

□ Again heat transfer rate in the entire heat exchanger can be expressed as

$$Q = UA\Delta T_m$$

$\Delta T_m \rightarrow$ mean temperature difference

The above equation is called **heat equipment design equation**

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Now, here the overall that heat transfer can be express as like this $\Delta A \Delta U A \Delta T_m$ that is the mean temperature difference that we have.

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Logarithmic mean temperature differences (LMTD)

- ✓ If the **temperature varies in both fluids** (either counter-current or co-current flow) the mean temperature difference (ΔT_m) will be logarithmic mean temperature difference (LMTD).
- ✓ It can be expressed as

$$\Delta T_{Lm} = \frac{\Delta T_2 - \Delta T_1}{\ln\left(\frac{\Delta T_2}{\Delta T_1}\right)}$$

Where, ΔT_2 and ΔT_1 are the temperature differences between hot and cold fluids at the ends of the equipment.

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And mean temperature logarithm the mean temperature difference is what? That is there that is a if the temperature varies both fluid either counter current or co current flow the mean temperature difference will be logarithm means of the differences.

So, it will be T_2 minus ΔT ΔT_1 equal to $\ln \frac{\Delta T_2}{\Delta T_1}$. So, this is like this we can express like this and this I will this logarithm average this mean value is considered in case of calculations.

(Refer Slide Time: 23:13)

Arithmetic mean temperature differences (AMTD)

- ✓ When one fluid in the heat-exchange system remains at a constant temperature such as in a fermenter, the mean temperature difference (ΔT_m) will be arithmetic mean temperature difference (AMTD).
- ✓ It can be expressed as

$$\Delta T_{Am} = \frac{T_F - (T_1 + T_2)}{2}$$

Where T_F is the temperature of fluid in the fermenter
 T_1 and T_2 are the inlet and exit temperatures of the other fluid.

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And arithmetic mean of the temperature difference that also can be calculated in case of one fluid in the heat exchanges system remain as the constant temperature. Such that the fermentation in temperature difference is T_m and we will be arithmetically mean temperature difference this will be T_F minus T_2 T_1 plus T_2 divided by 2.

This we can calculate like this because in fermenter suppose you want to maintain a particular temperature there you can do that.

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Problem

Hot, freshly-sterilized nutrient medium is cooled in a double-pipe heat exchanger before being used in a fermentation. Medium leaving the sterilizer at 121°C enters the exchanger at a flow rate of $10\text{ m}^3\text{ h}^{-1}$; the desired outlet temperature is 30°C . Heat from the medium is used to raise the temperature of $25\text{ m}^3\text{ h}^{-1}$ water initially at 15°C . The system operates at steady state. Assume that nutrient medium has the properties of water. The heat capacity of water can be taken as $75.4\text{ J gmol}^{-1}\text{ }^\circ\text{C}^{-1}$ for most of the temperature range of interest.

(a) What rate of heat transfer is required?
(b) Calculate the final temperature of the cooling water as it leaves the heat exchanger.

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Now we have two problem that related with this heat transfer I hope if we can solve this problem then our conception will be little bit clear. Now what you are saying that hot, freshly sterilized and nutrient medium is cooled in a double pipe heat exchanger um before being used in the fermenter.

Now, medium leaving the sterilizer as the 121 degree centigrade, the exchanger at a flow it we know the sterilization temperature is 121 degree centigrade that usual normal sterilization temperature and flow rate is 10 cubic meter per hour that desired outlet temperature is 30 degree centigrade and heat from the medium is raised it to raise the temperature is 25 cubic meter per hour of water initially at so, this chilled liquid is used to cool the temperature to 30 centigrade.

ah Though system operated as a steady state assume that the nutrient medium has the property of water ah. So, we assume the property of water remain unchanged with the change of temperature, and heat capacity of the water can be taken as 75.4 Joule per gram, per liter per gram per gram mole per degree centigrade.

Now, what will be heat transfer is 0? What is what are heat transfer is the, what rate of heat transfer is required? And calculate the final temperature of cooling water as it leave, the heat exchanger. So, this is the problem that we shall have to solve. Let us see how we can solve it.

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Solution

The density of water and medium is 1000 kg m^{-3} . Therefore:

$$m_h = 10 \text{ m}^3 \text{ h}^{-1} = 10 \text{ m}^3 \text{ h}^{-1} \cdot (1 \text{ h}/3600 \text{ s}) \cdot (1000 \text{ kg}/\text{m}^3) = 2.78 \text{ kg s}^{-1}$$

$$m_c = 25 \text{ m}^3 \text{ h}^{-1} = 25 \text{ m}^3 \text{ h}^{-1} \cdot (1 \text{ h}/3600 \text{ s}) \cdot (1000 \text{ kg}/\text{m}^3) = 6.94 \text{ kg s}^{-1}$$

$$C_{ph} = C_{pc} = 75.4 \text{ J gmol}^{-1} \text{ }^\circ\text{C}^{-1} = 75.4 \text{ J gmol}^{-1} \text{ }^\circ\text{C}^{-1} \cdot (1 \text{ gmol}/18 \text{ g}) \cdot (1000 \text{ g}/1 \text{ kg})$$

$$= 4.19 \times 10^3 \text{ J kg}^{-1} \text{ }^\circ\text{C}^{-1}$$

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Now, first we shall have to find out as I as I told you that we shall have to convert the unit and in two hour desired unit. As per example the what liquid flow rate that is 10 cubic meter per hour that you have to convert into the seconds. The 2.78 kg per second we can easily do that because we know the density of water is 1000 kg per cubic meter, so you can easily do that.

And in that the similarly we can convert the flow rate of cool water that is 6.994 kg per second. And the now the specific gravity of cold and hot water that also we can converted in the in the SI unit, the SI unit.

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Solution

(a) Now, for hot fluid (from the heat exchanger equation (case 2))

$$Q = m_h C_{ph} [T_{hi} - T_{ho}]$$
$$= (2.78 \text{ kg s}^{-1})(4.19 \times 10^3 \text{ J kg}^{-1} \text{ }^\circ\text{C}^{-1})(121 - 30)^\circ\text{C}$$
$$= 1.06 \times 10^6 \text{ J s}^{-1} = 1060 \text{ W}$$

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Then and we have the equation what is the equation we have? Q equal to we shall have to find out the heat rate of heat transfer, so we have $m_h c_p (T_{hi} - T_{ho})$.

So, we can easily find out that how much is the heat in that you know hotly fluid. How much is the heat is given by the hot fluid that you can calculate.

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Solution

(b) For the cold fluid

$$m_c C_{pc} [T_{co} - T_{ci}] = Q$$
$$(6.94 \text{ kg s}^{-1})(4.19 \times 10^3 \text{ J kg}^{-1} \text{ }^\circ\text{C}^{-1})(T_{co} - 15)^\circ\text{C} = 1.06 \times 10^6 \text{ J s}^{-1}$$

By solving, $T_{co} = 51.5^\circ\text{C}$

Therefore the exit cooling water temperature is 51.5°C

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Then for cool liquid we can similarly find out the how much that that the for a cool liquid it is the temperature we have. And we assume the temperature of the cool liquid is this am I right.

And if it is like this then we can from that we can find out that what is the cool liquid outlet temperature that is will be getting about 51.5 degree centigrade. Therefore, the exit cooling water temperature will be 51.5 degree centigrade.

So, what basically we have done we calculate the from the hot liquid that how much heat actually coming out from the hot liquid, then that is transferred to the cold liquid.

And from that cold liquid we can find out that what is the temperature of the outgoing temperature of the of the of the of that cold liquid that is have in the system that we that will be coming. Because the cold liquid is inlet temperature is 15 degree centigrade where we form the chiller and this is the outgoing temperature of the cold liquid. So, this is the, this is this is very simple problem.

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Problem

A fermenter used for antibiotic production must be kept at 27°C . After considering the oxygen demand of the organism and the heat dissipation from the stirrer, the maximum heat-transfer rate required is estimated as 550 kW. Cooling water is available at 10°C ; the exit temperature of the cooling water is calculated using an energy balance as 25°C ; The heat-transfer coefficient for the fermentation broth is $2150\text{ W m}^{-2}\text{ }^{\circ}\text{C}^{-1}$. The heat-transfer coefficient for the cooling water is calculated as $14000\text{ W m}^{-2}\text{ }^{\circ}\text{C}^{-1}$. It is proposed to install a helical cooling coil inside the fermenter; the outer diameter of the coil pipe is 8 cm, the pipe thickness is 5 mm and the thermal conductivity of the steel is $60\text{ W m}^{-1}\text{ }^{\circ}\text{C}^{-1}$. An average internal fouling-factor of $8500\text{ W m}^{-2}\text{ }^{\circ}\text{C}^{-1}$ is expected; the fermenter side surface of the coil is kept relatively clean. What length of cooling coil is required?

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And another problem that we have like a fermenter use for antibiotics production must kept at the 27 degree centigrade after considering the oxygen demand of the organism the heat dissipated from the stirrer and the maximum heat transfer rate required is estimated 550 kilowatt.

Then pulling water is available 10 degree centigrade the exit temperature of the cooling water is calculated using the heat balance at 25 degree centigrade.

Now, heat transfer coefficient of the fermentation broth is given and heat transfer coefficient of the cooling water calculated as this and it is proposed to install a helical cooling water coil inside the fermenter and outside the diameter of the coil pipe is 8 centimeter, and pipe thickness is 5 millimeter and thermal conductivity of the steel is 60 watt per meter per degree centigrade.

And at the, and average internal fouling factors of 80 8500 watt per square meter per second is expected. And fermented side surface of the coil is kept relatively clean. What length of cooling coil is required?

So, this is very interesting problem that we have and we shall have to solve how this can be solved? And let us see how we can solve this?

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Solution
Given data,

$$Q = 550 \text{ kW} = 550 \times 10^3 \text{ W}$$
$$T_F = 27^\circ\text{C}$$
$$T_1 = 10^\circ\text{C}$$
$$T_2 = 25^\circ\text{C}$$
$$x_w = 5 \text{ mm} = 5 \times 10^{-3} \text{ m}$$
$$R = \text{coil radius} = \frac{8}{2} \text{ cm} = \frac{8 \times 10^{-2}}{2} \text{ m}$$
$$L = \text{coil length}$$
$$k = 60 \text{ W m}^{-1} \text{ }^\circ\text{C}^{-1}$$
$$h_o = 2150 \text{ W m}^{-2} \text{ }^\circ\text{C}^{-1}$$

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Now as I mentioned that we shall have to always jot down what are the data is given? The heat transfer that that is already amount of heat transfer capacities is already given this is 550 kilo watt. And temperature respective temperature is also given am I right that final temperature and all, this thing is given and the thickness of the pipeline that also given, and all I have to converted into the SI unit.

(Refer Slide Time: 30:23)

Solution
Given data,

$$h_i = 14000 \text{ W m}^{-2} \text{ }^\circ\text{C}^{-1}$$
$$h_{fc} = 8500 \text{ W m}^{-2} \text{ }^\circ\text{C}^{-1}$$

Now the arithmetic mean temperature difference

$$\Delta T_{Am} = \frac{T_F - (T_1 + T_2)}{2}$$
$$\Delta T_{Am} = \frac{27 - (10 + 25)}{2} = 9.5^\circ\text{C}$$

Here, h_{fh} is negligible

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So, we converted into the SI unit everything and then after converting into SI unit then we find out an h_i and h_{fc} also given in this problem. There you have first we shall have

to find out the arithmetic mean temperature difference and because we maintain a want to maintain a particular temperature.

And so, this is the final temperature is 27 degree centigrade, and this is 10 to 25 by 2 we can easily find out and h f following factor of the hot surface is neglected.

(Refer Slide Time: 30:51).

Solution

$$\frac{1}{U} = \frac{1}{h_i} + \frac{x_w}{k} + \frac{1}{h_o} + \frac{1}{h_{fc}}$$

$$\frac{1}{U} = \frac{1}{14000} + \frac{5 \times 10^{-3}}{60} + \frac{1}{2150} + \frac{1}{8500} = 7.38 \times 10^{-4} \text{ m}^2 \text{ } ^\circ\text{C W}^{-1}$$

$$U = 1355 \text{ W m}^{-2} \text{ } ^\circ\text{C}^{-1}$$

Applying heat exchanger design equation

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

$$550 \times 103 \text{ W} = (1355 \text{ W m}^{-2} \text{ } ^\circ\text{C}^{-1}) A (9.5^\circ\text{C})$$

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Then this is the resistance that we have 1 by U equal to this. So, this we can easily calculate and we find out the U value.

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Solution

By solving

$$A = 42.7 \text{ m}^2$$

Again

$$A = 2\pi RL$$

$$42.7 \text{ m}^2 = 2\pi \left(\frac{8 \times 10^{-2}}{2} \text{ m} \right) L$$

$$L = 169.9 \text{ m}$$

The length of coil required is 170 m. The cost of such a length of pipe is a significant factor in the overall cost of the fermenter.

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So, U value we can calculate and the, this is the U value you can calculate. Then we know rate of heat transfer equal to U into A into this is temperature difference. So, if you put all this thing here and we can easily find out the area that is required for the heat transfer that a, that heating pipeline.

Now we know that this is the surface area required for the heating purpose, and the, we know area is a twice pi R into, twice pi R is the peripheral area, and L it is the length, though this from that you can easily find out the length of the pipeline.

So, in this particular lecture I try to discuss the heat transfer and in heat transfer is very important aspects as per chemical and biochemical engineering is concerned. And we find that 3 type of heat transfer we have conduction, convection, and radiation. We try to find out how you can calculate the conductive heat transfer? How you can calculate the convective heat transfer? Then we try to solve two problems.

And on the basis of that we can find out that what is the surface area required for cooling the, that heating surface and also that we what is the what is the temperature required or, of the outgoing the chilled water.

Thank you very much.