An Introduction to Electronics Systems Packaging

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Module No. # 08

Lecture No. # 39

Thermal Design considerations in system packaging

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Good day to all of you. In today's session, we discuss on a very important aspect which is associated with electronic packaging and that is the thermal issues. All the electrical components that are mounted on the Printed Wiring Boards are dissipaters. They dissipate heat and we need to find mechanisms where by the heat is removed from the Printed Wiring Board and the components such that the components junction temperatures are kept at a predefined or prescribed levels for them to reliably function.

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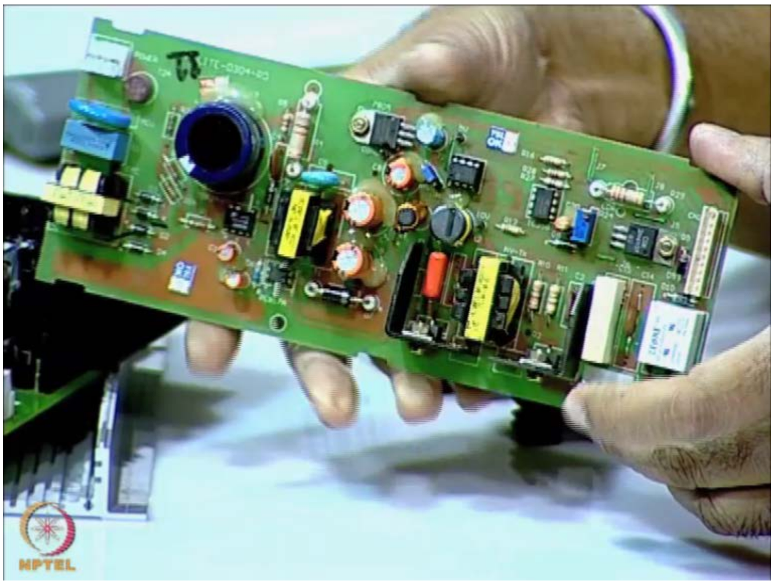

So, the important aspect of removing the heat from the component and the Printed Wiring Boards is very crucial for reliable working of the circuits. If you look at PCBs many of the Printed Wiring Boards which have power components in them, they will have some form of heat sinking done which will remove the heat from the components. Look at this particular component. This is nothing but an aluminum plate which is bent in the shape of an l so also bent in the shape of an l and look within you will see the component here; this is a 220 package component which is mounted on the PCB, the leads are mounted on the PCB right here or may be it is clearer here and the body is affixed to this aluminum plate which will act as a heat sink.

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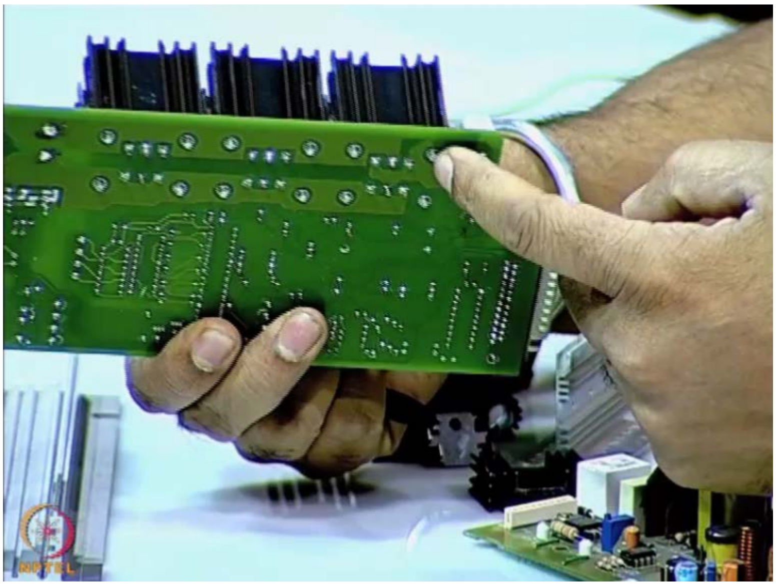

This is a very simple heat sink. But you have different varieties of heat sinks. For example, take this particular board here where the heat sinking is by extruded aluminum lengths. These are aluminum extrusions and in between inside you will see the components placed, inside will be the components placed and the leads will be - the three leads here which come out are those of the components and these are also used for basically to keep the junction temperature of those particular power components cool. You see another type of heat sinking here. Likewise, you have different shapes. You see there is another heat sink which is of a different cross-section. This is also aluminum extrusion; another PCB mounted mountable heat sink. You have a possibility of attaching it to the Printed Wiring Board through a screw, here a mounting hole, the component will be mounted here and on to the PCB which will probably fit something like this. It will fit something like this. We mount it in this fashion with the component leads going into the PCB.

You also have these types of cylindrical cross-section heat sinks. These are for TO of high package type of devices which are circular, may be OPAMPs also and some BJTs which have a circular cross-section like that and it is fixed around that and it will be mounted on PCB like that.

Like that you have many such heat sinks. This is another type of extrusion piece with components which would be mounted on through that. The leads will go in through these holes on to the PCB. You have another type of a bit more heavier heat sink with different cross-section here. The components are mounted inside here and fixed to the enclosure through these mounting holes.

So, you have heat sinks of varying sizes, still farther bigger ones depending upon the type of heat that has to be removed from the junction. So, the culprit, of course, is where the heat source is actually at the semiconductor junction and the semiconductor junction is the source of heat, which is actually coming as a consequence of current flowing through it and a potential across it.

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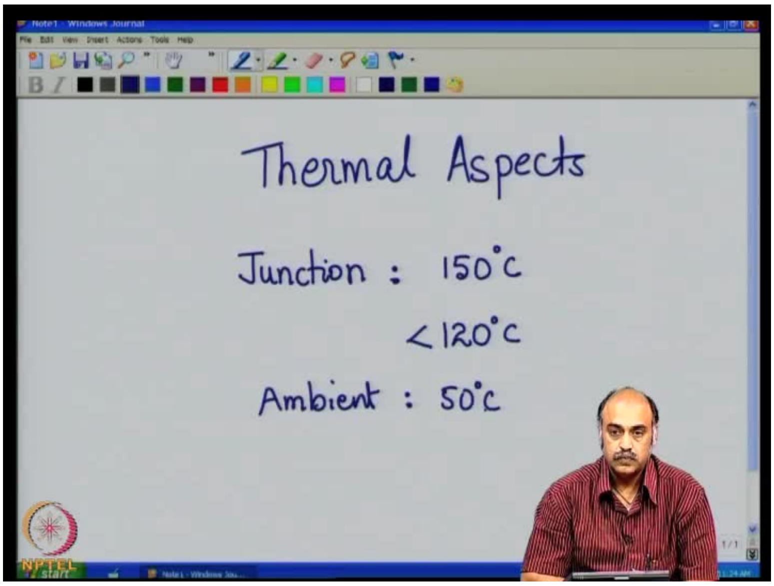

Therefore, today's main discussion is on the Thermal Aspects. This is what we will be talking on and the junction temperature in most of the semiconductor devices that you will be using would be upper limit of 150 degrees centigrade. This is actually the breaking point; you should never go to that and almost all the designs will see to it that the junction temperature is less than 120 degree centigrade. It should not go beyond that one even at an ambient temperature of 50 degree centigrade. These are some numbers that you need to keep in mind and normally the designs are performed for these extreme numbers.

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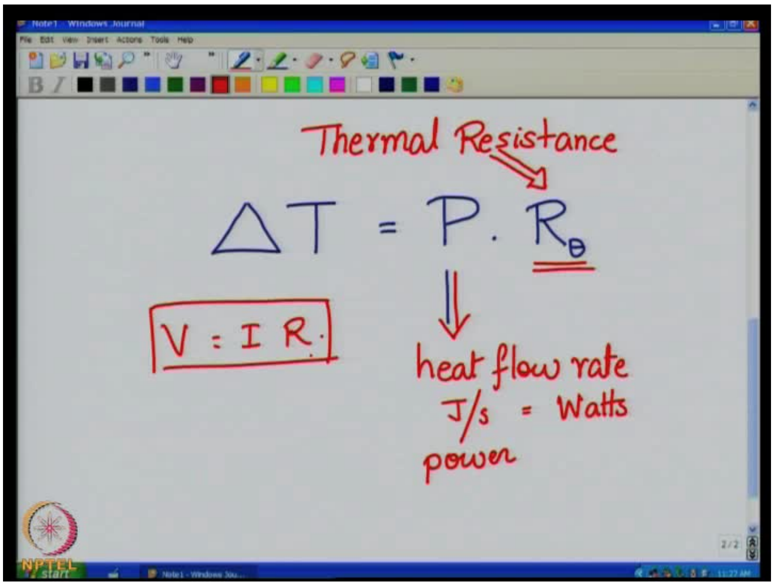

When we come to removal of heat, there is something similar to an Ohm's law for the heat which is given in this form, I will call it as delta T - the temperature difference. The temperature difference is equal to the heat flow rate into some parameter. We will see what that parameter is. This temperature difference is basically the difference in temperature between two points; let us say for example, the one point is within the semiconductor, which is at the highest temperature and that temperature is actually linked through all the material properties to the ambient, which is at let us say worst case 50 degree centigrade. So, the heat has to flow from the higher temperature potential to the lower temperature ambient potential.

This P is nothing but heat flow rate. Heat is having units of energy that is joule and heat flow rate is joule per second which is nothing but watts. So, heat flow rate is nothing but the power dissipated within that particular component and you have another parameter which comes here, which is the property of the material and this is called the thermal resistance. Thermal resistance is not actually the resistance like in the electrical sense. That is not a dissipater. It is only going to impede the flow of heat. It is a measure of the speed with which the heat can be conducted away or removed away from the hot source.

So, this needs to be understood in that fashion. The thermal resistance here just means that the speed at which the heat can be removed from the hot source.

This equation is the governing equation and for electrical engineers they say that this something equivalent to the Ohm's law as we know in electrical engineering, V which is equal to I into R something similar to that but not exactly same.

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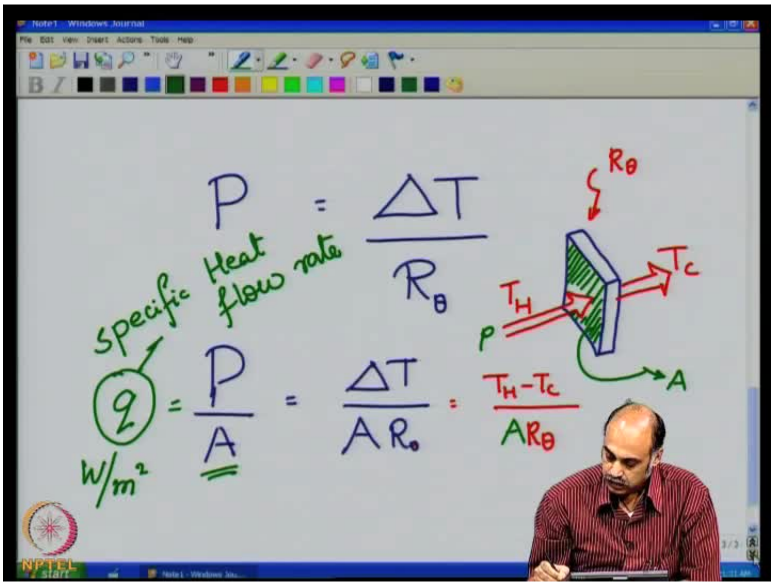

The heat flow power P rewriting it, we have the temperature difference divided by R theta or R thermal. This is called the thermal resistance. This has a unit. Remember if you write it in a different way, R thermal is equal to delta T by P and therefore the units of this is degree Kelvin per watt. Degree Kelvin per watt is the unit of the thermal resistance. Keep that in mind.

Now, this form is a very generic form. But there are many derived forms and many literature give this law in different notations and different forms. In order to avoid confusion, let us have a look at the various notations that are there in the literature. They are actually the same thing expressed in a slightly different manner.

Firstly, power sometimes is expressed with respect to unit cross-section area; power per unit cross sectional area given in this fashion A R theta. What is A? If you have a square block like this solid piece of block and let us say, this is the hotter side TH. This is the colder side TC and the heat is flowing from this hotter side to the colder side in this fashion. So, delta T is nothing but TH minus TC and R thermal which is the property of this is material which is being used, it has an impedance which resists the flow of heat good conductors of electricity in many cases are good conductors of heat too.

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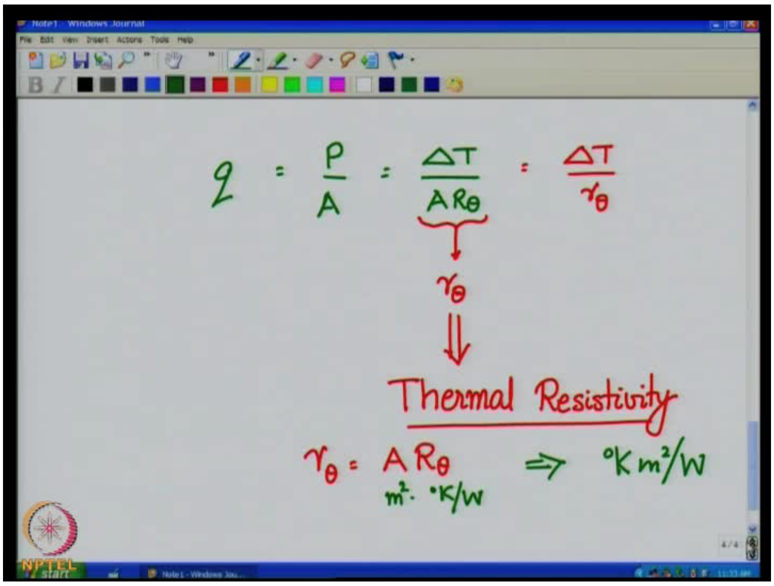

Now, this particular solid, let us say, has a cross sectional area perpendicular to the heat flow and that is A. That is the A that we are saying power by the cross sectional area is called q. This is called specific heat flow rate. q is nothing but the specific heat flow rate, watts per meter square. That is its units, watts per meter square. So, this is one way of expressing this P is equal to delta T by R theta. You have P which is equal to P by A which is equal to delta T by A R theta. Now this A R theta is given a different symbology in many, smaller case lower case R theta, so it is written as delta T by r theta. What is this r theta? This is called thermal resistivity. So, we had R, which is the thermal resistance, you have lower case r theta which is called the thermal resistivity which is given by this relation A into thermal resistance. So, you have the units for this meter square into degree Kelvin per watt. So, thermal resistivity is expressed in the units degree Kelvin meter square per watt. So, this is one way of looking at it.

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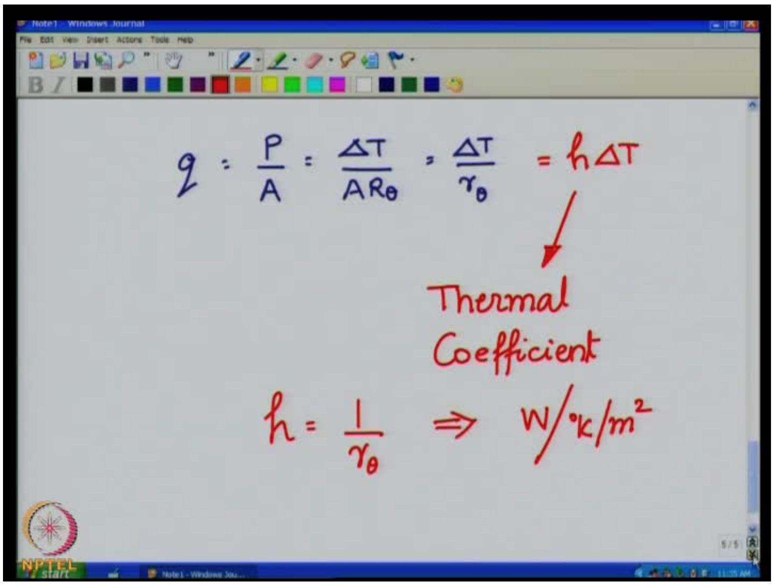

So, what do we have? We have q, the specific heat flow rate which is given by heat flow rate by the area of cross section perpendicular to the heat flow which is given by delta T by A R theta which is given by delta T by lower case r theta called the thermal resistivity. Now to this, there is a different notation. It is equal to h delta T, where h is another constant used in many literatures. This is called the thermal coefficient. h is called the thermal coefficient. It is nothing but 1 by lower case r theta, 1 by thermal resistivity and therefore, its units we know that the thermal resistivity has units of degree Kelvin meter square per watt, so thermal coefficient will be watt per degree Kelvin per meter square. This is another way of expressing the same heat flow equation relationship.

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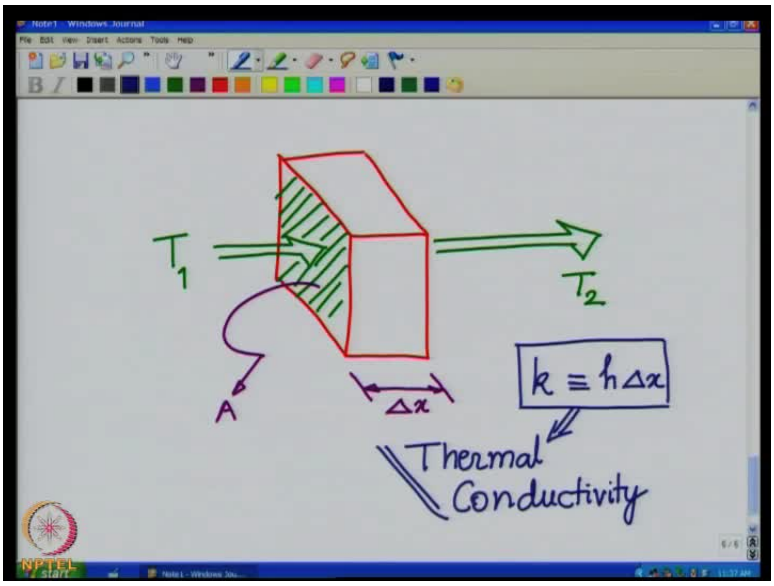

There is one more way of expressing the heat flow relationship. Let us say that we take up that similar kind of a situation where you have a block and this block has a temperature H s. No, w will call it H1. H1, the hotter side and then we have heat flow in this fashion. The area of cross section perpendicular to the flow of heat, we shall call that as A and the thickness of the block, we will call it as delta x. Thickness of the block we call it as the delta x. Heat is flowing to the colder side and we call that one as T2. Now, the property of the block which normally we used to express in terms of thermal resistance, thermal resistivity or even the thermal coefficient h we have one more constant k which defines the property of the material and this is defined, you know there is a definition in terms of thermal coefficient h delta x. This is the definition and this is called in the literature as thermal conductivity. Thermal conductivity is also very popular notation. Thermal conductivity which is used in many literatures and this in fact gives the nicely famous heat equation form.

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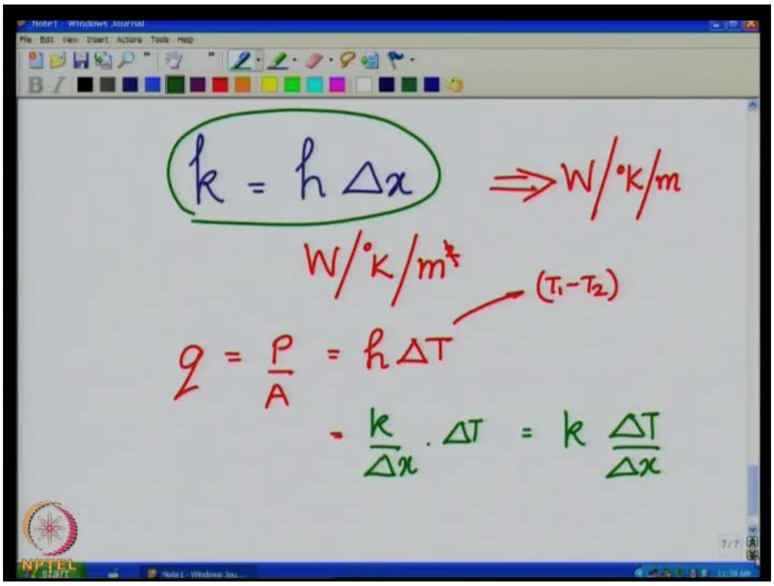

So, if you take the thermal conductivity k which is expressed as h delta x and we know that the units of h is watt per degree Kelvin per meter square where there is a delta x the numerator. So, it will become per meter. So, thermal conductivity has units of watt per degree Kelvin per meter.

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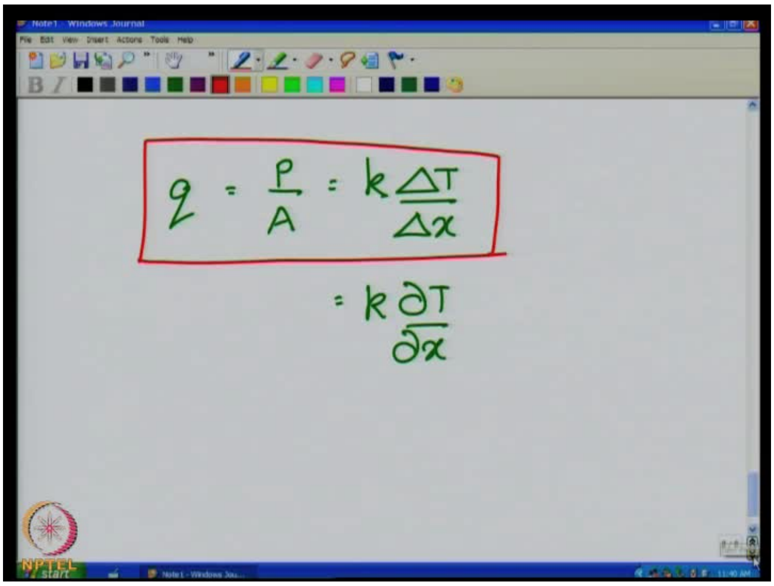

Now, going back to the equation q, specific heat flow rate given by P by A and which is equal to h delta T, thermal coefficient into the temperature difference. Now this temperature difference is nothing but T1 minus T2 in the case that we just now described. If you want to make use of this thermal conductivity equation here h can be written as k by delta x into delta T and this is nothing but k delta T by delta x and therefore, you have q which is equal to P by A; it is equal to k delta T by delta x. This is the famous heat flow equation which is also written as this form, if you have continuous temperature gradient with respect to the distance through the solid. So, this is a very popular expression which is used in many literatures.

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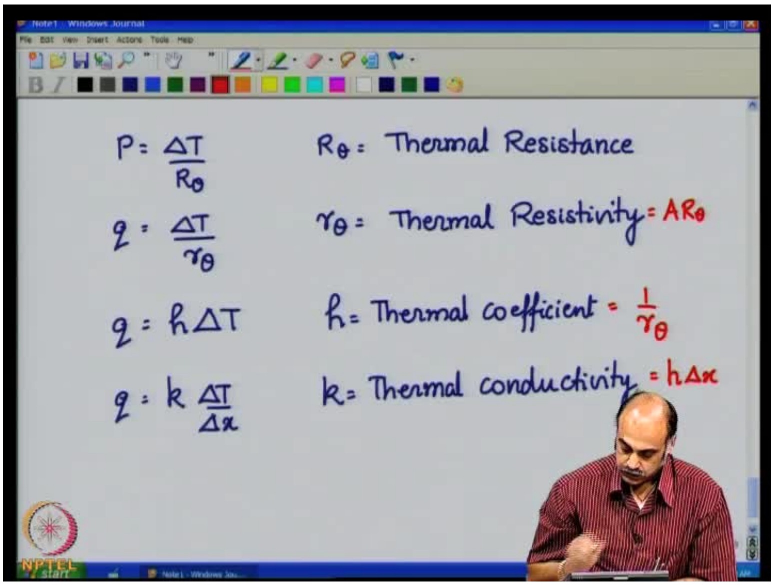

So, you should be aware of these things. You saw that the same notation was used in different forms. Let us just summarize so that you do not get confused at this point. We started with P which is equal to delta T by R thermal. Now, this R thermal is called the thermal resistance. You have q which is equal to delta T by lower case r theta where r theta is the thermal resistivity. You have another form q which is equal to h delta T, where h is called the thermal coefficient and you had the other form q which is equal to k delta T by delta x, where k is called the thermal conductivity. So, these are the four forms that are very popular in the literature. You will see these forms. They are one and the same form except that the notations are slightly different and you knew you should not get confused when you see one of the forms you can always convert one form to other. You see that this I nothing but A R theta. This is nothing but 1 by the thermal resistivity and this is nothing but thermal coefficient into delta x.

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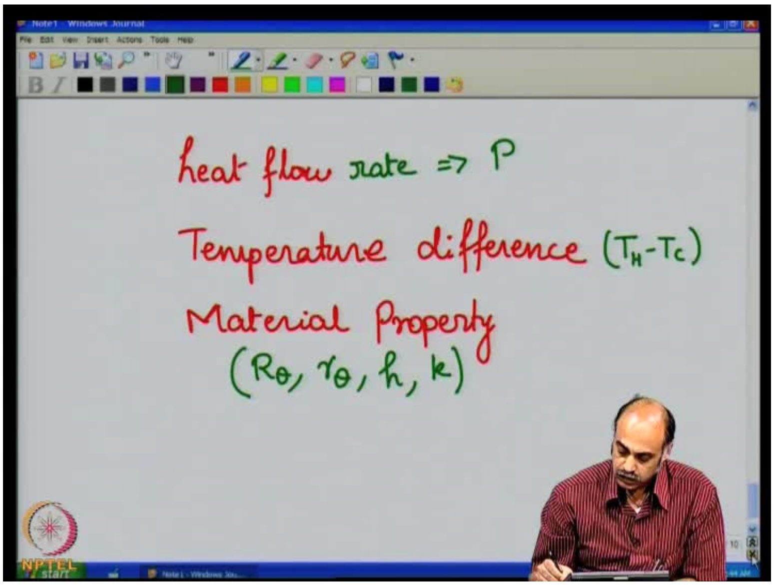

So, this is the basic relationship of heat flow rate, heat flow energy, temperature difference or temperature gradient and the material property. So, the material property is the one which is actually represented by these thermal resistance, thermal resistivity, thermal coefficient, thermal conductivity and such these are measurable quantities. This is the potential temperature of the hot minus temperature of the cold, two points temperature points, where the heat flow occurs. Now, the heat flow rate is nothing but the power flow, the power that is dissipated within the semiconductor. The power that is dissipated within the semiconductor is coming from the electrical circuit equivalent analysis. You know the currents that are flowing through the various components. You know the voltage across the various components then you should be able to derive the power that is getting dissipated within the semiconductor junction, in the diodes, in the BJTs, in the MOSFETs or within the ICs or the magnetic components or even in the capacitances and the inductances.

Now, once you know the power that is dissipated then it is a matter of getting it into the thermal domain and then relating it with the material properties in this fashion.

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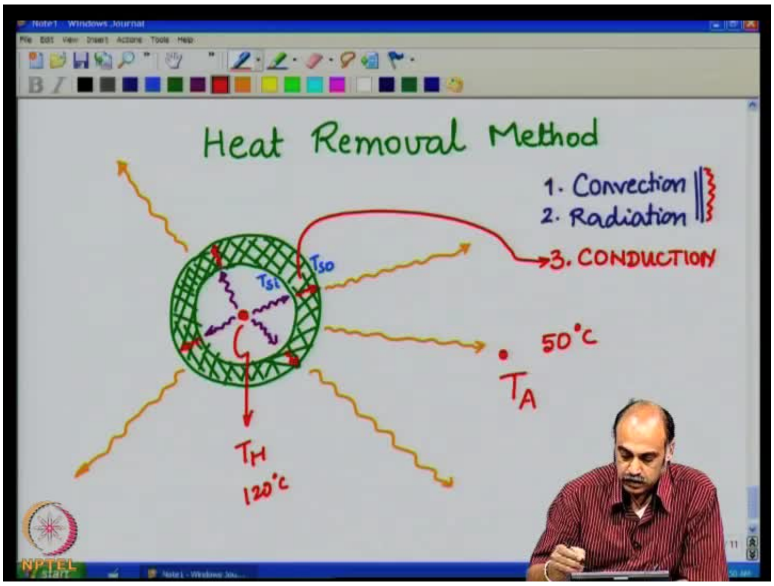

Heat removal methods. So, our main motivation for this topic here now is that there is dissipation that is occurring within the components and we want to remove the heat so that we can keep the junction of the components cool enough and working reliably.

If you take for example, a closed space. This closed space is having an enclosure, a solid enclosure as shown like this and this solid enclosure contains a hot spot. So, this solid enclosure contains a hot spot here shown in red and that is the highest temperature point in the system let us say TH. Now this temperature, the heat source should ultimately get conducted to the ambient let us say this is TA ambient, let us say the maximum is around 50 degree centigrade this is much greater. This is around 120 degree centigrade.

What all can happen? The heat energy needs to reach this inner surface of the solid and it can reach in all directions. The inner surface of this particular enclosure is at some temperature T surface inner and the heat is to be conducted from this inner surface to the outer surface all directions. So, I am showing these wiggly arrows to indicate heat flow and the temperature at the outer surface we will call it T S O, T surface outer temperature and from this outer temperature, the heat is supposed to go out to the ambient in all directions. So, this is the typical way the heat flow happens but if you look at the mode, now from this hot spot point to the inner surface it contains a fluid let us say air, there are two possible ways in which the heat transport can occur from this hot spot to the inner surface.

We shall call that two methods, as one is by convection and the other is by radiation. So in a fluid medium, you can have these two possibilities, convection and radiation. Radiation does not need a medium. Convection needs a fluid medium and then once you are at the inner surface, solid, the heat has to get conducted to the outer surface through the solid and the method of heat conduction through the solid is called conduction and again when it comes to the solid outer surface, it goes through the air or some other fluid medium and again it is through this convection and radiation.

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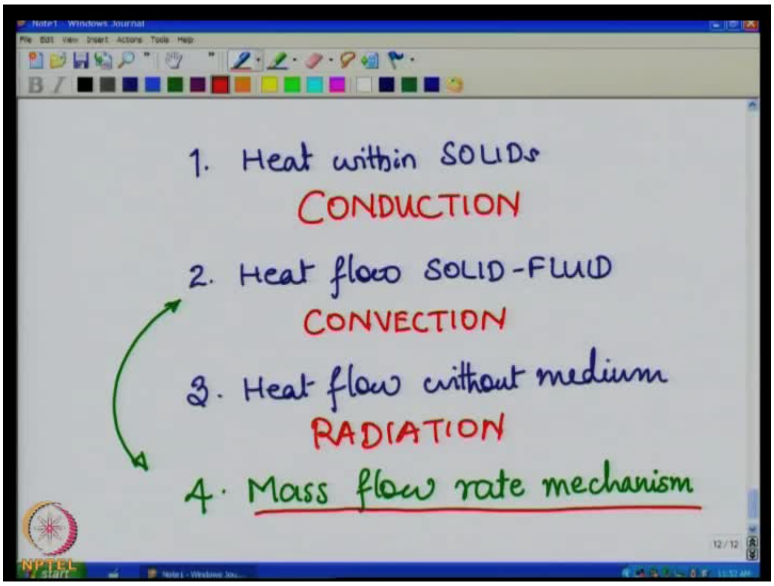

We do not have too many methods to deal with. You have just three plus one. I will say what is that plus one. Heat flow within solids. We call it conduction, heat flow, solid fluid interface, we call it convection. So for convection, you need to have a fluid which is interfacing with the solid so that the fluid is the actual medium which is removing or conducting the heat away and the third method heat flow without medium through radiation. This is called radiation.

There is one more method I shall put that one in green. It is also in some way linked with convection, it is also solid fluid interface. This is called mass flow rate. Heat transfer through the mass flow rate mechanism. In the convection, the fluid flow is not tightly controlled or regulated whereas, in the mass flow rate mechanism, the fluid flow is tightly regulated and therefore, you have this as a separate mechanism part of the convection mechanism and we call that one as a mass flow rate mechanism. So, these are the four basic types that you will have in methods that are used for conducting the heat away from the junction.

Coming to the methods by which you can try to remove the heat away, let me show some scenarios which will give you the basic idea.

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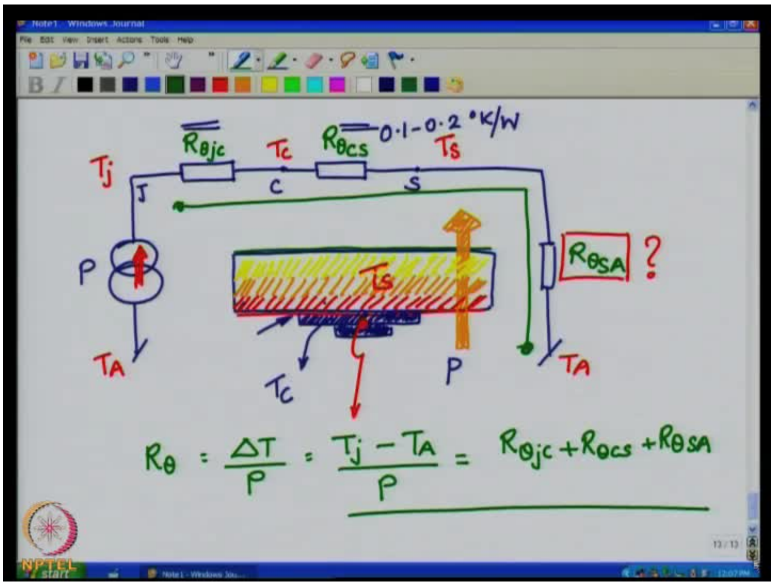

Probably, first a simple explanation with conduction. Let us take an example, where we are trying to conduct the heat from the semiconductor to the ambient, let us say we have some solid material where this portion is the hot portion which is at temperature TH and this portion is the cold portion which is at temperature TC. The heat will flow from the hot to the cold in this manner. Now to this, let us affix a component let us say, we have some component and this component is fixed to the material in this fashion very similar to the way the components are fixed. Here, if you look at these components here in this PCB, you see that this component is fixed to this aluminum plate here. So, the hot spot is within this component at the junction and that has to be removed out to the ambient.

So, here this component is having a hot spot where right in and that is called the junction temperature Tj. Now, let me erase this portion, these symbols and make way for new symbols. Now, the heat flows from the junction, the hotspot to the case, the surrounding case. Surrounding case, the blue colored one is at a temperature TC. TC is lower in temperature than the junction and from there the power flows on to the heat sink which is I should say the bottom portion of the heat sink, I have shown here. Now, there is a temperature gradient you will see that heat starts flowing from the bottom to the top as shown and somewhere here we will say is the ambient, which is at around 50 degrees centigrade. So, the junction is at around o120 degree centigrade and we want the heat to flow in this fashion.

How do we model this? Power flow P is modeled as a current source like this. I will reposition things in a slightly different way, is modeled as a power source like that. Now, this power source is basically the dissipation which is happening within the junction. The power source which is generated at the junction is at junction temperature with respect to ambient T amb.

Now, there is a thermal resistance between junction and the case. This is the junction. This is the case and results in a temperate TC at the case slightly lesser due to the presence of a thermal resistance R theta junction to case R theta j c, let us say then from the case now the component is attached to the aluminum block or the heat sink block through a compound called heat sink compound which is supposed to make proper contact with the surface of the heat sink. So that also is going to bring about a thermal impedance from case to sink S. So, this gives rise to another thermal impedance or thermal case to sink and then from the sink to the ambient. The sink is at sink temperature. The average sink temperature, I will put this as T s and somewhere outside you have the ambient.

R thermal sink to ambient, there is a resistance there. So, electrically you will see that it is equivalent to a current sourced circuit. This is ground and this is ground, a reference potential the ambient is called the reference potential. So, looking at this figure very easy to get the equation the R thermal junction to case is the property of that particular semiconductor or semiconductor IC or the component from the junction to its case which is generally given in the data sheet. This is given in the data sheet.

The R thermal case to sink is basically giving you the goodness of the contact which the component makes to the heat sink. So, the quality of the contact is dependent on way it is assembled, amount of torque that is applied to the screws, the heat sink compound that is the layer of heat sink compound that is applied, all those will influence R theta c to s and it is normally of the order of 0.1 to 0.2 degree Kelvin per watt if it is done by professional thermal packager.

Generally, we need to find out what is this so that you can buy from the market, a suitable heat sink of suitable extrusion and cross section containing such that the R thermal sink to ambient is as required. So, what is the governing equation? We know that P equals delta T by R thermal. This is our basic governing equation. Let us reframe this equation in this following manner.

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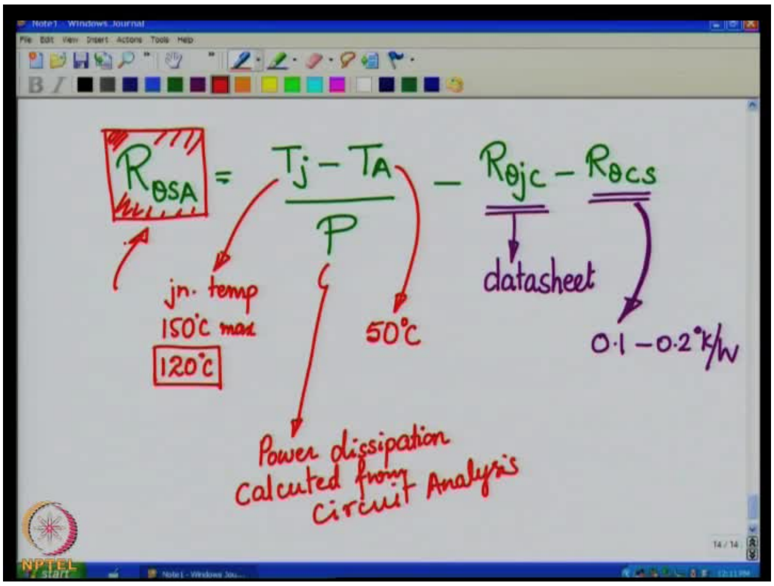

R thermal is equal to delta T by P or we should say delta T is nothing but T j, junction temperature minus T A, the ambient temperature divided by P is the total thermal resistance which you see in this whole link from T j to T A. So, what is it? That is equal to R theta junction to case plus R theta case to sink plus R theta sink to ambient. Therefore, this can be rewritten in the following manner R theta sink to ambient. This is what you normally would need to buy from the market, which is given by Tj junction temperature minus T ambient temperature by the heat power flow rate minus R theta junction to case minus R theta case to sink. So, this would be the governing equation by which you go and buy a particular heat sink. So, this T j is the junction temperature and most of the semiconductors it is 150 degree centigrade maximum and normally we do not allow it to go more than 120 degree centigrade.

T ambient, this is not the room temperature. Keep that in mind. This is not the room temperature. This is the temperature in the immediate neighborhood of the heat sinks. So, if you have an enclosure like this and this heat sink, this particular card is supposed to fit into this enclosure like this let me fix this. Wait a second. Let us say this is going to fit like this. TA does not mean the temperature of the room which is surrounding this enclosure, it is the temperature in the immediate neighborhood of the component of the heat sink within the enclosure which will be at a higher temperature than the room temperature when all this enclosures are closed and packed.

So, this is the temperature which would be designed normally for around 50 degree centigrade much higher than the ambient temperature and this P is the power dissipation within the component. This is calculated from circuit analysis. This portion, R theta j c for that specific component you can get this from that data sheet of the component; the electrical data sheet of the component itself will give R theta junction to case.

This depends upon the quality of the contact made by component with the heat sink and this varies by around 0.1 to 0.2 degree Kelvin per watt. So, knowing all this one can calculate this and put the required and from the market get the heat sink according to the thermal resistance requirement of sink to ambient and connect it to the component.

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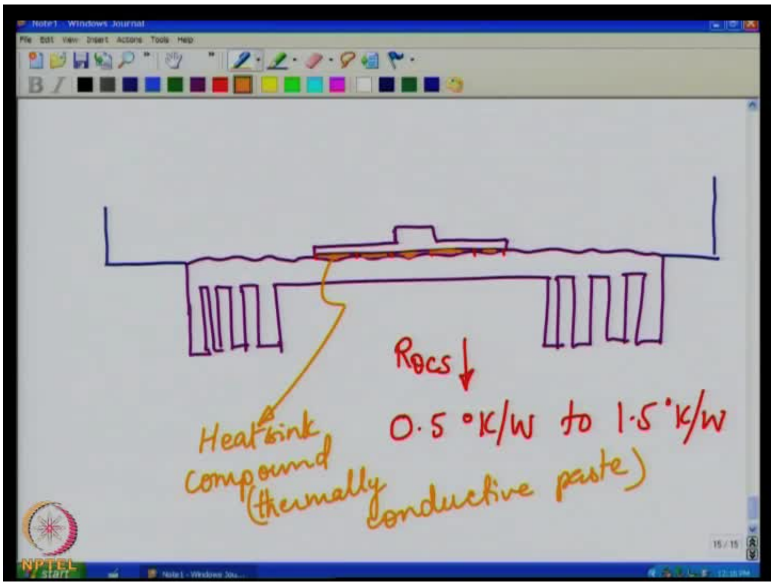

While you are mounting the component, let us say that we have a flat piece of heat sink and let me draw the heat sink like this. Let us say, this is your heat sink. One particular cross section. The component is mounted on this let us say, if the component is within the enclosure, then the component is mounted like this and the fins are out sometimes the components are also mounted from outside and with the leads coming in but in many cases the leads are on the side of the component in which case it has been mounted inside the enclosure. So, that has to be accordingly decided.

What is crucial is, if you zoom in to the surface here, let me remove that, the surface is not actually smooth, it is very jacked. so this is a extremely zoomed case and on that if you mount the component you will see that these micro hills will actually make point contact. It will only make point contact with the component and therefore, the contact will not be good and as a result R theta c s will go down, will be poor. Will go down meaning it will deteriorate and deteriorate mean and that thermal resistance will become high. It can go even as high as between 0.5 degree centigrade Kelvin per watt to 1.5 degree Kelvin per watt. This is a poorly fixed component to the heat sink.

Therefore, what is normally done is that to improve the contact, one has to apply a paste which just fills these valleys within the hills. It just fills. You should not apply too much of a paste then you will have a thick layer of paste above the valleys and therefore, again it will deteriorate the contact thermal resistance. You have to apply just that much amount of paste which will just fill the valleys and make very good contact between the component and the heat sink.

These valleys are filled with a paste called heat sink compound. It is a thermally conductive paste and that has to be done. It is mandatory if you have to get a good case to sink thermal resistance. This is the way that the components will be mounted and the heat sink will be used for removing the heat. In power electronic components, you should note that there is one more issue. The heat that can be removed by a natural process without any force, forcing the fluid flow is limited and therefore, we may have to apply forced cooling in some of the high power equipments in which case fans are used.

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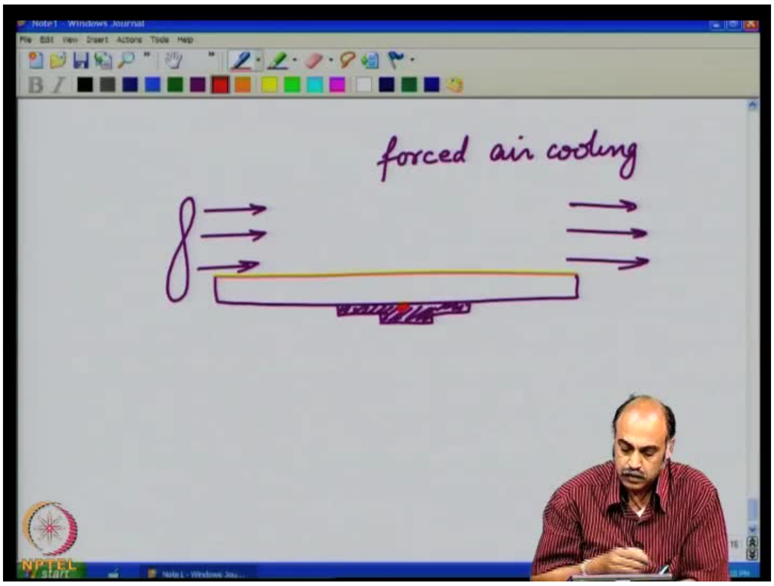

So, you must note that if you have a heat sink surface like this, let me show it as surface like this, and let us say you have mounted a component in this fashion. A fan is also mounted which will force air flow through this top of the surface and this forced air cooling will give much better thermal resistance to lower the thermal resistance drastically and remove the heat away from this component with the hotspot here much at a much more rapid rate.

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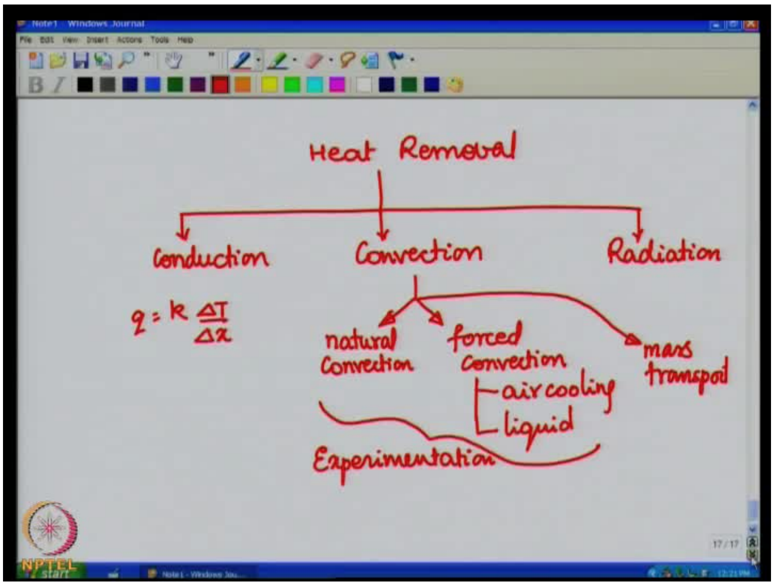

So, if you see in the hierarchy, the heat removal methods can be classified like this: you have conduction, you have convection, and you have radiation. We saw the relationship in the case of the conduction where the specific heat flow rate is given by k delta T by delta x. Similar such relationships are there even in convection and radiation. However, it is out of the scope of this particular class. However know that there are two methods in which you bring about convection, one is natural convection and the other of course is forced convection.

So in the natural convection, there is no fan incorporated into the enclosure. The density of the air changes as it becomes hot, it will rise up and cooler air comes down and there is a fluid cycle due to the natural density gradient which will occur. Forced convection is as I mentioned just now, through the application of forced cooling, either forced air cooling or forced liquid cooling. Liquid cooling is much lower in a thermal resistance.

The thermal resistance of this convection is best obtained by experimentation. Even though models are available using Nusslet's number, Rally number and the Reynold's number for fluid flow. One can arrive at a mathematical model and estimate the value. However in most cases, you will find that the estimates are of by more than 50 percent to 100 percent. Therefore, it is better to experimentally find out the thermal resistance in this case and so also the thermal resistance for radiation can be estimated. However it is right now out of the scope of this particular class.

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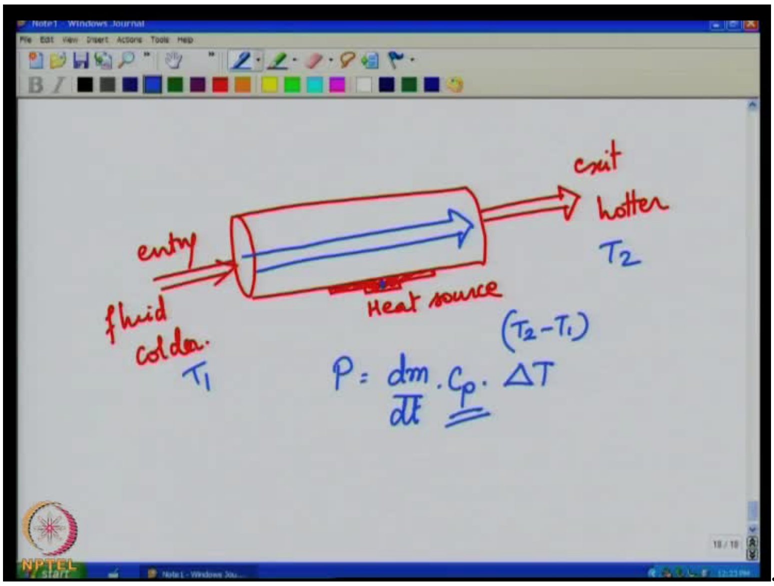

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Apart from this, as I said, we have one more method which falls very similar to the convection, which is the mass transport. In mass transport what is actually done is you have let us say a pipe, the fluid or which could be oil or water is allowed to flow through this pipe and it exits out. Entry at lower temperature, exit at hotter temperature and the heat source is here in between. This is the hot body and the fluid flow within the pipe is controlled.

The control flow rate and that power is given by the mass flow rate into Cp into delta T if let us say, this is T1 and this is T2 this delta T is nothing but T2 minus T1. So, the amount of heat that is conducted away, taken away from this heat source is given by the mass flow rate of the fluid. Cp is called the specific heat of the particular fluid and the temperature difference and by far the mass flow rate can give you some of the least thermal resistance and can conduct away the heat at a very good rate

So these are some of the methods that we have seen and this is just a basic class on the thermal aspects which was used to sensitize you to the problems that are involved thermal aspects and how it is removed away to the ambient and it is very crucial that this has to be done and the proper functioning of the whole enclosure and the whole equipment and the Printed Wiring Board depends upon the goodness with which you are able to remove that hat away from the junction. Thank You.