Heat and Mass Transfer
Prof. S.P. Sukhatme
Dept. of Mechanical Engineering
Indian Institute of Technology, Bombay
Lecture No. 03

Last time we considered the fundamental laws with which we would be concerned while studying heat transfer. What were these? These laws were the law of conservation of mass, Newton's second law of motion and the first law of thermodynamics and both for the case of closed system as well as the control volume. We made, stated equations corresponding to these fundamental laws. Remember fundament laws always have to be satisfied while solving a problem in heat transfer. Then I also said last time that we have subsidiary laws. Subsidiary laws are empirical in nature; we will use those laws which are of interest to us for a particular situation.

The three subsidiary laws which we will be primarily concerned with are Fourier's law of heat conduction, Newton's law of cooling and the Stefan Boltzmann law which is one of the laws of radiation. Now let us look at them one by one.

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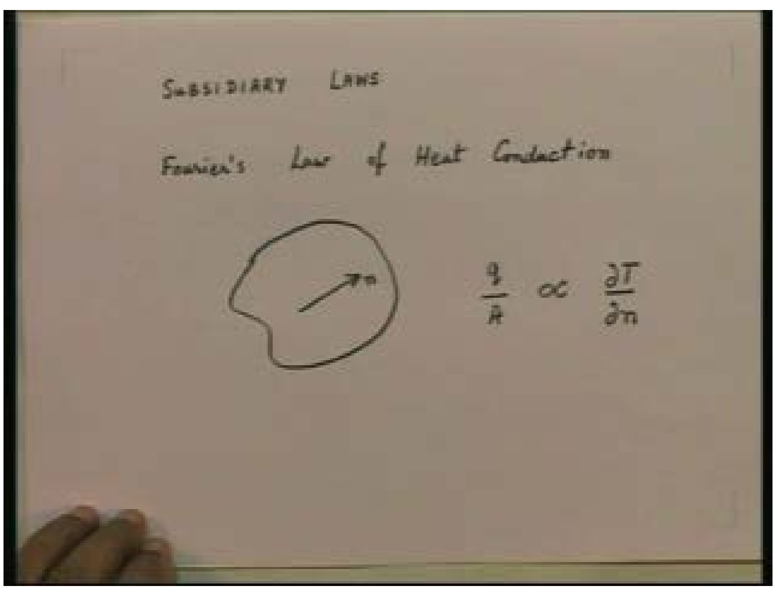

First, Fourier's law of heat conduction-the statement of the law is like this. Let us say I have some material, it doesn't matter which it is, let us say a solid and there are temperature variations in this material. So, we know heat will flow in the direction of decreasing temperature. Let us say I have some direction n; i have marked some direction n in this material. Fourier's law of heat conduction states that the heat flux q by A is proportional to the heat flux by conduction in a particular direction n - in any arbitrary direction n - inside the material is proportional to the gradient of temperature in that direction. That is Fourier's law of heat conduction. So, if I want to remove the proportionality sign, then the statement of the law would be the following.

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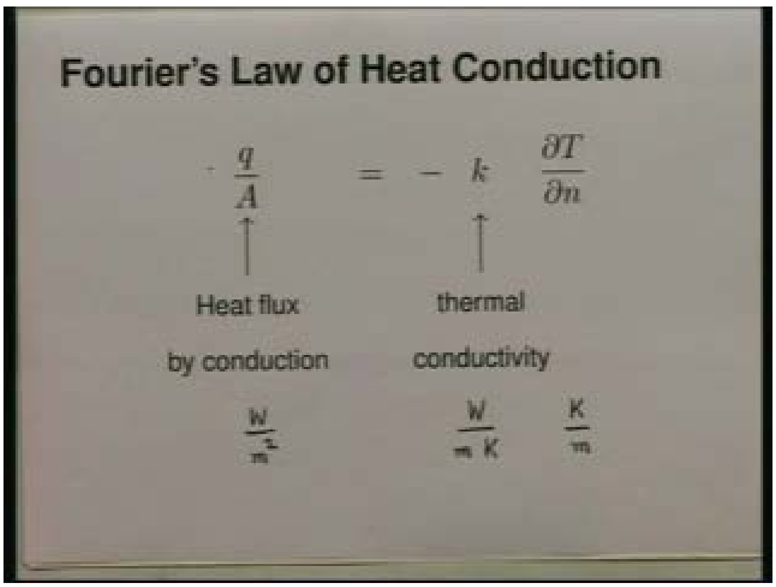

I would get q by A is equal to proportionality constant k multiplied by dt dn. Now, notice I have put a negative sign there and i will talk about the need for that sign in a moment but first let us look at the units of the quantities involved. q by A is the heat flux by conduction in a particular direction. q by A stands for the heat flow rate per unit area. So, it will be in watts - the units would be always watts - per meter square. The gradient of temperature dt dn would be in degrees Kelvin per meter. It follows therefore that the units of the proportionality constant which we call the thermal conductivity of the material would be: thermal conductivity would be expressed in the units - watts per meter Kelvin. The conductivity of a material is measured in watts per meter Kelvin.

And what is conductivity? It is a measure of the ability of the heat of the material to conduct heat that is what thermal conductivity is. Why do we put a negative sign? Because heat flows in a direction of decreasing temperature. So, in order to make the heat flow positive in the positive direction - since the dt dn would be automatically negative if it is to flow in the positive direction - we put a negative sign. This serves to make the heat flux vector positive in the positive n direction. So, that is the purpose of the negative sign; it is a convention adopted by everybody. So, Fourier's law of heat conduction says q by A is equal to minus k dt dn where n is any arbitrary direction inside the material under consideration. Now, suppose I want to make this statement for some coordinate system. Let us say I want to make this statement for a cartesian coordinate system.

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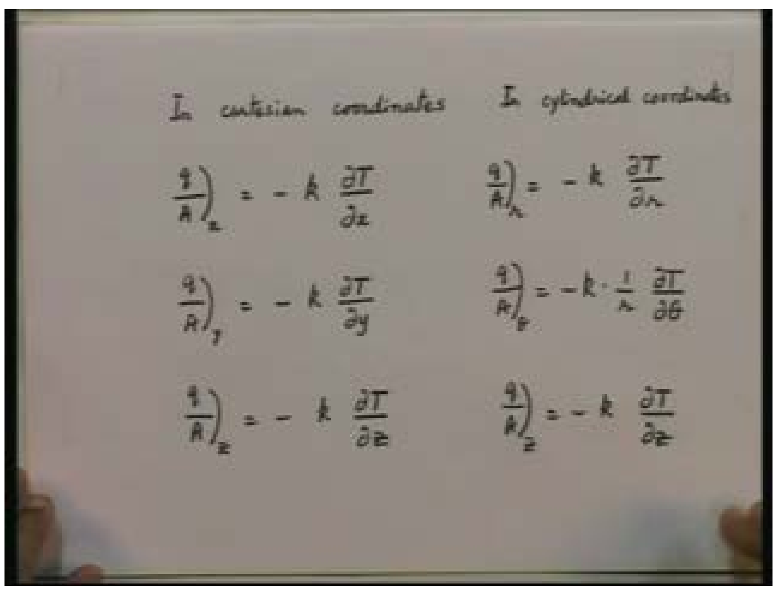

Let us take a cartesian coordinate system and for a cartesian coordinate system I would get - in cartesian coordinates, the statement of Fourier's law would be q by A in the direction x is equal to minus k dt dx. q by A in the direction y is equal to minus k dt dy and q by A in the direction z is equal to minus k dt dz.

Or in any other coordinate system, for instance suppose instead of cartesian coordinates x y z system I have cylindrical coordinates. I am dealing with the cylindrical coordinate system. In cylindrical coordinates, the statement of Fourier's law would be q by A in the r direction - cylindrical coordinates are r theta z - q by A in the r direction is equal to minus k dt dr in the radial direction. q by A in the theta direction is equal to minus k into 1 by r dt d theta. Notice theta is an angle so I need a distance r d theta and q by A in the z direction is equal to minus k dt dz r theta z. Similarly, I could write the statement of Fourier's law for any other coordinate system as well.

You would have noticed that I am using the same symbol k for thermal conductivity for all directions - whether it is x direction, y direction, z direction. What in effect I am assuming is that at a particular point in the material, whether heat flows in one direction - the x direction, the y direction or the z direction - the value of k in all directions is the same. That is what I am assuming when I use the same symbol k. This assumption means that i am assuming the material to be what is called as an isotropic material. So, the statements I am writing down are for an isotropic material. The value of k at any point is the same in all directions. However, notice k may vary from point to point but at any given point, regardless of the direction, the value of k is the same; that is what we mean by isotropic material.

Now when Fourier originally stated his law of conduction - heat conduction - he thought k would be a constant for a particular material - say for copper you have one value of k, for steel you have one value of k and so on. It turns out that k is not all that fixed a number for a particular material.

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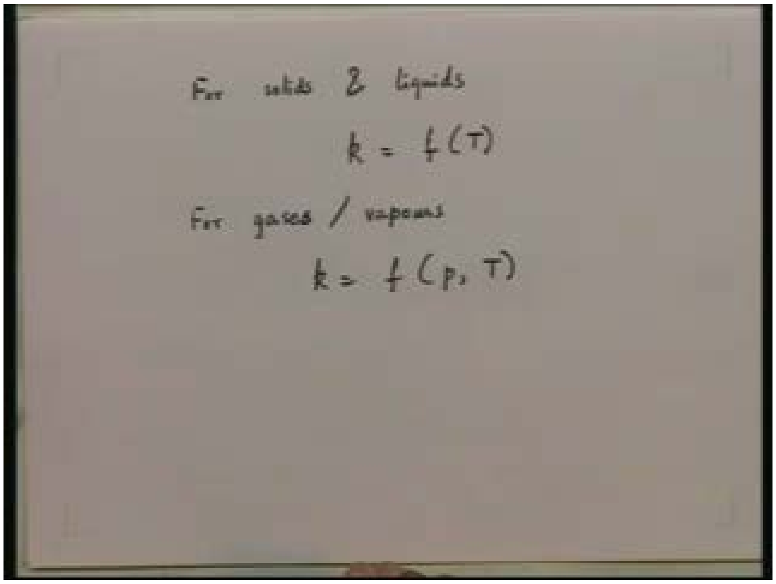

Generally, for solids and liquids, k is a function of temperature for solids and liquids; k is a function of temperature and for gases like air, for gases or vapors like steam say, k is a function of pressure and temperature. In many applications however, the variation of k over the range of temperatures associated with that application is quite small. So, very often, what we do is - though we know k varies with temperature, we use a constant value which corresponds to the average temperature of that particular situation we are dealing with. So keep this in mind; so though k varies with temperature for solid and liquids, we will very often use an average value - a value corresponding to the average temperature - which is occurring in that particular situation with which we are dealing. Now, it is useful to have some feel for the values of k that we encounter for different materials.

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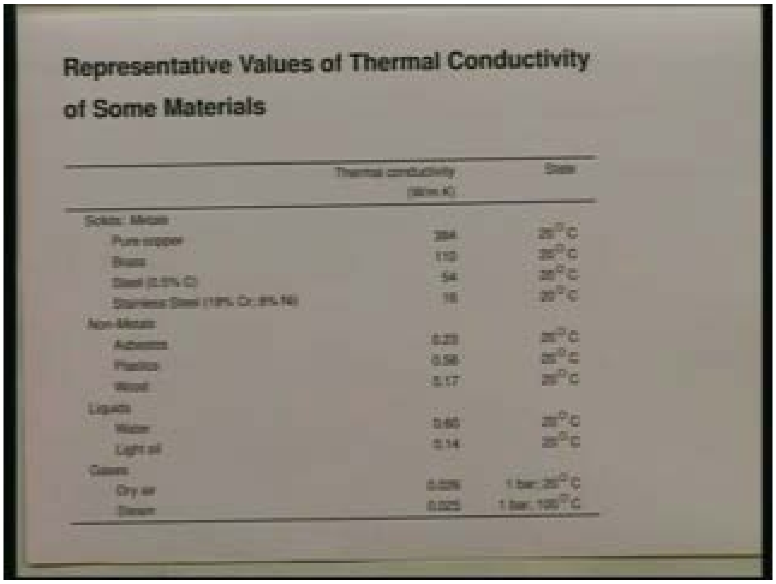

And i want you to look at this tabes in order to get that feel for the values of k. What I have done here is - I have listed the values of k first for solids then for two liquids then for two gases and vapors. In the case for solids, first I have given for metals, the first four values are for metals. Starting with a very pure metal like pure copper, then brass which is an alloy of copper and zinc, then steel and then stainless steel. Notice that for a very pure metal - pure copper - the value for k is in hundreds in the units that we are talking about, watts per meter Kelvin. three hundred and eighty; for pure aluminium it will be something like two hundred and fifty or something like that. The moment I have an alloying material like in brass or in steel or in stainless steel, the value of k drops and typically the value may drop to as low as about ten watts per meter Kelvin. So, the range for metals is all the way from about ten or twelve all the way up to three hundred. The highest values being for very pure metals and the lowest values for alloys like stainless steel.

Non-metals like say - what are listed here is asbestos .23, plastics .58, wood .17. Non-metals like this typically have values of k in the range of .1 to 1. Liquids - water .6, light oil .14, liquids like water and oil will also have values in the range of .1 to 1 and gases like dry air .026, steam at 1 bar and 100 centigrade .025, will haves value which are typically .02, .03, .04. So, you see the wide range of ks that we get in practice. In metals, anything from 10 to few 100; the highest value is very pure metals. Non-metals .1 to 1, liquids .1 to 1, gases and vapors less than .1 typically .02, .03, .04. So, keep these orders of magnitude in mind because in future as we go along, we may find it useful to use these orders in order to judge the magnitude of a quantity that we are dealing with.

So, keep this orders of magnitude in mind when, we as we go along. Exact values for a given metal - you can always get from a handbook. There are measurements made of these; all the metals and non-metals and materials that we use, people have extensive measurements of the thermal conductivities. So, there are whole handbooks on this to get exact values, but approximate values, it is important to keep approximate values in mind for doing rough calculations. Now let us move on to the next subsidiary law and the next subsidiary law is Newton's law of cooling. Newton's law of cooling states the following. Let us look at Newton's law of cooling.

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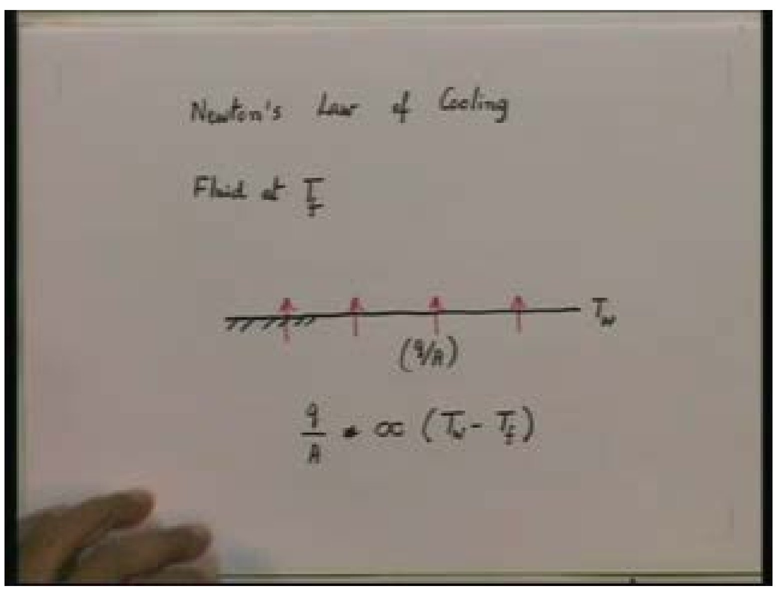

Newton's law of cooling states the following; it says that - suppose I have some surface, some solid surface and that solid surface let us say is at a temperature T_{w}. Let us say there is a fluid - air typically or water - at some temperature T_f in contact with this solid surface; a fluid at a temperature T_f in contact with this solid surface. The two temperatures are different, so heat is either going to flow from the wall to the fluid if T_w is greater than T_f ; it is going to flow from the fluid to the wall if T_f is greater than T_w Newton's law of cooling states that the heat flux by convection from the wall to the fluid or from the fluid to the wall is proportional to the temperature difference T_w minus T_f proportional to T_w minus T_f - that's the statement of Newton's law. Although it is called the law of cooling because Newton did his original experiments to cooling of spheres which were heated; really speaking the law applies either way - heat may be flowing into the solid body or out of the solid body. It doesn't matter. Statement of the law is the heat flux by convection is proportional to the temperature difference. Now, if I remove the constant of proportionality I get an equation and the equation I get is of the following form.

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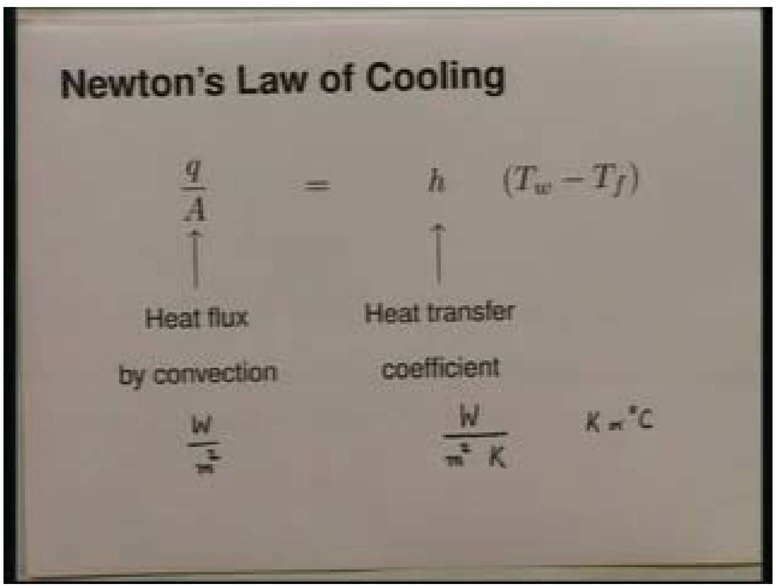

I get the equation q by A is equal to h into T_w minus T_f ; q by A is the heat flux by convection; T_w minus T_f is the temperature difference between the value and the fluid and h - the constant of proportionality - is called the heat transfer coefficient. So, let us look at the units again. q by A would be heat flux - heat flow rate per unit area, watts per meter square; temperature difference T_w minus T_f would be in degrees Kelvin or degree centigrade. Doesn't matter which one, it is a temperature difference - it will be numerically equal. And therefore, the units of h would be watts per meter square Kelvin. Those will be the units of h.

By definition, h is a positive number; it is always positive. So, if let us say heat is flowing from the wall to the fluid that is T_w is greater than T_f ; heat is flowing from the wall to the fluid. I will put T_w minus T_f here. If on the other hand heat is flowing in the reverse direction, then instead of T_w minus T_f , I will put T_f minus T_w and ensure that h will always come out to be a positive number. So by definition, h is always a positive quantity. Keep that in mind. Now, when we define this quantity, it is useful also to talk a little bit about the fluid flow classification.

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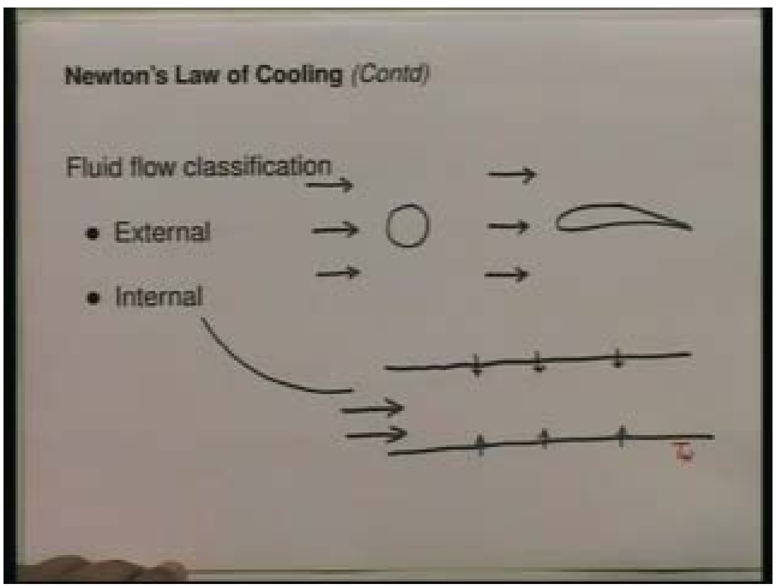

I just said there is a fluid in contact with that wall; it is useful to classify the fluid flow taking place above that solid surface as being either an external flow or an internal flow. What do we mean by that? An external flow is a flow which, say for instance, is around going around a tube. Let us say, I have some tube like this and there is a flow of air or water over this tube; that's an external flow. Or let us say I have an aerofoil cross-section like this of a plane - typically of a plane - again a flow over that aerofoil would be an external flow. An external flow is one which once you go a little far away from the surface is more or less infinite in extent. So that if I have say a temperature and a velocity associated with that flow far away from this solid surface, I will attain that temperature and velocity T_f , V_f typically.

On the other hand, an internal flow is a flow which is inside a tube. For instance, let us say I have a tube like this and I have water flowing inside this tube and the wall is at some temperature T_w so that the wall of the tube is at some temperature T_w so that heat flows from the wall to the fluid. Now, this is called an internal flow. I think the two words sort of tell the story. Now, let us look a little bit more at an external flow for a moment.

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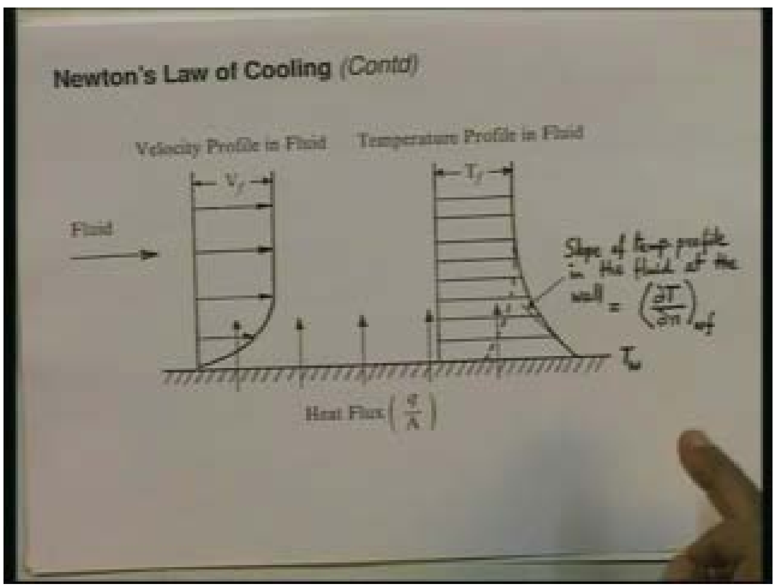

Here is the picture here which I am projecting now shows an external flow. Here is fluid which is flowing over a wall; this wall could be the surface of an aerofoil. It could be the surface for some flat surface over which flow is taking place; it doesn't matter. This fluid is far away from the wall, is at a temperature T_f and at a velocity V_f and it is flowing over this wall. Now the velocity and temperature profile of this fluid near a surface would look something like this. Close to the surface; at the surface, the velocity has to be zero; as we go little further away from the surface the velocity of the fluid will go on increasing. Then, it will gradually merge asymptotically into the free stream value V_f . Temperature at the wall, the temperature would be the wall temperature T_w and far away from the wall the temperature of the fluid will gradually emerge asymptotically into the fluid temperature T_f .

So, the two profiles of fluid - velocity profile and temperature profile is something like this. If T_w is less then T_f , then the temperature profile instead of going out like this would typically come in something like this. That would be a temperature profile you will get if T_w is less than T_f and heat flows because of this temperature difference. The tangent that I have drawn here is the tangent to the temperature profile at the wall. So what we have here is the slope of temperature profile tangent, is the slope of the temperature profile in the fluid at the wall. That is what we have got here and we can give; symbolically write it as equal to dT dn. n is the normal direction to the wall bracket at the wall w in the fluid wf. w stands for the wall and f stands for the gradient in the fluid. So, dT dn wf would be the slope of the temperature profile in the fluid at the wall.

Now, given this situation notice right at the wall the fluid is stationary; so right at the wall pure conduction is taking place in the fluid because the fluid is stationary. Therefore, this gives us a means for stating the Newton's law of cooling in another manner at the wall.

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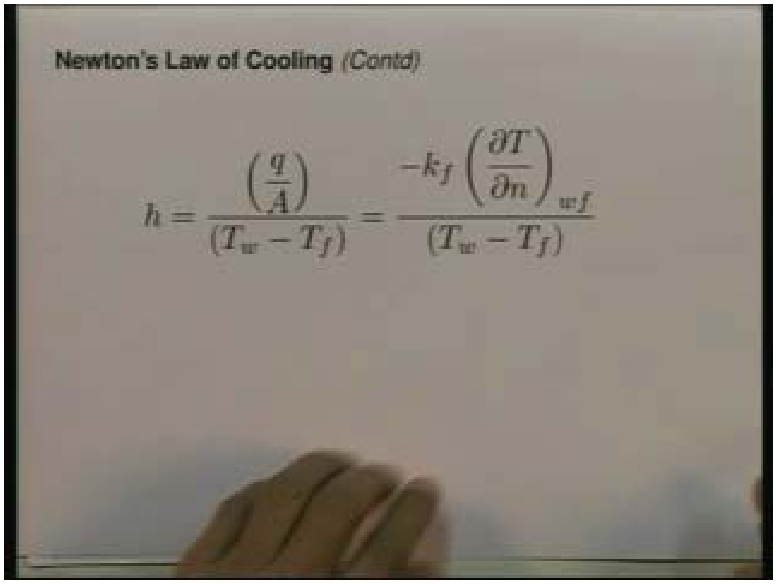

We can say q by A, h is equal to q by A upon T_w minus T_f - that's our definition, Newton's law of cooling. But q by A at the wall is nothing but - from Fourier's law of heat conduction, minus k_f dt dn at wf where dt dn and wf is the gradient of the temperature profile in the fluid at the wall and kf is the thermal conductivity of the fluid. k_f is the thermal conductivity of the fluid. So, we are using for the numerator now, Fourier's law of heat conduction, because we know that right at the wall pure conduction is taking place; the fluid is stationary. So the numerator which stands for the heat flux by convection can be converted to this expression by applying Fourier's law of heat conduction at the wall and we get therefore this alternative definition of the heat transfer coefficient or an alternative statement of Newton's law of cooling.

Now, just as in the case of thermal conductivity, it is useful to have a feel for some approximate values for the heat transfer coefficient that we will encounter in practice. When Newton originally stated his law of cooling, he thought that the heat transfer coefficient would be some constant quantity but in fact the heat transfer coefficient is a very complex number. It depends on the properties of the fluid that we have; properties like viscosity, thermal conductivity, density, etcetera of the fluid, specific heat all these influence the value of heat transfer coefficient. It depends on the shape of the surface over which the flow is taking place and it also depends on the nature of the surface whether it is rough surface or a smooth surface and on some other factors as well; the law it also depends of course on the velocity of fluid. If I have no velocity, I have no heat transfer coefficient; higher velocities give me higher heat transfer coefficient.

So, the heat transfer coefficient is very complex function of a variety of parameters; not really a constant. You can't say h is so much for water or h is so much for air. No, you can't do anything like that. We need to develop equations for h for a variety of situation. That is really what the study of convection is all about - getting these equations so that we can calculate h for a variety of situations. Now however, it is again useful to have a feel for the magnitudes of h that we will encounter in practice and let us look at this table which I am projecting now.

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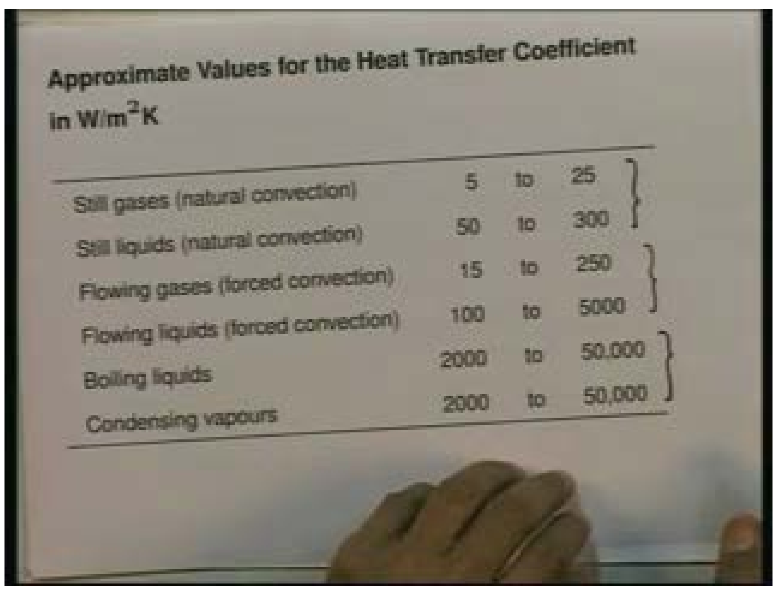
Approximate Values for the Heat Transfer Coefficient in W/m^2K

Still gases (natural convection)	5	to	25
Still liquids (natural convection)	50	to	300
Flowing gases (forced convection)	15	to	250
Flowing liquids (forced convection)	100	to	5000
Boiling liquids	2000	to	50,000
Condensing vapours	2000	to	50,000

Here are some approximate values for the heat transfer coefficient in the units - watts per meter squared Kelvin; that is the unit. This is the set of units which we will always use for heat transfer coefficient at the SI system of units. The first two values are for still gases or still liquids; that is situations which we have defined earlier as those of natural convection. If I have natural convection heat transfer to a gas, the values of h will typically be in the range from about 5 to 25. 5 would be for low temperature differences; 25 for higher temperature differences between the solid surface and the fluid. If instead of gases, I have liquids - still liquids - then in natural convection, typical values of h will be from above 50 to above 300. Again, the value depends on the thermal conductivity of the liquids; for water typically values like 100 200 are typical; for oils values like 50 or 75 may be typical and also of course the value depends on the temperature difference between the water; between the liquid and the surface.

The moment we have flow - the next two lines - the moment we have flow, we have situations of forced convection. With gases – flowing gases - values typically range from about 15 to about 250; the low values for low velocities, high values for very high velocities; for liquids 100 to as much as few thousand, five thousand, typical. The low values for low velocities of the liquid, the high values for high velocity values. And then with a change of phase that is if I have a situation in which I give heat so that the liquid boils or I give, take away heat so that a vapor is condensed, the change of phase situation - boiling or condensation. Typically the values of h are extremely high, always in thousands, generally always in thousands. Typical values will range from about 2000 to above 50000; as high as 50000, 10000, 20000, 30000. So again, keep these magnitudes in mind.

The first two lines are for situations of natural convection to gases and liquids; the next two lines are the ranges that we encounter in forced convection and the last two lines are the ranges that we would encounter with change of phase that is with boiling liquids or with condensing vapors. We will use these orders of magnitude from time to time in order again to develop a feel for situations that we encounter in practice.

The third law, the third subsidiary law which we want to talk about is a law of radiation and the particular law which we want to now state is the Stefan Boltzmann law.

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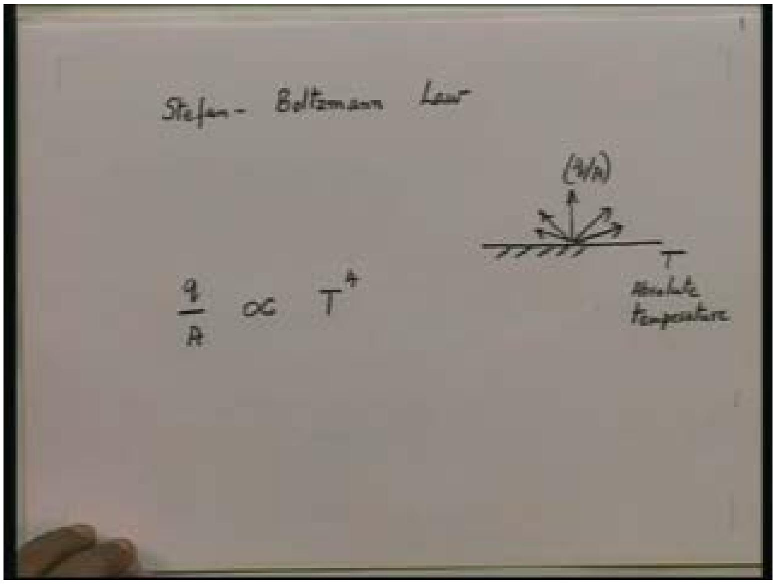

The Stefan Boltzmann law states that if I have a surface which is at a temperature which is at an absolute temperature T, then that surface will emit thermal radiation and the thermal radiation heat flux will be - is proportional to the fourth power of the absolute temperature of that surface. So if I have a surface; let me draw a surface and let us say it is at an absolute temperature T. Note the word now; I am saying it is an absolute temperature that is in Kelvin; an absolute temperature T. Then every element of that surface will emit radiation - thermal radiation - in the form of electromagnetic waves in all directions and this heat flux due to thermal radiation is proportional to the fourth power of the absolute temperature of the surface; that is the statement of the Stefan Boltzmann law. Units would be the following.

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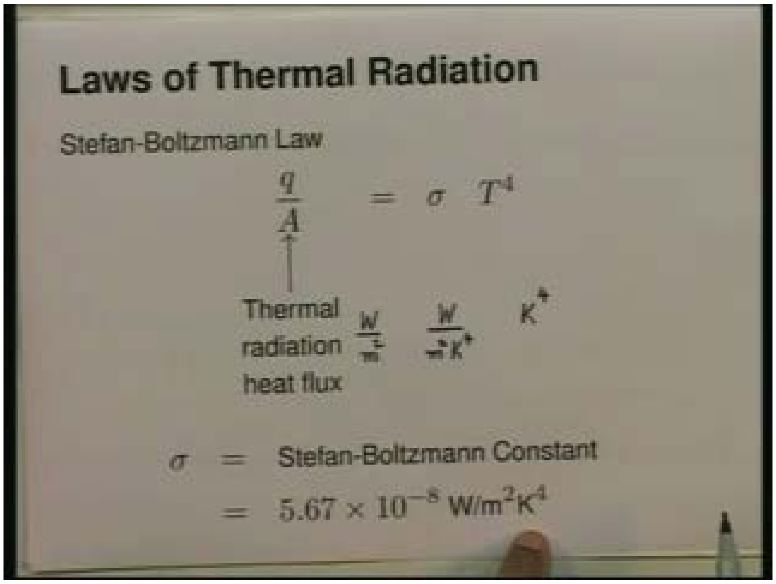

If I remove the proportionality sign and put in a constant, the statement of the law will become q by A is equal to sigma into T to the power four. q by A would be in watts per meter square; heat flux due to thermal radiation; T to the power 4 would be Kelvin to the power of four - absolute temperature to the power of 4. So the proportionality constant sigma which is called the Stefan Boltzmann constant - the units of that would be watts per meter square Kelvin to the fourth. And from experimental data the value of sigma as been determined to be 5.67 into 10 to minus 8 eight watts per meter square Kelvin to the power of 4. This is the value of the Stefan Boltzmann constant.

The nature of the Stefan Boltzmann law q by A proportional to the T to the power of four was derived by Stefan and Boltzmann based on certain considerations, thermodynamics, etcetera. The constant comes from experimental data – 5.67 into 10 to the minus 8 watts per meter square Kelvin to the power of 4. This is the law of radiation say subsidiary law of radiation which we will use quite often but it is not the only law mind you. We have apart from this; we have number of other laws in radiation let me just mention them here.

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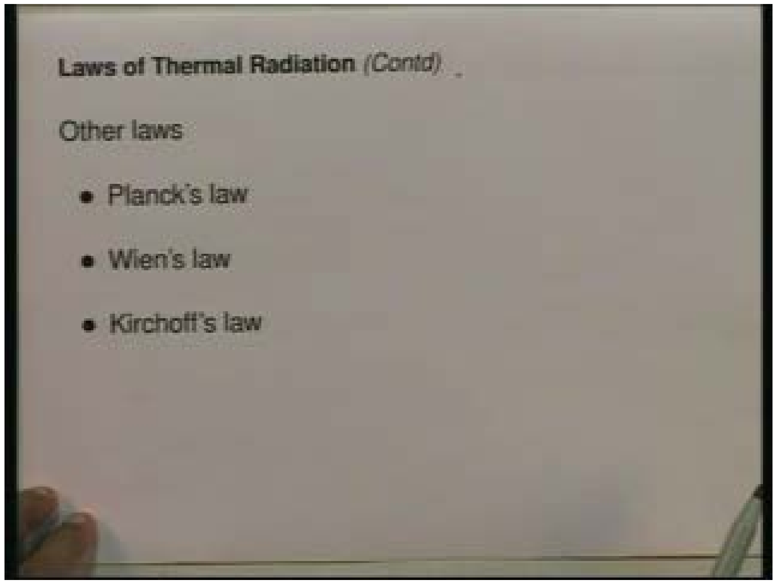

The other laws of radiation that we have are Plank's law, Wien's law and Kirchoff's law and we will be mentioning these, stating these and using all these when we come to our chapter on thermal radiation. Right now, I am saying these laws will also be taken up later; there are also important laws. The most commonly used law is of course the Stefan Boltzmann law which I have stated for you. So, we have gone through now three subsidiary laws; we will use these quite frequently and that is why I wanted to mention them to you but I again repeat a subsidiary law will be used depending upon the nature of the situation we are dealing with. It is not compulsory that I have to satisfy a subsidiary law always.

There are other subsidiary laws also in mind; keep that in your consideration. For instance, I may need an equation of state; i may need Stoke's equation relating stress and rate of strain and so on. So there are other subsidiary laws; we may also use those from time to time if we need them; that is one thing. The second thing which I want you to note is that these subsidiary laws are based, are empirical in nature and are based partly on experimental evidence. Now, let us do one simple problem to illustrate ideas.

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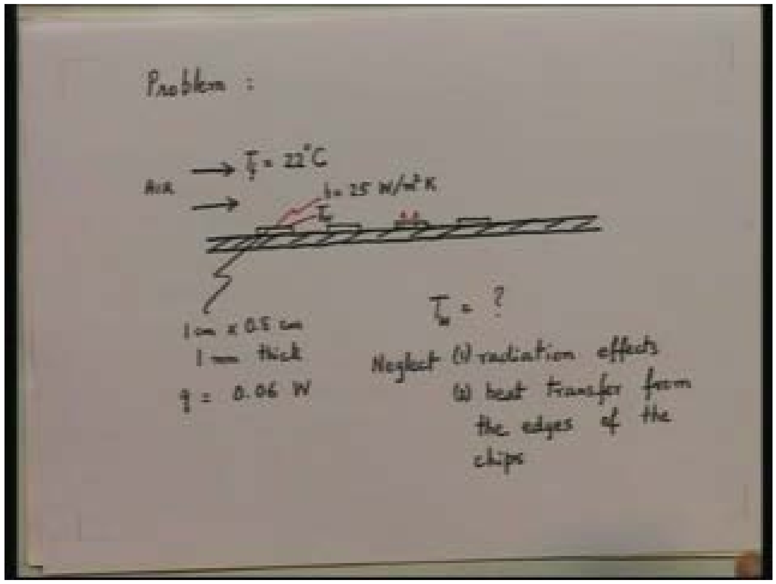

I want to take up a problem of cooling of chips - electronic chips; a numerical problem. The problem is the following which I want to look at. Let us say I have an insulating board and on this insulating board I have a number of electronic chips fixed like this. And let us say the dimension of a chip is 1 centimeter by .8 centimeters and it is 1 millimeter thick. Each chip is of this size - a rectangular chip 1 centimeter .8 centimeters and a millimeter thick and obviously some heat as been generated and let us say the quantity of heat being generated in each chip q is .06 watts; this is the rate at which heat is being generated in each chip.

Now in order to keep the chip cool I have already, you recall when I talked about problems of interest towards the heat transfer as a cooling of electronic chips is one such application in which we are very much interested. In order to keep the surface temperature of this chip down to some particular value, we have here air flowing over this chip and let us say it is an external flow let us say and T_f the temperature of the air is equal to 22 degrees centigrade. You are told that the value of h at the surface of this chip, the heat transfer coefficient is 25 watts per meter square degrees Kelvin; that is the value of h.

So you know the dimensions of each of the chips; you know the amount of the heat being generated, rate at which heat is being generated in each chip. The temperature of the air which is flowing over the chip to keep it cool, the value of the convective heat transfer coefficient at the surface of the chip that is given. We don't know enough theory of convection so instead of calculating it from any equation I am just giving you a value of h; say take it to be 25. Thus, calculate the temperature surface temperature of the chip. The surface temperature of the chip would be some value T_w and the problem is what is that value for this given situation. You are also told while doing the calculation - neglect effects of radiations; neglect radiation effects.

One, that is one quantity. Two, neglect heat transfer from the edges of the chips. These are the edges the one millimeter thickness all around. So assume that all the heat that is being generated is flowing out by convection through the 1 centimeter by .8 centimeter that means all the heat is flowing out like this. Neglect any heat flowing out through the edges and neglect radiation effects; this is for simplifying the problem. If you take that into, if you have to take it into account, it is going to be more complicated situation.

So, it is a straight forward situation. First of all before calculating T_w with the help of Newton's law of cooling, notice the value of 25. What does 25 mean? 25 means we have a typical value of h for forced convection to air that is the first thing to notice; so at a natural convection situation, we have a typical value of h which we will get with forced convection to air; that is the first thing to notice.

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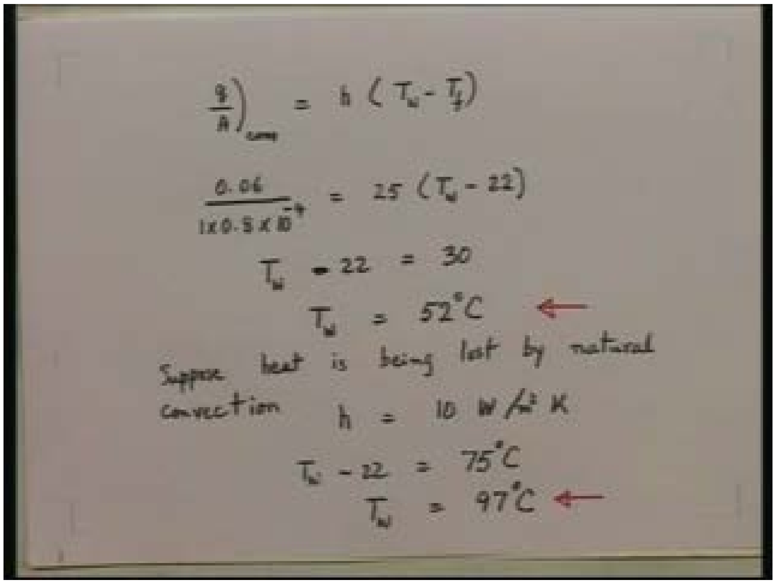

Then, what will be that value of T_w that we will get? If I apply Newton's law of cooling, I have q by A by convection is equal to h into T_w minus T_f . So, if I simply now substitute the data, I will get .06 watts. I am assuming that heat transfer radiation can be neglected so .06 is all lost by convection so .06 divided by 1 into .8 so many square centimeters into 10 to the minus 4 gives me so many square meters. So I get watts per square is equal to the value of h – 25 - into T_w minus 22 and since I am putting in degrees centigrade my answer for T_w would come in, T_w minus 22, let me put it like this, will be coming out to be 30 and T_w would be 52 degrees. So the value of w Tw would be 52 degrees centigrade.

Suppose, instead of losing heat by forced convection, heat was being lost by natural convection just for sake of argument. Suppose heat is being lost by natural convection not by forced convection. What is the typical value of h? In natural convection, a typical value of h might be say 10 watts per meter square Kelvin - typical value of h. So what would I get now? With ten I will get T_w minus 22 would be 75 degrees centigrade and T_w would be 97 degrees centigrade. So, if it is a forced convection situation, the answer that I got earlier was T_w equal to 52 centigrade. If I have a natural convection situation the value of T_w would be 97 degrees centigrade.

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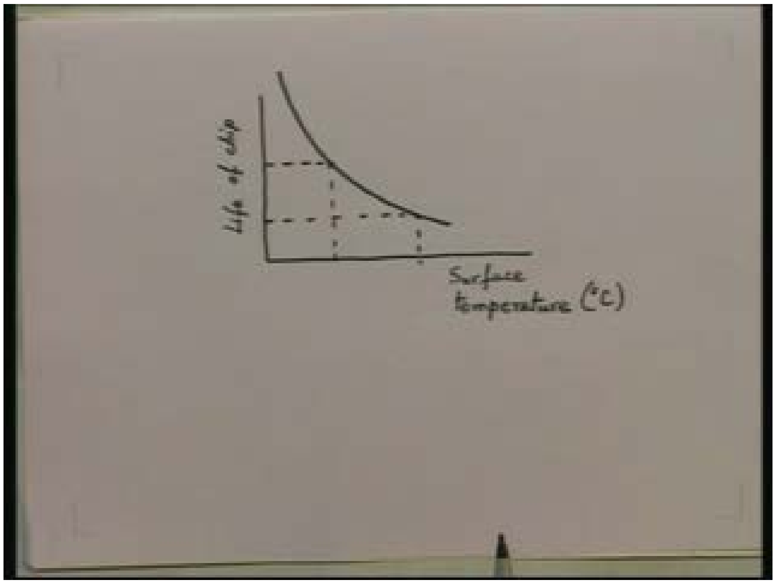

Now 52 and 97 - numbers like these have a great deal of significance because if I were to plot a graph of the life of the chip against the surface temperature - let us say I have surface temperature here; suppose I have surface temperature here in degrees centigrade and here I plot the life of the chip in let us say thousands of hours of operation. Then typically, I might have a graph which might look something like this: with a temperature like 52, I might have a value somewhere here; this might be a typical value at say 52. At 97, the typical value might be somewhere here. At 52, the number of hours of operation that I get might be quite enough, say 10000 hours. At 97, the value that I might get would be much less than what I need. So going from 52 to 97, if the temperature does go up or stays at 97 for long enough time, I might reduce the life of the chip to a value below what is desirable for continuous safe operation of the chip.

In fact, typical temperatures that we need for chips - surface temperatures - are in the range of 50 to 60 degrees centigrade. We don't like temperature 60, 70 or much higher. The moment we reach temperatures like 90 or 100 for surface that is not a good sign because a high surface temperature means a still higher temperature inside the chip. The surface if it is 100 or 97, inside the chip where the heat is being generated, temperature will be another 10 or another 15 degrees centigrade more. So, a temperature like 50 or 60 may be acceptable; temperatures like 97 would probably not be acceptable at all.

Right now, we did this problem neglecting radiations; we will be in a position to do the same problem later considering radiation effects as well. Keep that in mind. Right now we have neglected radiation; the moment we have taken up radiation we will be in a position to take up the radiation effect itself and see what is the effect on this answer of 52 or 97. The moment we study natural convection, instead of taking a value of h equal to 10, we should be able to put in an equation for an expression for calculating h rather than just saying its approximately 10. The moment we study forced convection, we will be in a position to put down a value for h for forced convection which will be a better value than the rough value of 25 that we have put.

So, keep in mind, right now we have done an overall study of this problem; we have neglected radiation, we have assumed two values of h - one for forced convection and natural convection. As you go along and study this subject more, you will be in a position to calculate the value of h more accurately. You will be able to take account of radiation effects and in fact, if you start getting more sophisticated, you can even take account of the values of edge effects and consider heat loss even from the edges. So, the problem can be solved even more accurately as we go along and study the subject more.

Now, let me ah conclude today's lecture as well as this whole topic by a summing of what we have done in this whole topic - the first three lectures which we called as the introduction. First of all, remember, we described various problems of interest to us in heat transfer. I described for you the problems like the insulation round a pipe, heating of water - cooling water - as is flowing in a tube, heating of steel strip as it is passing through an electrical furnace, the cooling of electronic chips. These were various problems I described to you and in fact we took up the electronics chips problem again today.

Having done that, we discussed various modes of heat transfer – conduction, convection and radiation. Then we took up one particular device. What was that? That was the solar flat plate collector and my purpose in taking it up was to show how various modes of heat transfer are occur in one device. It is not as if a situation is there in which we have only conduction or only convection. Very often all the things occur together; we need to consider them simultaneously; we did that also.

Then we came to the laws of heat transfer and I said to you the laws that we consider which lay the foundation for our subject and will be used by us can be broadly classified as of two types - fundament laws and subsidiary laws. Fundament laws are laws that we must always satisfy regardless of the problem that we have at hand. We cannot ignore a fundament law and what were our fundament laws? Our fundament laws were the law of conversation of mass or continuity as we called it, Newton's second law of motion and the first law of thermodynamics. You have to satisfy these - whatever be the situation that you are dealing with. You have to satisfy them either by considering a closed system or you have to satisfy them by considering flow through a control volume. Typically, if it is a conduction problem in a solid, you will take a closed system approach; if you are looking of flow of fluid – water, air flowing through a pipe, over a pipe, outside a pipe, etcetera - you will typically take a control volume approach. Whatever it is, you have got to satisfy your fundament laws.

The other set of laws which we will use depending upon our convenience are the subsidiary laws and we stated three of them which we will use depending upon our needs. What are the three? We stated Fourier's law of heat conduction; we stated Newton's law of cooling and we stated the Stefan Boltzmann law of thermal radiation. There are other laws of radiation; we will take them up later but these are the three subsidiary laws which we will use most often and therefore I stated them for you today. In each case, I gave a statement of the law; I defined a constant which comes out of the proportionality of that law. Heat flux is proportional to something and we get a proportionality constant; in the case of Fourier's law of heat conduction – it is thermal conductivity; in the case of Newton's law for cooling – it is heat transfer coefficient and in case of Stefan Boltzmann law - it is the Stefan Boltzmann constant. And for these quantities - thermal conductivity, heat transfer coefficient - we talked a little about them; talked about how they vary and gave some representative values which we will encounter in practice in the case of thermal conductivity for various materials and a heat transfer coefficient for various situations like natural convection, forced convection, change of phase, etcetera. Next time, we will start with our study of conduction. Thank you