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, conviction, 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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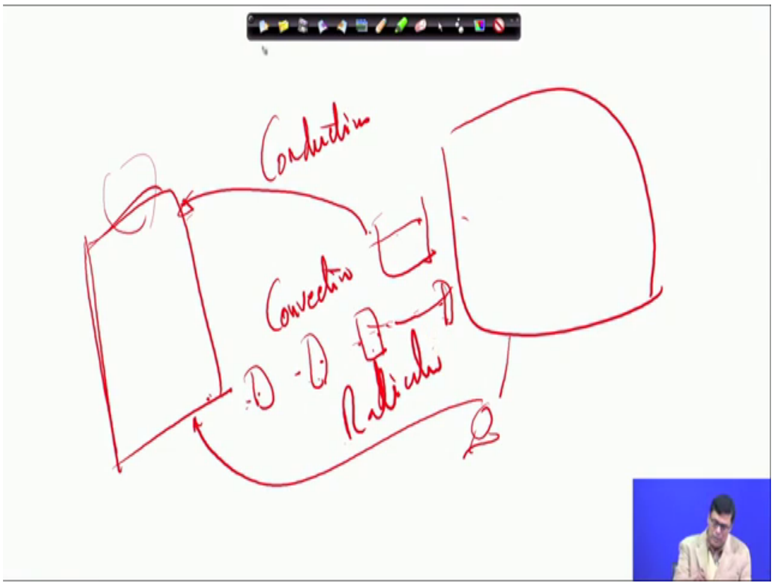

Then there are 3 different approaches we have suppose there is a pond here and in this pond I can with the help of bucket I can take the water, one percent can take the water and put the water in this for the fire extinguishing purpose.

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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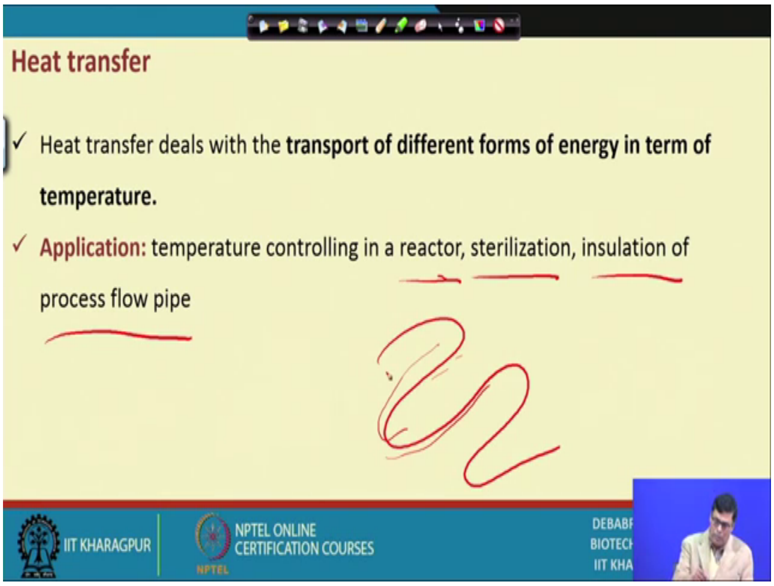

So, this is three mechanism and which is largely a apply in case of heat transfer. Now let us see that heat transfer deals with the transfer transport of different form of energy in the form of temperature, so this we understand.

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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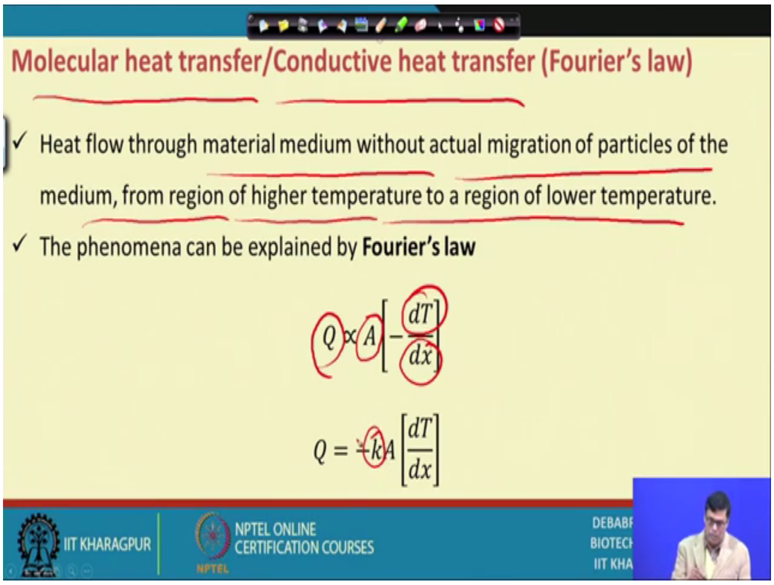

So, so these are the now, question comes that how you do the analysis of this heat transfer first is the molecular. If you look at molecular heat transfer or conductive heat transfer how you can express?

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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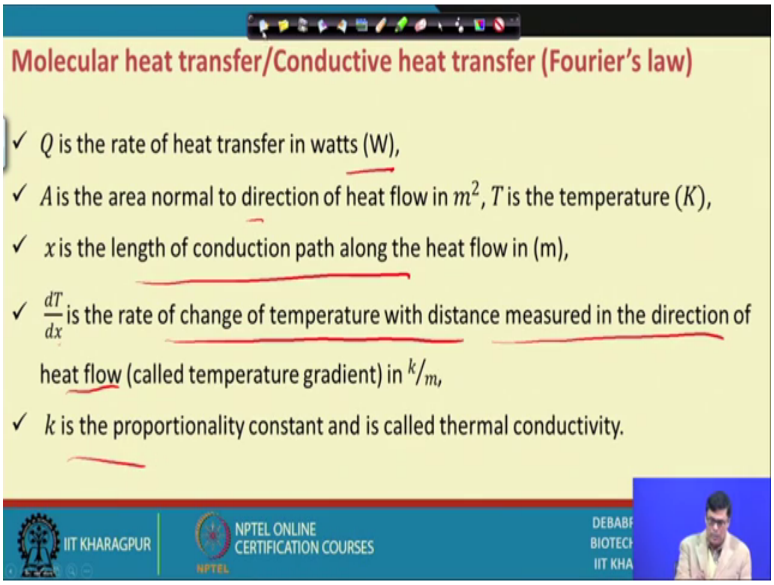

Now Q is the heat transfer that I told you heat transfer in the watt, and A is the area, x is the length of the conductive path. And d T by d x is the rate of change of temperature with distance measured in the direction of the heat flow, and k is the proportionality constant.

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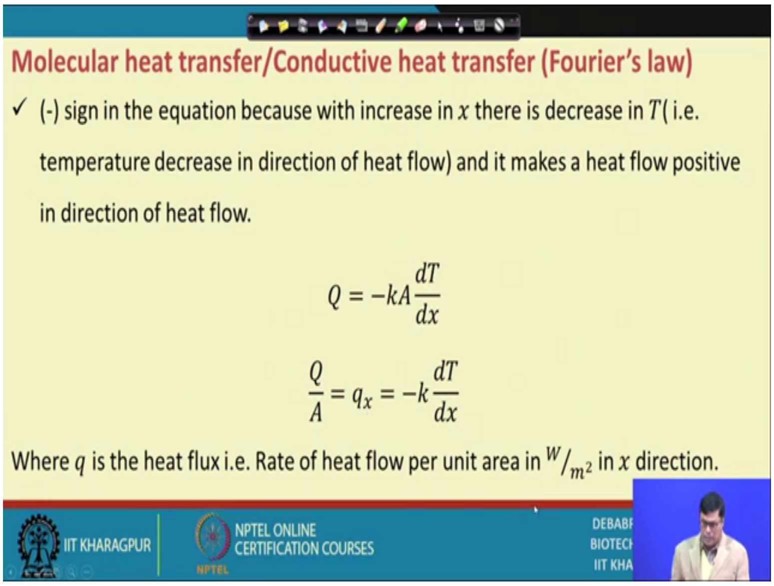

Now, this is the Q equal to this we can write, so this we can write Q by A equal to k x you can write this form.

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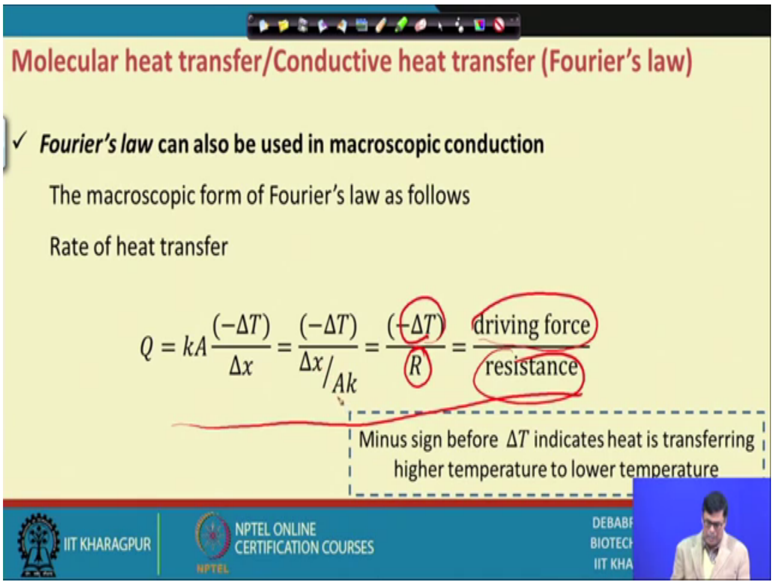

And so Q equal to Q A in to dx by d T, the now this is initially you can remember we asks any kind of transfer is equal to driving force where resistance.

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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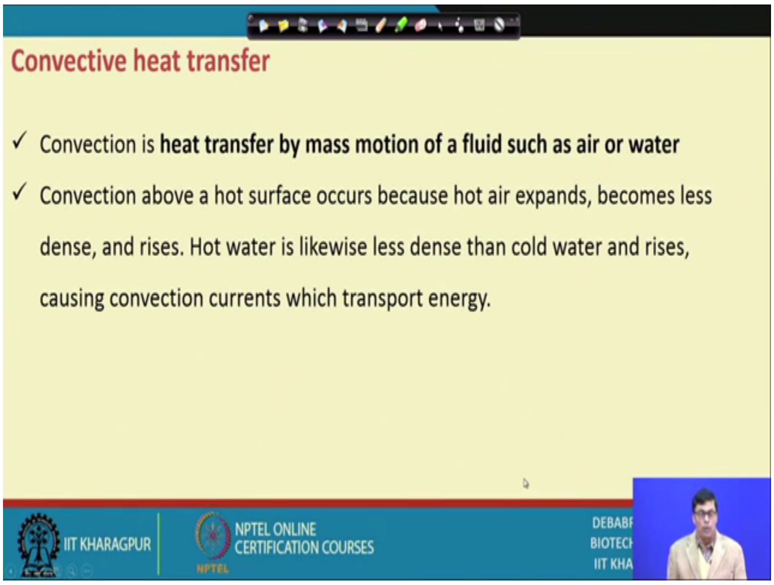

Now, next is the convictive convictive heat transfer and conviction of the heat transfer by the mass motion of the fluid in such air, or water. And convection amount of the hot surface occurred because of the hot air expands.

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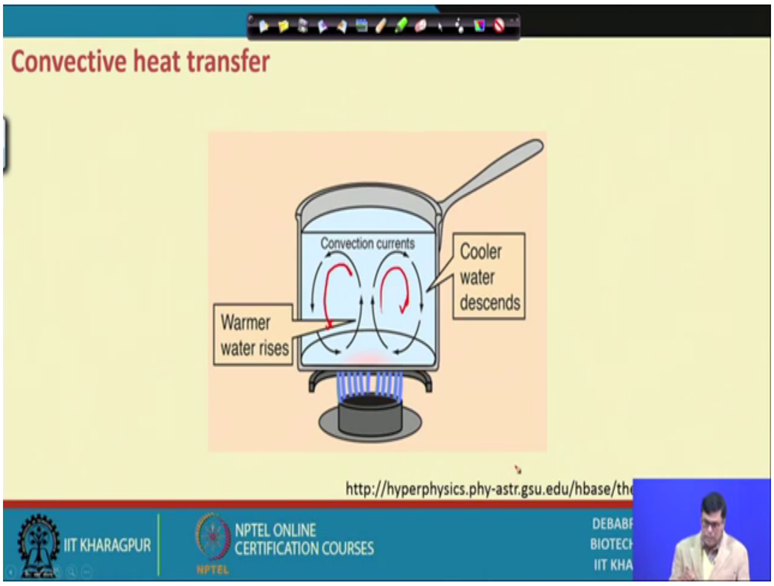

And between because let me give the example like this. It is the hot surface with the close at the bottom you can see that your hot surface. So, it is going like and it will go rise, it will it will go rise, and it will come back like this it will go rise, and come back like this.

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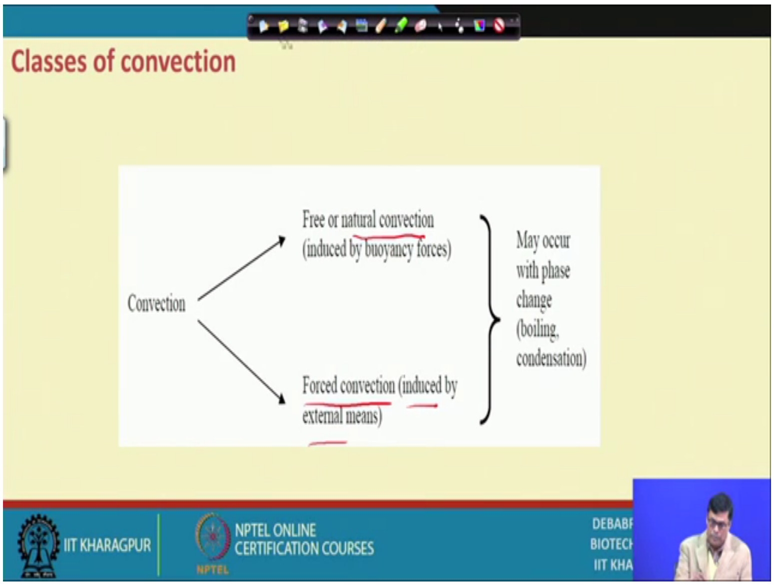

So, this is the cooler water descends and this is the warmer water rise, this is this is this is this is the phenomena, this is going on reusing convection process. So, convection may be of two types one is called natural convection, or free convection. Another is force convection we induced by the external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

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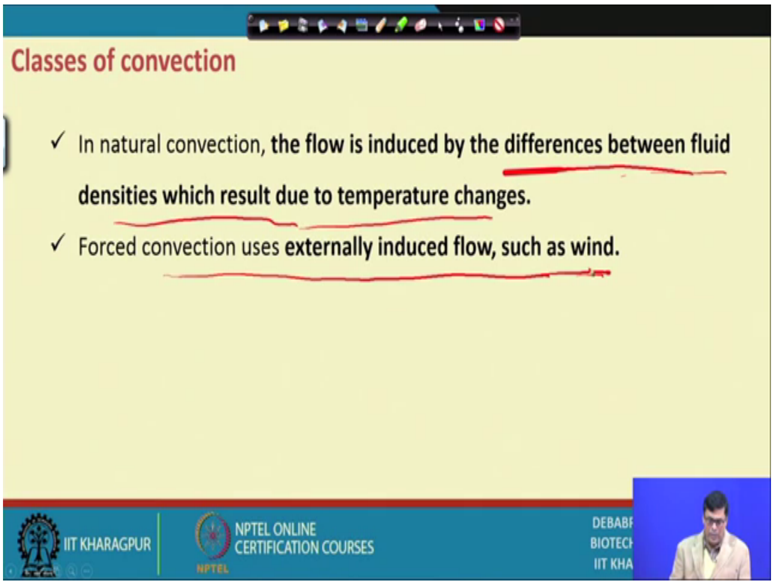

Now, the natural convection the flow induced by the different differences between the fluid density I have with the result due to temperature changes. Now we understand that as we increase the temperature the density is reduced am I right, so that results a temperature changes.

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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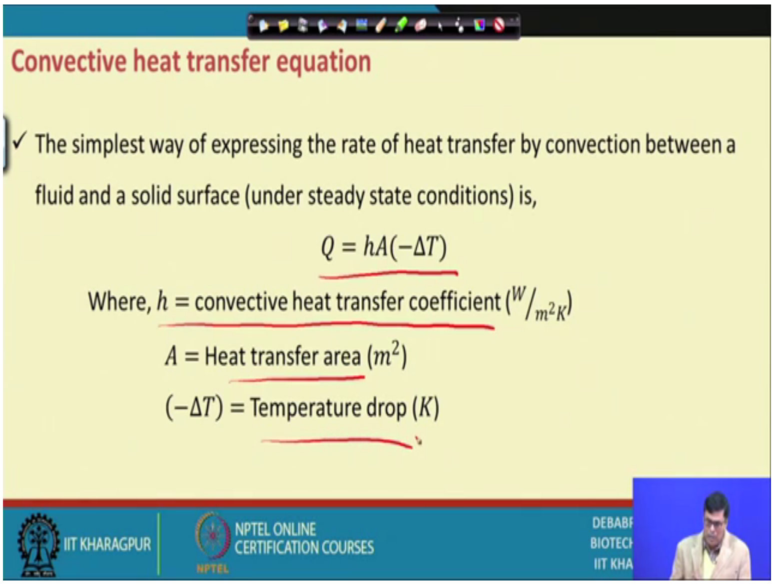

So, here the rate of heat transfer can be expressed like this that Q equal to A into h into A del T, where h is the convective heat transfer coefficient, A is the heat transfer area, and del T is the temperature drop.

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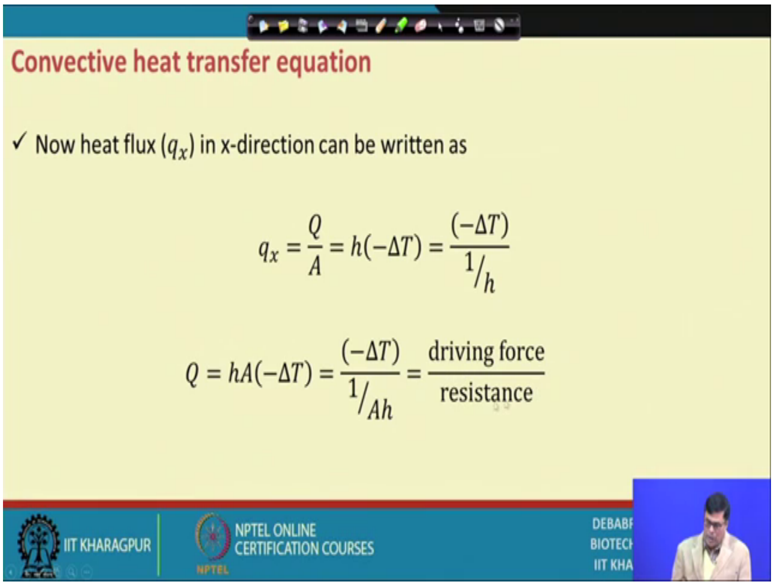

Now this is equal to I can similarly we can as we did in case of conduction we can write in the same form, driving force by resistance and this will be 1 by A h.

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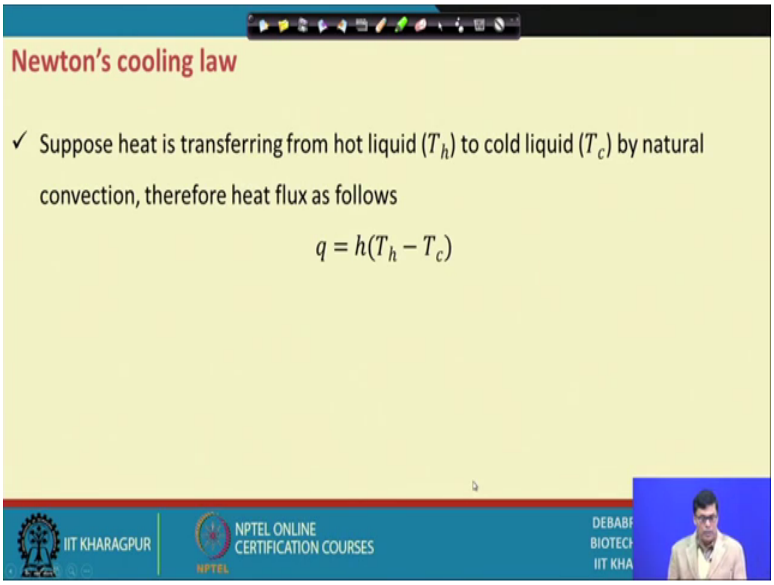

Now, Newton's law of cooling is that that when the heat that hot liquid temperature is T h, and cool liquid T c, then natural convection heat flux equal to q h T h by T c.

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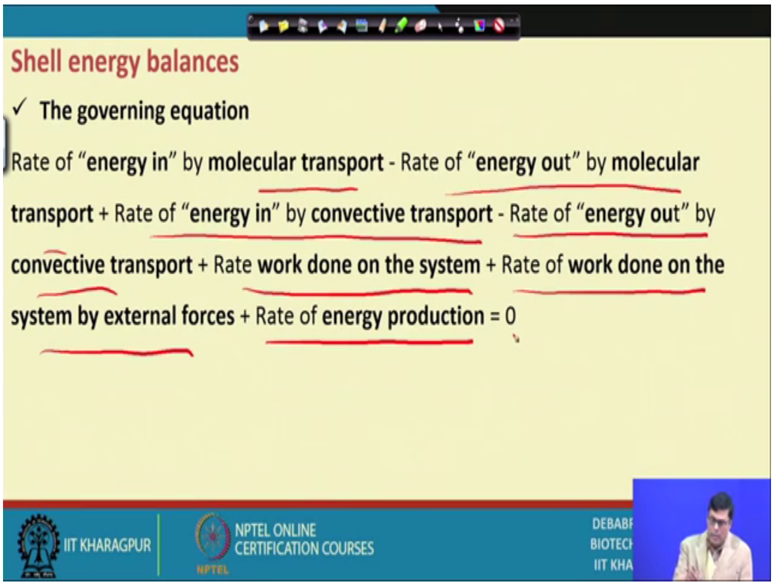

Now the cell energy balance the governing equation we can explain like this. The rate of energy by molecular rate of energy by molecular transport minus rate of energy by molecular energy out by molecular transport, rate of energy by convective transport, rate of energy out by convective transport.

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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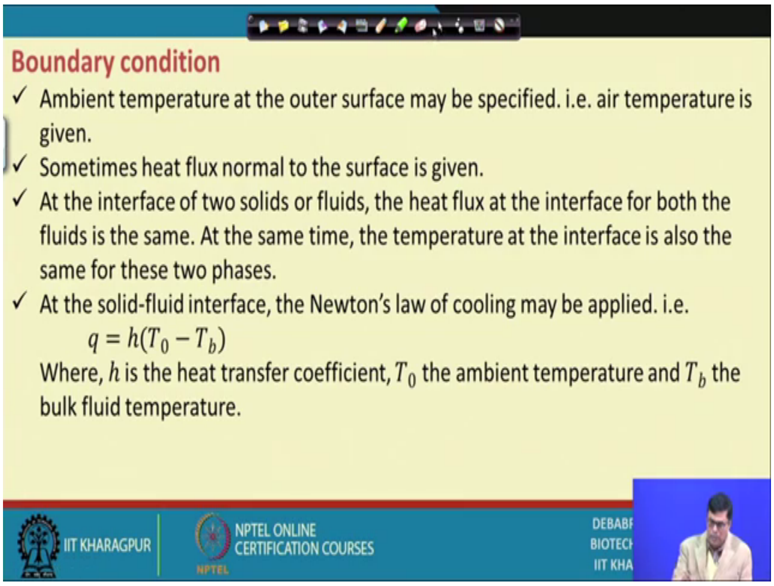

Now, this is the boundary conditions we have. The ambient temperature of the other surface may be specified at air temperature, is the given sometime heat flux normal to the surface is given. So, these are given I am not going through any details you can easily very easily find out.

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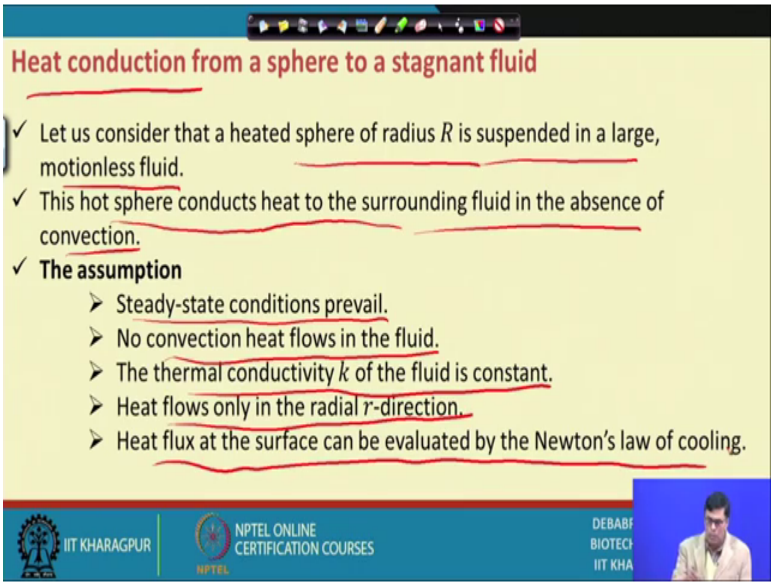

Heat of conduction from a sphere, now people that we discuss about the, that in case of the convection now heat of conduction from sphere of a stagnant fluid this can be the let us consider the heat of sphere of radius R is suspended in a large motion, less fluid. And hot sphere hot sphere conducts heat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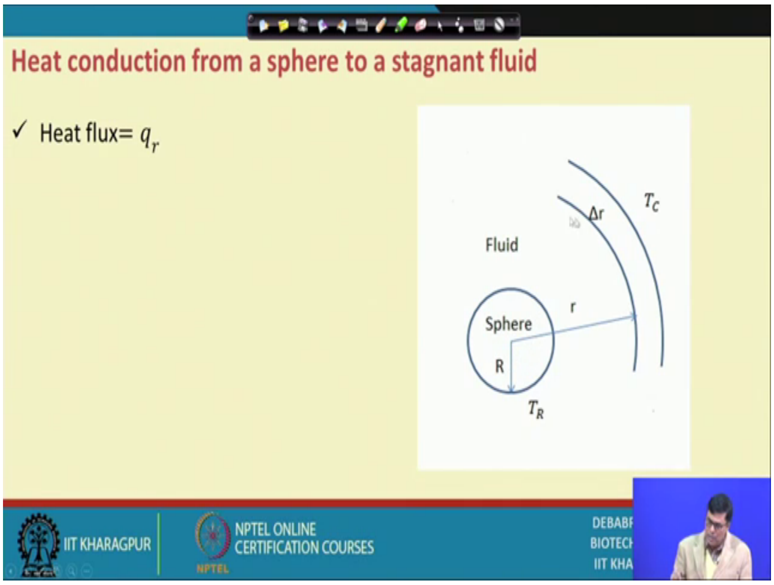

So, this was how we can do that this is the this is the sphere, and this is the sphere and this is the fluid that we have, this is the r, and this is the T c, and this is the T R is the in difference.

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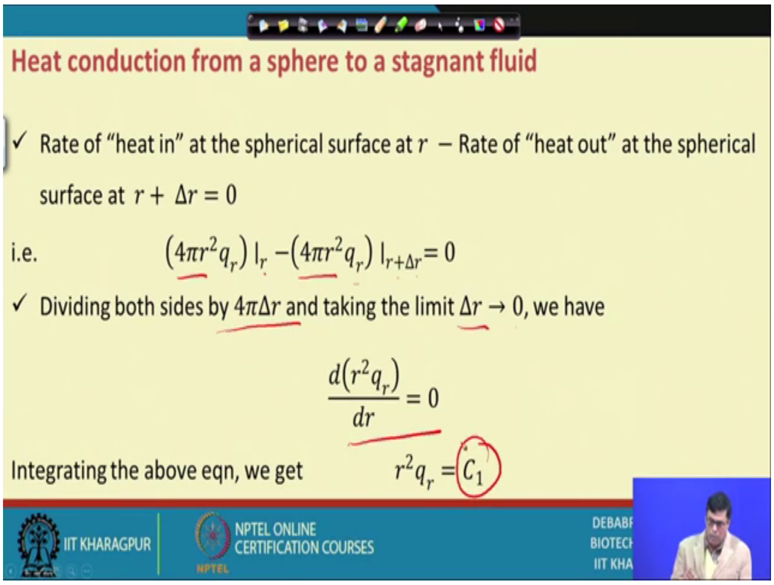

So, rate of the rate in the spherical surface r, and rate r in their or heat out at the spherical surface r plus r, there should be equal to 0. And which can be represented like this is the surface area am I right in this field, surface area of a sphere is 4 pi r square into q r, this is the r, and 4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

Now, this if you divide by 4 pi del r and del r tends to 0, we can write this equation in this form and this we can integrate it we can write r square q r equal to C 1, C 1 is a constant.

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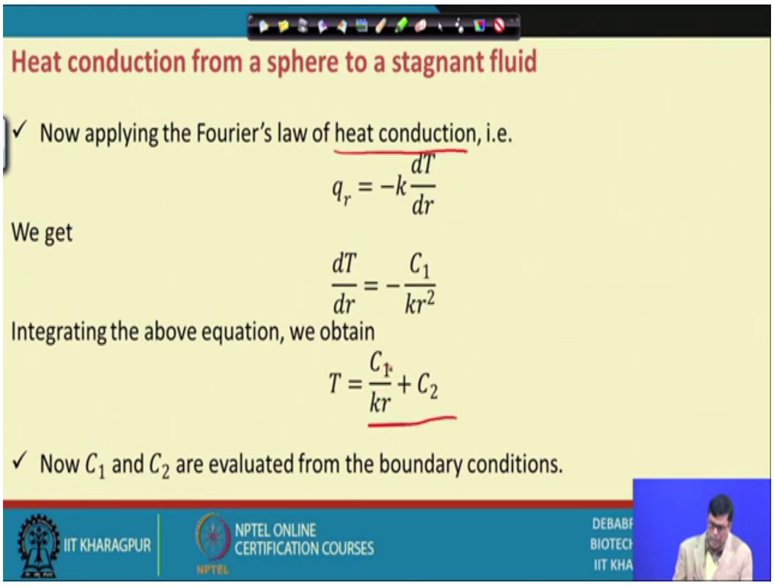

Now, then by applying the Fourier's law of heat of conduction we can write q k d T by d r and then we can write d T y by d r equal to q r.

This we can we can we can we can write this is 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 equal to and that C 1 by k r plus C 2.

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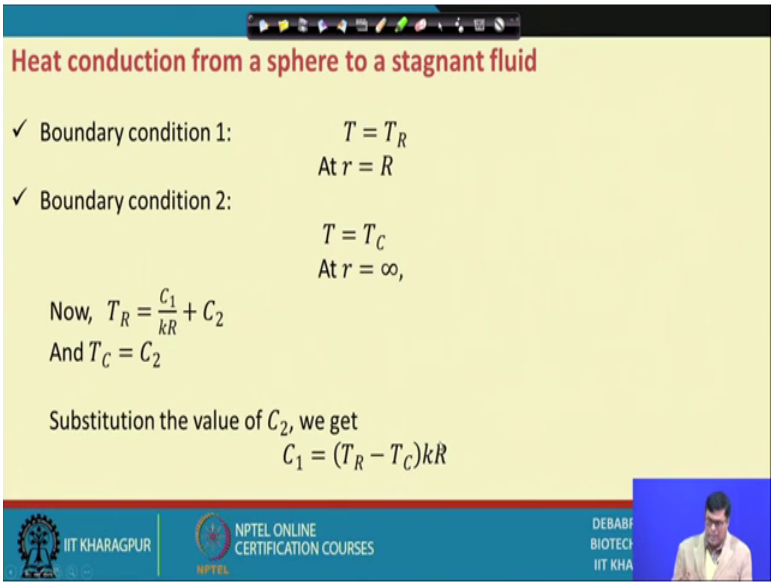

Now, here the heat of combustion of sphere to a stagnant fluid the boundary condition T equal to T R, where small r is equal to capital R and T into T C, where r tends to a infinity. Then your equation will be T R equal to T by C 1 by k R plus C 2 and T T C equal to C C 2 then we can write in this form, C 1 equal to T R minus T C into k R

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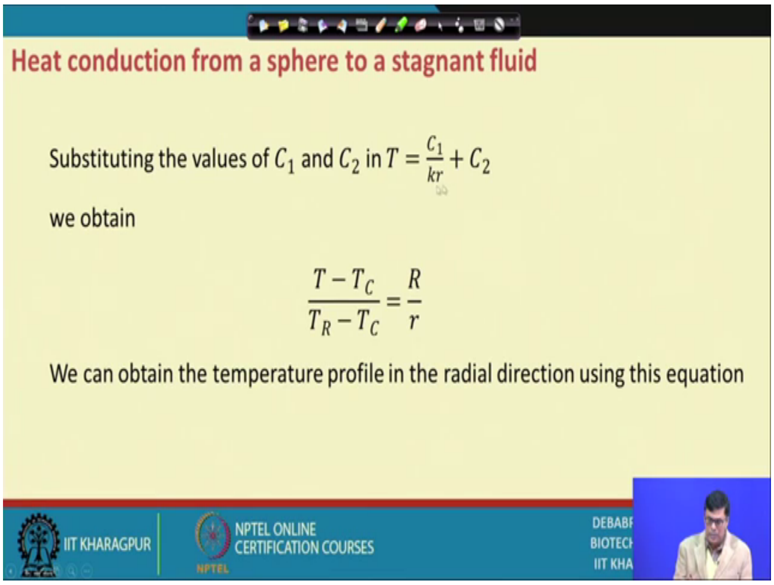

Finally we can write this equation that T equal to C 1 into k r. And T 1 minus T C by T R minus T C equal to capital R by small r.

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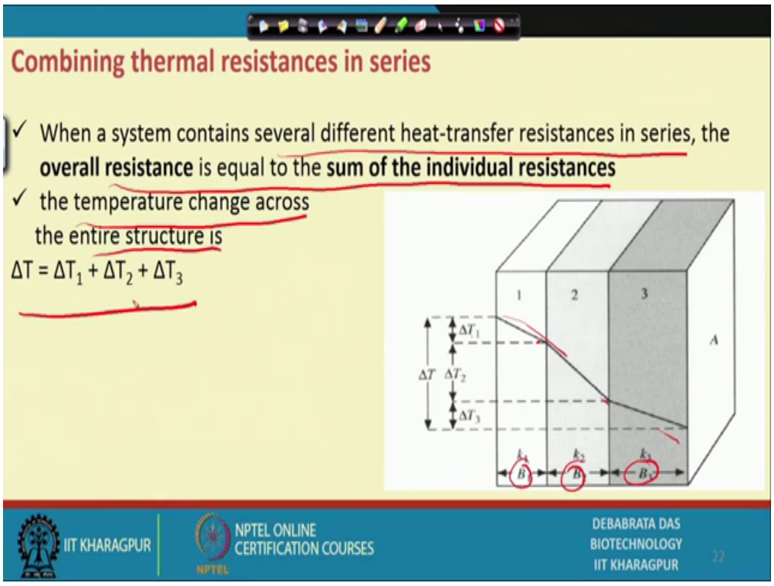

Now, this is the combining resistance because this is very important. This is a when a system contains the several heat transfer resistance in series, overall resistance is equal to sum of the individual resistance, and temperature changes the across the entire structure.

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 del T across this layer, and del T del 2 across this resistance, the del 3 across this resistance.

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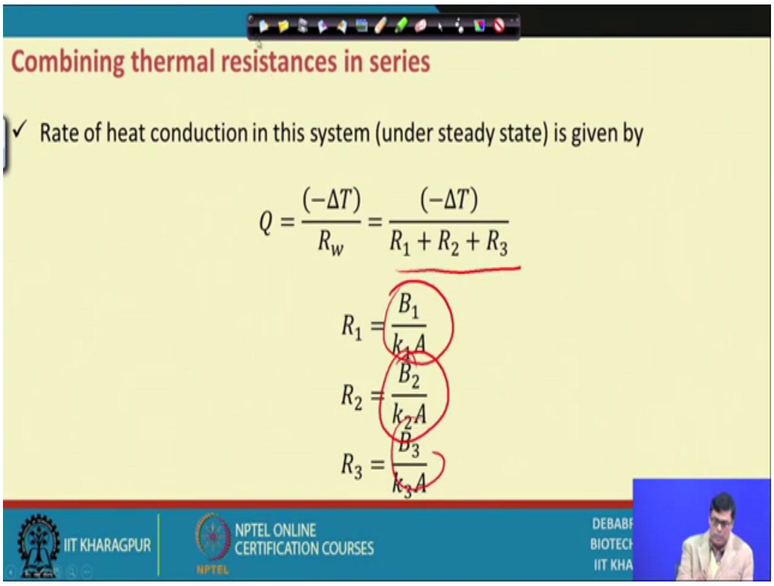

Now the rate of heat conduction in the in the system under steady state condition governed by this equation, this is the driving force, and this is the resistance, a resistance is the R 1, R 2, R 3, and R 1 can be expressed like this. We have shown than B 1 then this is the, this like this.

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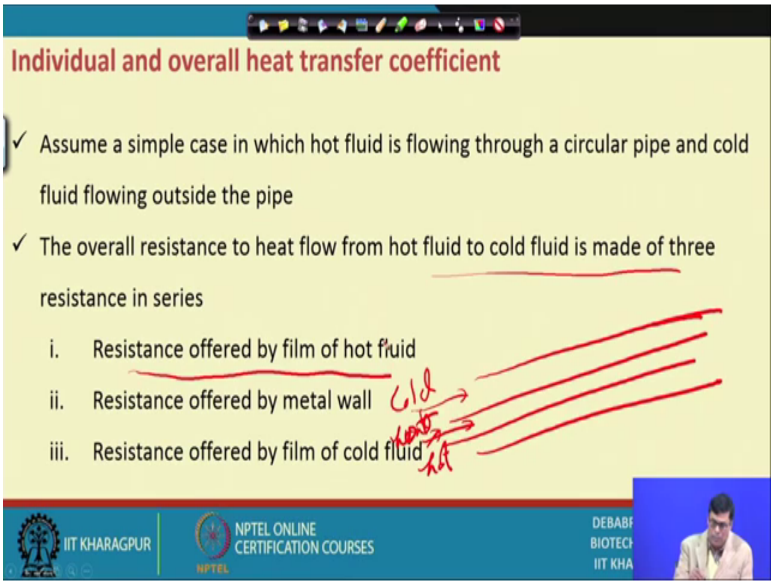

Now, individual and overall heat transfer coefficient assume the, assume a simple case in which the hot fluid is flowing through a circular pipeline, and cold fluid is a flowing outside the pipe line.

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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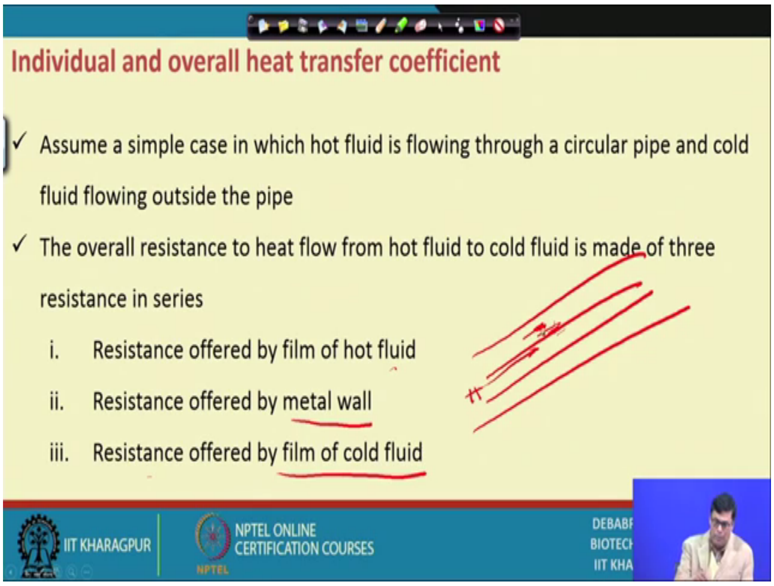

So, you have 3 different layers. So, I have shown you this like this. So, here what he is saying that resistance offered by whole fluid there will be, but this is hot the, this is they have the resistance. Then the wall has the resistance and this is the cold fluid, now cold film they have the resistance.

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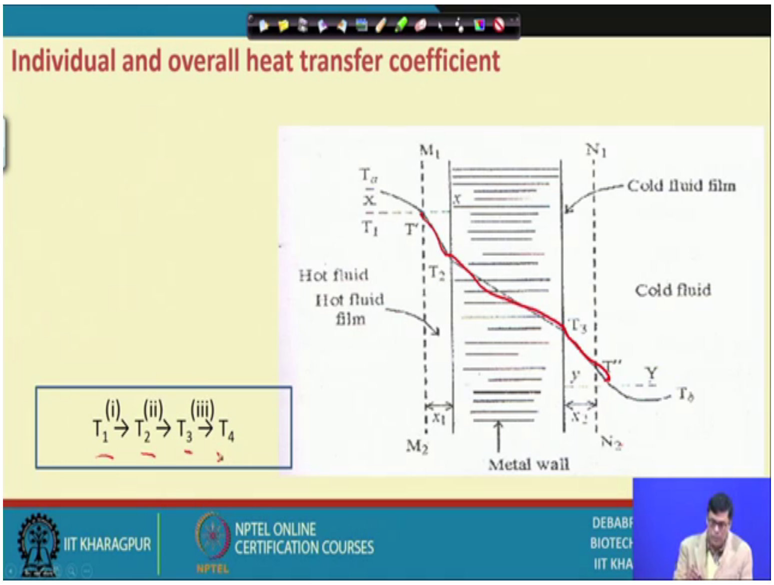

Now this is how we can explain like this is a, this is different layered that we have. And different resistance we can we can measured at different places and this was 1, 2, 3, the difference situation that we have that this is different region that we have, that is cold film, and this is a and this 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 2 to T 4 ok.

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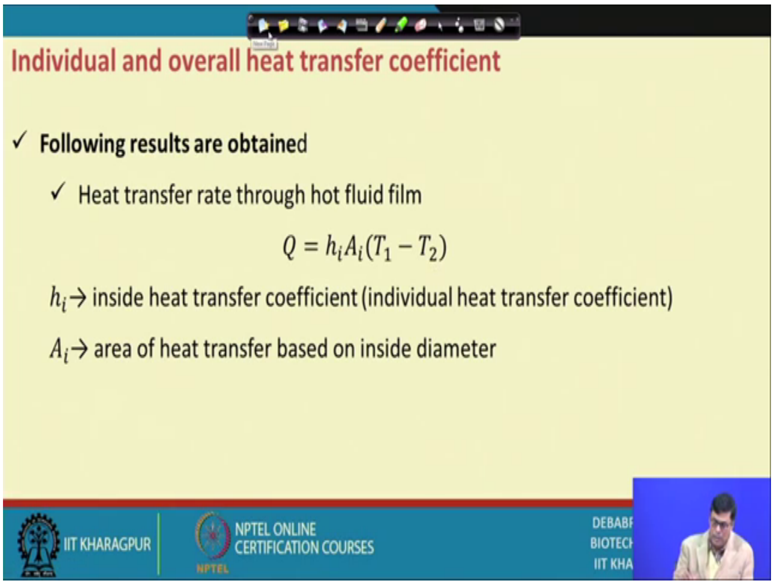

So, here the heat transfer rate in the hot fluid can be expressed as Q into h i A i T 1 by T 2 am I right.

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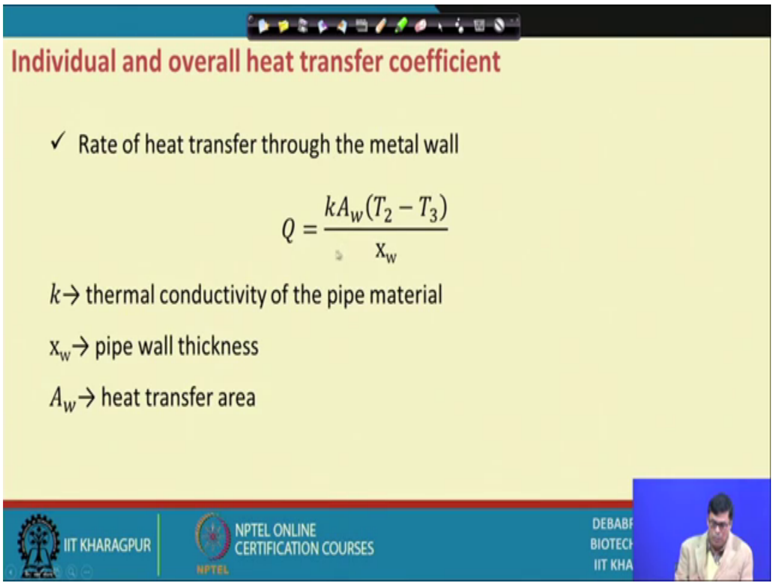

So, in case of wall we can right what you can write what you can write Q equal to A k into A w T 2 minus T 2 into X X u then and A w is equal to what? A w is the surface area am I right.

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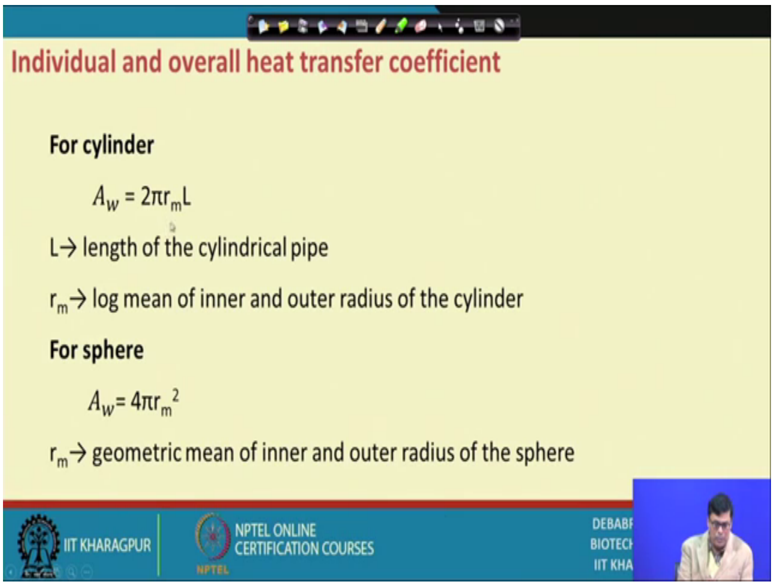

So, twice pi r is the temperature in to length the. So, you can you cover all the surface area of the circular tube. And this is the, this for sphere we shall have to have the area is 4 pi R square.

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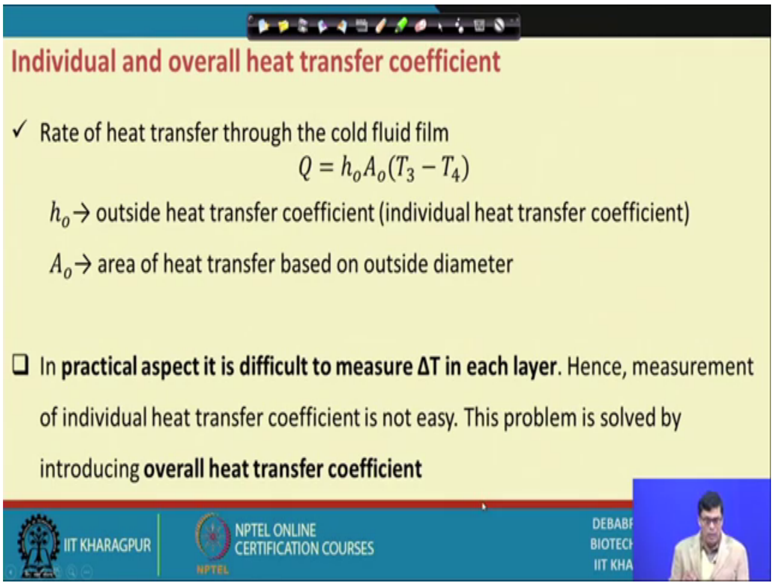

And in case of rate of heat for the cold fluid, we can write Q equal to h 0, into A 0 T 2 minus T 4.

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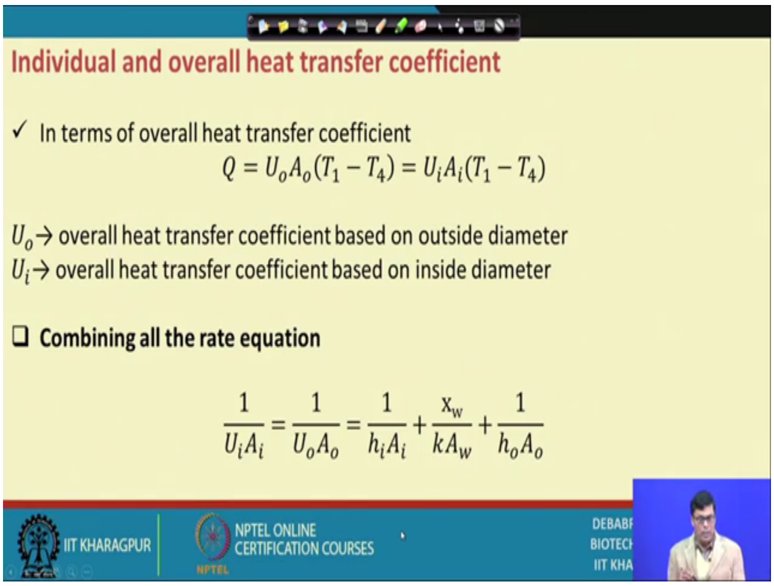

So, when we the overall heat transfer that you have the Q into U 0 A U A 0 A 0 T 1 minus T 4 T 1 minus T 4. Now you combine all the equations we will get in this form am I right

1 by U i A i equal to 1 U 1 by U 0 A 0 equal to this into this into this is the overall equation we will get.

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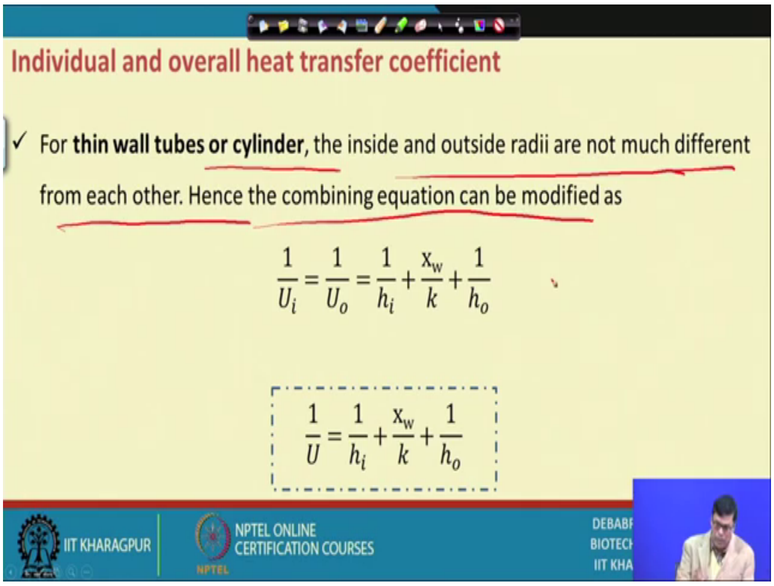

From that we can write this equation you can see that equation this one and from this we can easily find out this equation. This is for thin tubes of cylinder inside and outside radii radius are not much difference for the each other and hence there is a combined equation will be like that.

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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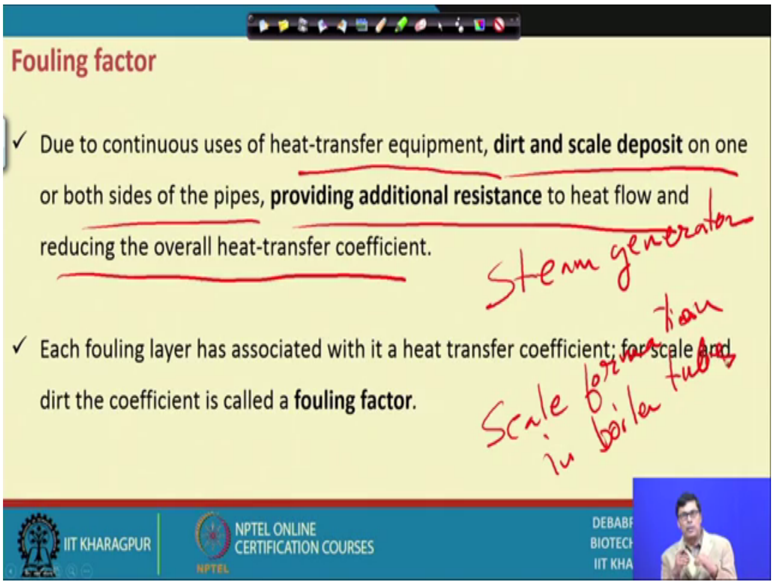

Then what we can write we can write this equation in this form. This is the form we can write. So, fouling factor that is the, another important thing that we have in case of heat transfer; this is due to the continuous use of the heat surface equipment dirt, and scale deposit on one, or both side of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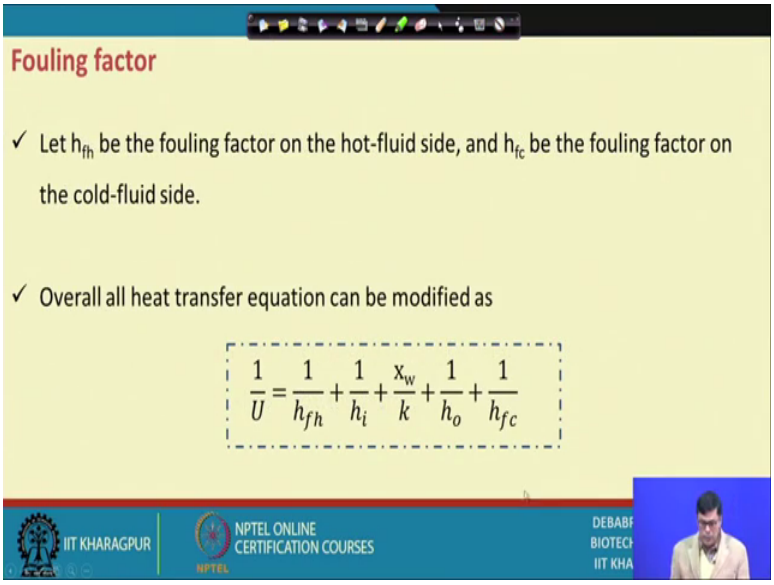

So, this is a if we consider that that heat hot surface and cold surface then we get the overall heat transfer equal to this is the, and there we can write like this.

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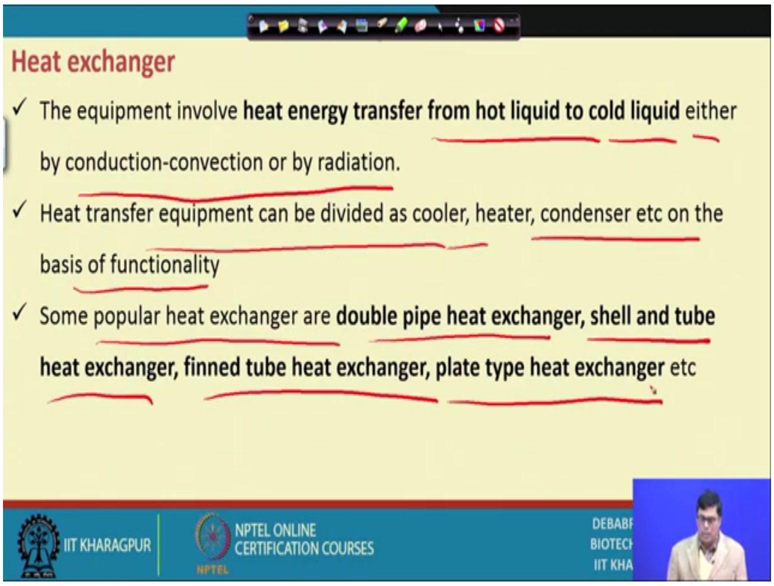

Though heat exchanger the equipment involve in a heat exchanger it is from hot liquid to cold or to cold fluid either by conduction, convection, or by radiation. Heat transfer equipments can be divided as cooler, heater, condenser etcetera on the basis of it is functionality.

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.

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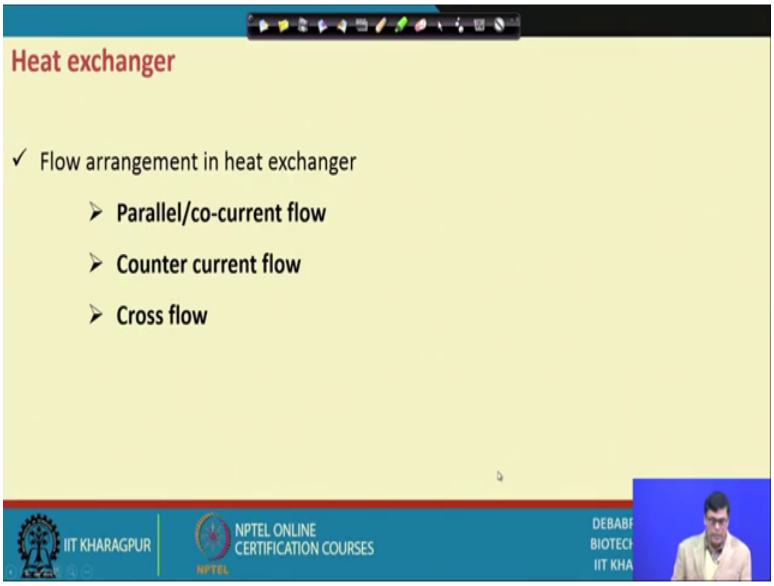

So, there are a heat ratio exchange exchanger may be of different arrangement; one is parallel, or concurrent flow, counter current flow, and cross flow. So, this is the kind of energy balance, in the heat exchanger.

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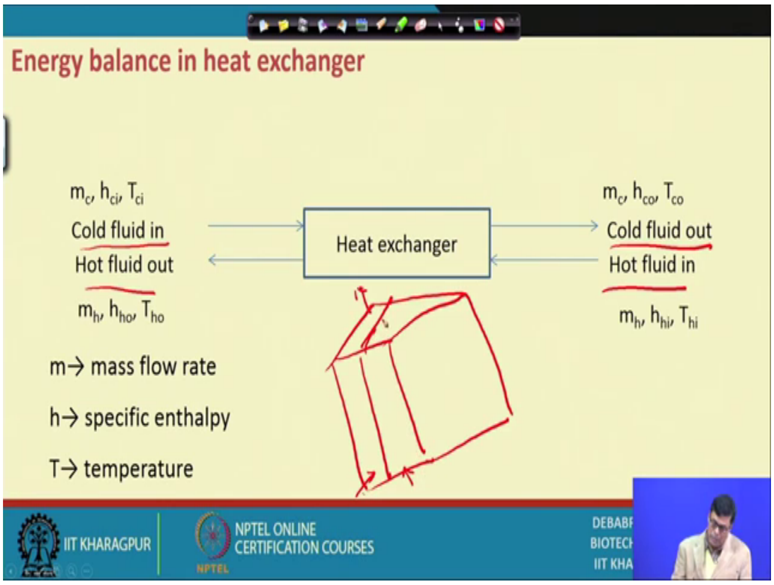

This is the cold or hot you know cold the, you can see this is the cold fluid in and the hot fluid out. And did the heat exchanger and cold fluid out and hot fluid in that is that is have.

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.

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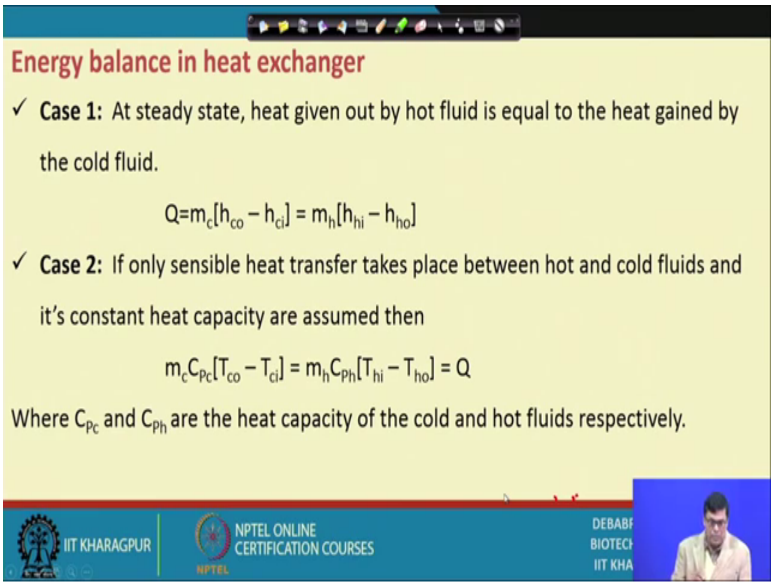

Now, this case one the steady state as steady state heat given out in the hot fluid is equal to the heat gained by the cold liquid. It can be express like this that m c equal to like h c 0 minus c i. And similarly hot surface we can express.

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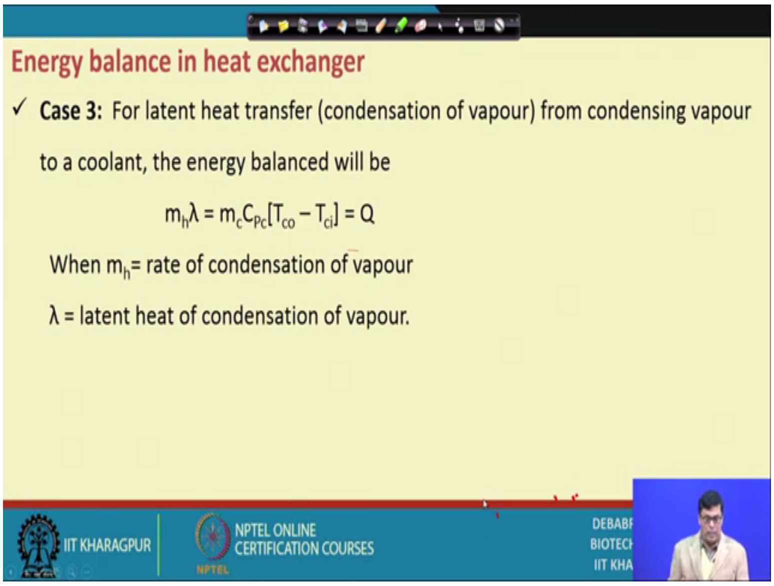

And the so if you if you look at that case 3 is the latent heat for the condenser surface of the coolant though it can be expressed at m h lambda and m c C PC T c T c c o, 0 minus c c i equal to Q. You may choose the a rate of condensation of vapor and lambda is the latent heat of condensation of vapor.

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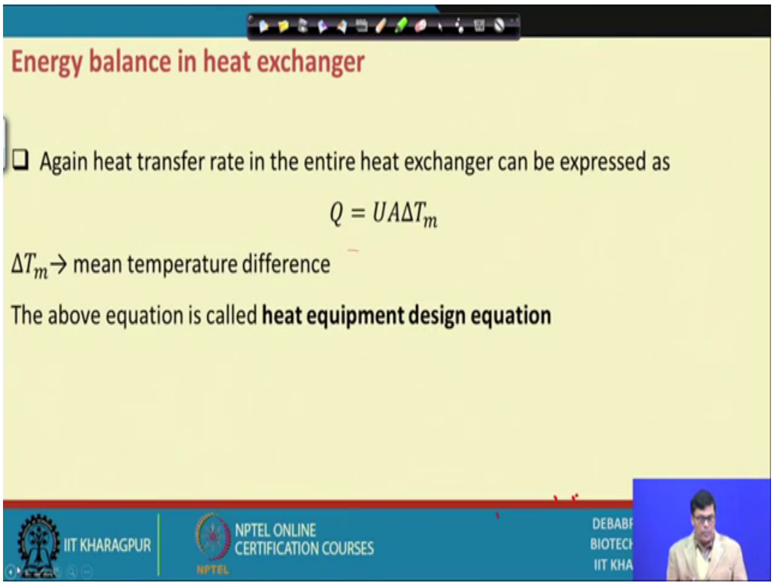

Now, here the overall that heat transfer can be express as like this del A del U A del T m that is the mean temperature difference that we have.

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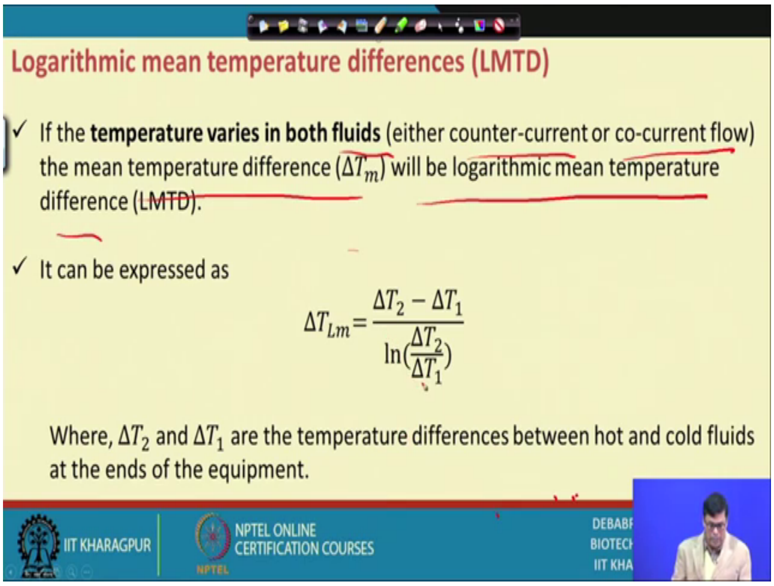

And mean temperature logarithm the mean temperature difference is what? That is there that is a if the temperature varies both fluid either counter current or co current flow the mean temperature difference will be logarithm means of the differences.

So, it will be T 2 minus del T del 1 equal to l n del 2 by del 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.

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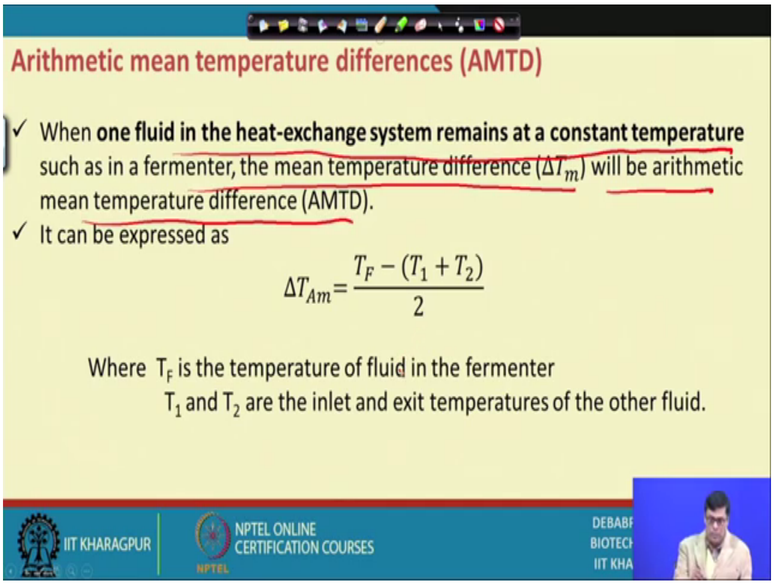

And arithmetic mean of the temperature difference that also can be calculated in case of one fluid in the heat exchanges system remain as the constant temperature. Such that the fermentation in temperature difference is T m and we will be arithmetically mean temperature difference this will be T F minus 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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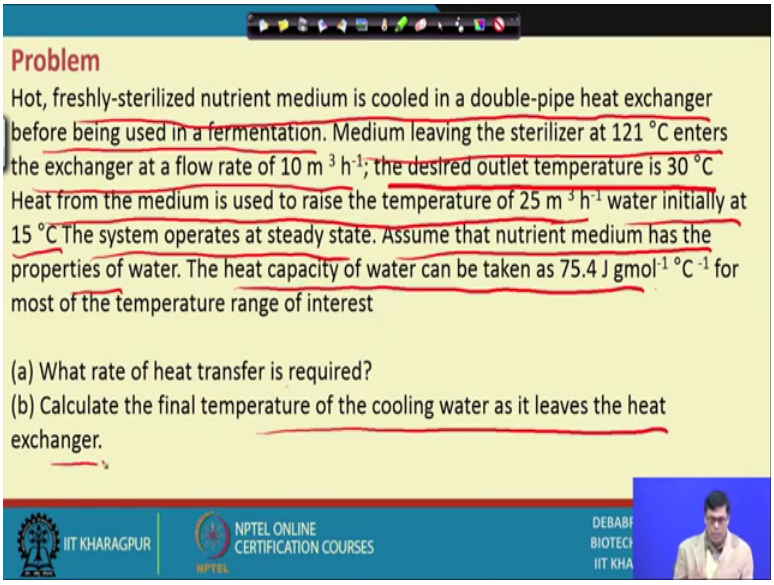

Now we have two problem that related with this heat transfer I hope if we can solve this problem then our conception will be little bit clear. Now what you are saying that hot, freshly sterilized and nutrient medium is cooled in a double pipe heat exchanger um before being used in the fermenter.

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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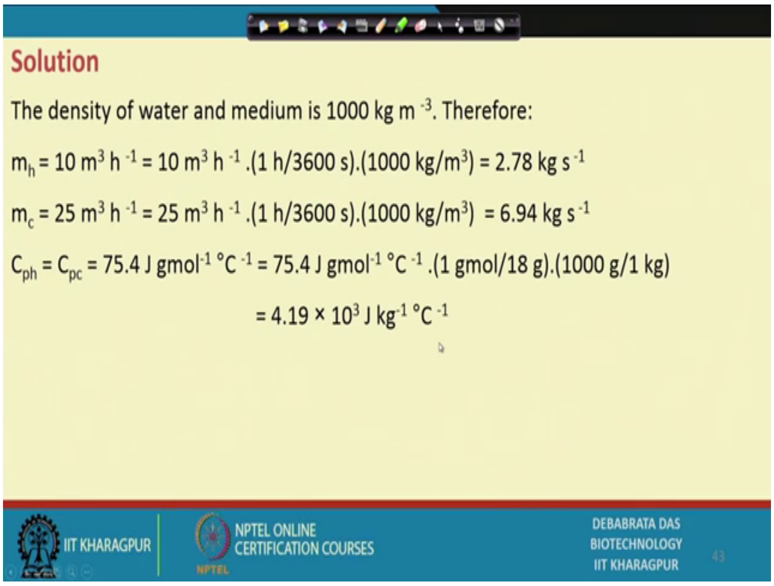

Now, first we shall have to find out as I as I told you that we shall have to convert the unit and in two hour desired unit. As per example the what liquid flow rate that is 10 cubic meter per hour that you have to convert into the seconds. The 2.78 kg per second we can easily do that because we know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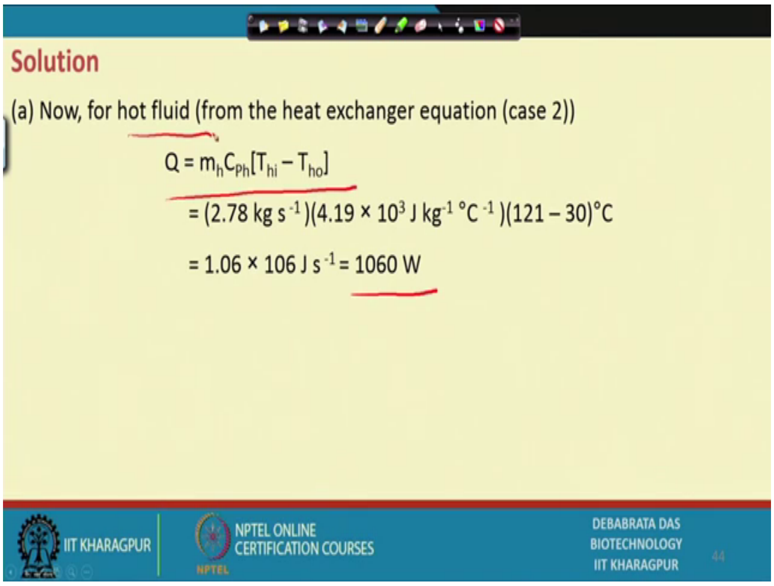

Then and we have the equation what is the equation we have? Q equal to we shall have to find out the heat rate of heat transfer, so we have m h c p h T i T h i minus T h o.

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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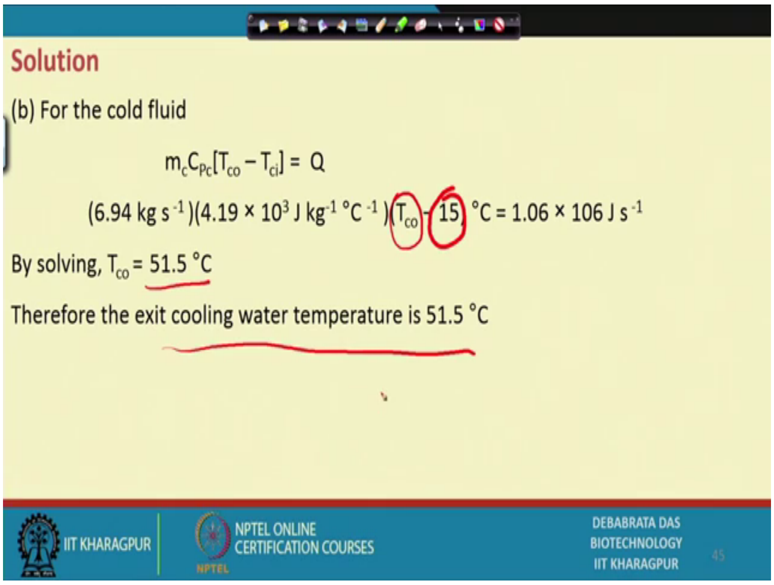

Then for cool liquid we can similarly find out the how much that that the for a cool liquid it is the temperature we have. And we assume the temperature of the cool liquid is this am I right.

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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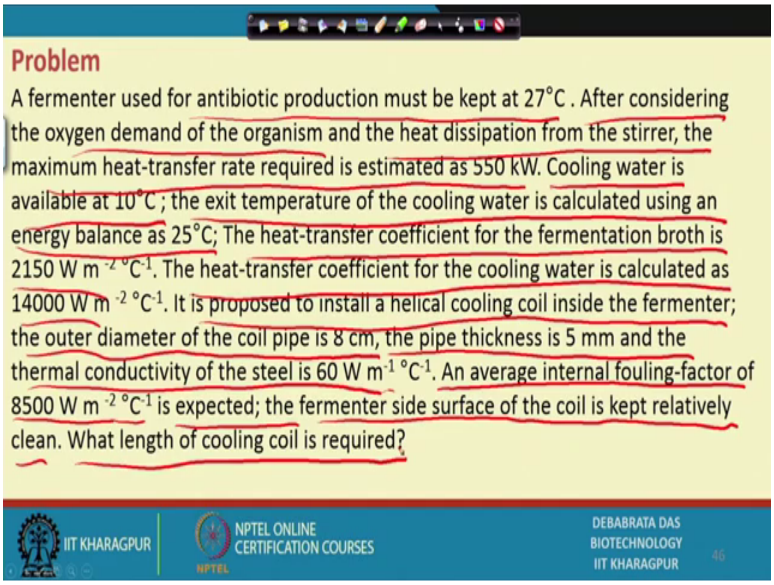

And another problem that we have like a fermenter use for antibiotics production must kept at the 27 degree centigrade after considering the oxygen demand of the organism the heat dissipated from the stirrer and the maximum heat transfer rate required is estimated 550 kilowatt.

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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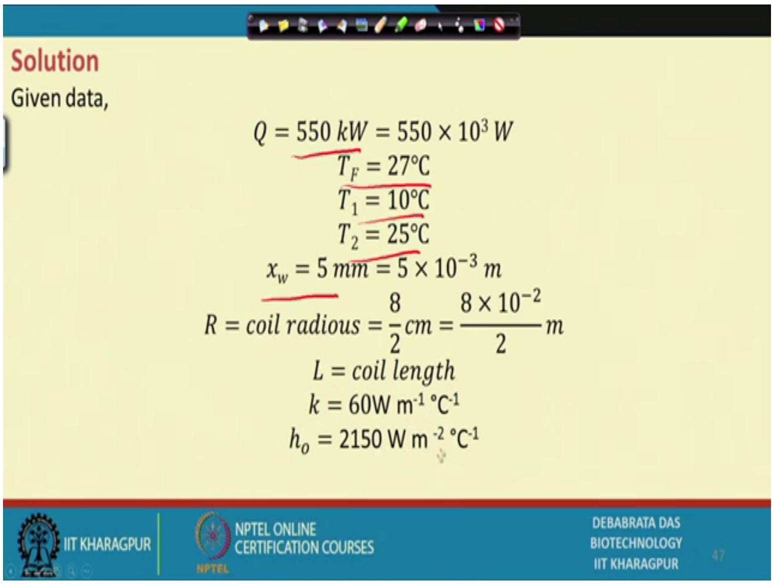

Now as I mentioned that we shall have to always jot down what are the data is given? The heat transfer that that is already amount of heat transfer capacities is already given this is 550 kilo watt. And temperature respective temperature is also given am I right that final temperature and all, this thing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

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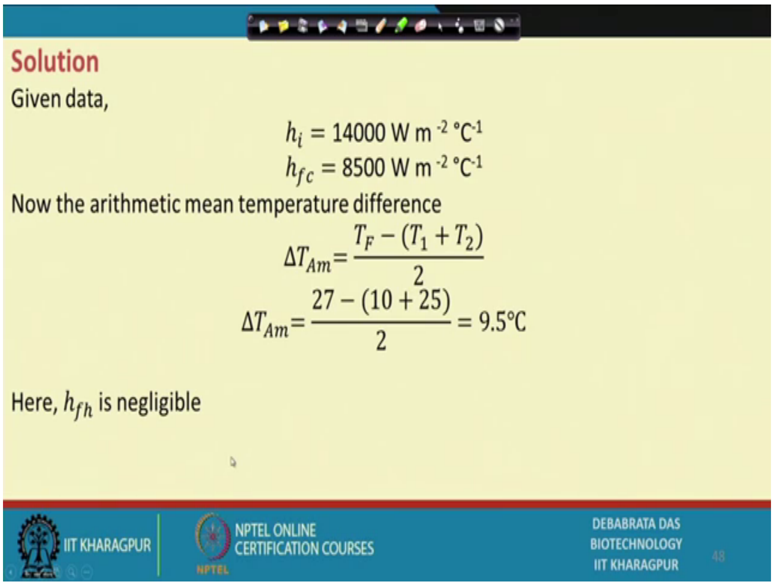

So, we converted into the SI unit everything and then after converting into SI unit then we find out an h i and h i c also given in this problem. There you have first we shall have to find out the arithmetic mean temperature difference and because we maintain a want to maintain a particular temperature.

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.

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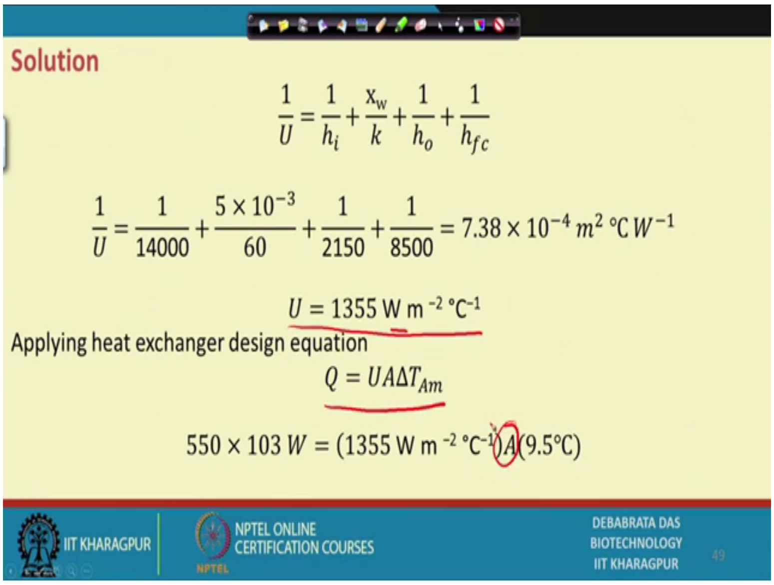

Then this is the resistance that we have 1 by U equal to this. So, this we can easily calculate and we find out the U value.

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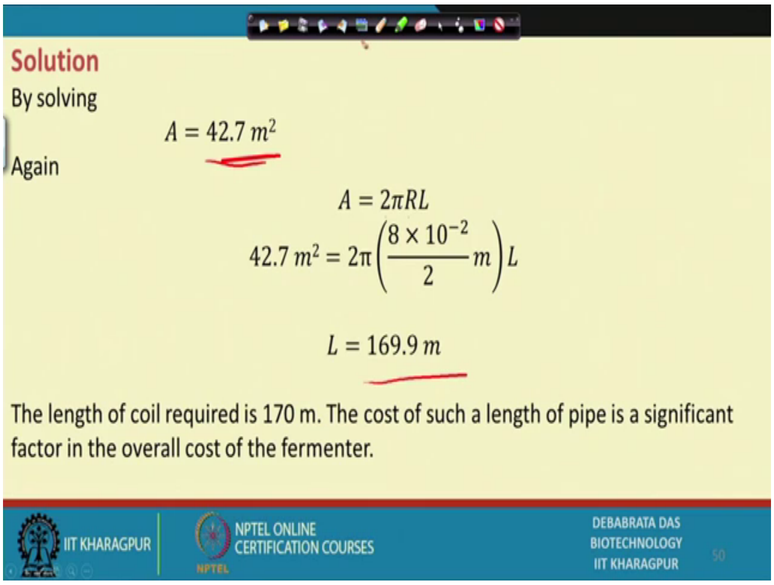

So, U value we can calculate and the, this is the U value you can calculate. Then we know rate of heat transfer equal to U into A into this is temperature difference. So, if you put all this thing here and we can easily find out the area that is required for the heat transfer that a, that heating pipeline.

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.