Refrigeration and Air conditioning
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Lecture No. # 7
Fundamentals of Heat Transfer

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Welcome to the seventh lecture. In this lecture we shall review the fundamentals of heat and mass transfer.

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So the specific objectives of this lesson are to present equations for basic modes of heat transfer namely conduction radiation and convection, introduce the concept of thermal resistance, discuss analogy between heat mass and momentum transfers and discuss multimode heat transfer and finally introduce heat exchangers.

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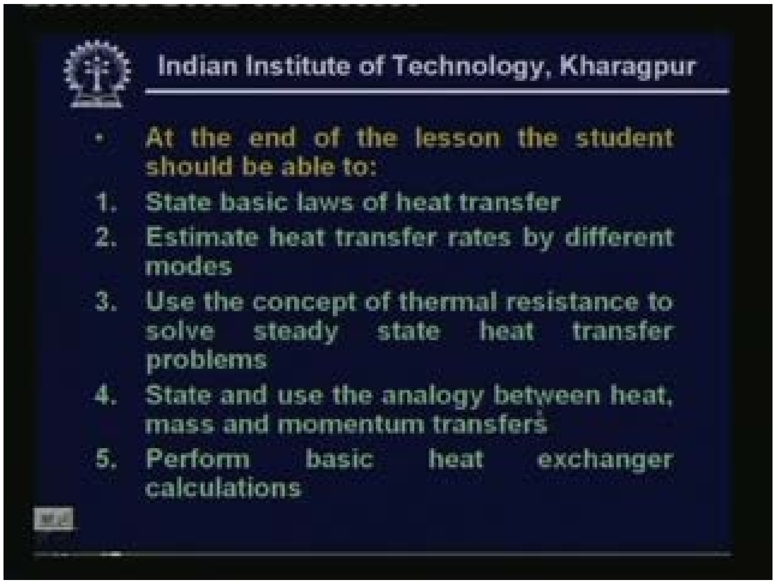

So at the end of this lesson you should be able to state basic laws of heat transfer, estimate heat transfer rates by different modes, use the concept of thermal resistance to solve steady state heat transfer problems, state and use the analogy between heat mass and momentum transfers and perform basic heat exchanger calculations.

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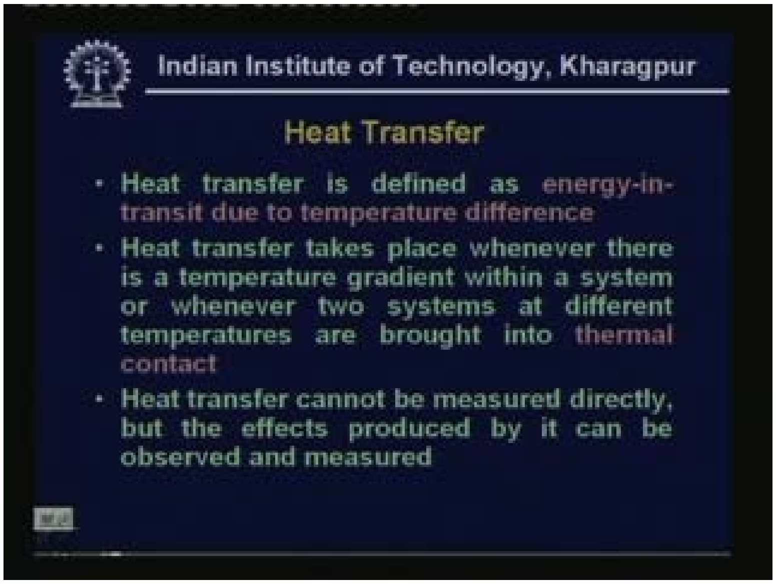

So let us look at heat transfer as we have seen in thermodynamics heat transfer is defined as the energy in transit due to temperature difference. And heat transfer takes place whenever there is a temperature gradient within a system or whenever two systems at different temperatures are brought into thermal contact. Heat transfer cannot be measured directly but the effects produced by it can be observed and measured for example when heat transfer takes place. Some property of the system will change for example the temperature may change or some other property will change. So by measuring the property or by observing the property we can say that heat transfer has occurred.

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All heat transfer processes must obey the first and second laws of thermodynamics because basically heat transfer is nothing but energy in transit. So they have to obey the first and second laws of thermodynamics. But in addition to the first and second laws of thermodynamics we also have to apply certain rate laws of heat transfer to estimate the heat transfer rates. And estimating rate of heat transfer is a key requirement in the design and analysis of any refrigeration or air conditioning system.

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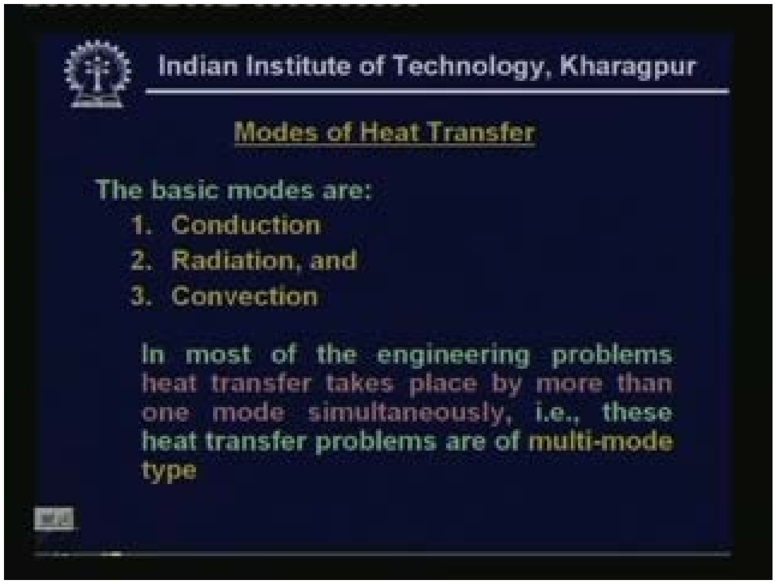

Now let us look at the basic modes of heat transfer as you know probably the basic modes are conduction radiation and convection. Even though we treat them separately we find that in most of the engineering problems heat transfer takes place by more than one mode simultaneously. That means you have what is known as a multi mode heat transfer in most of the engineering problems. But when we are treating the subject for initially we treat them separately and then we see how to club them when they are occurring simultaneously.

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Now let us look at conduction heat transfer. Conduction heat transfer takes place whenever a temperature gradient exists in a stationery medium and on a microscopic level conduction heat transfer is due to on the elastic impact of molecules in fluids and in solids it is due to the molecular vibration and rotation about their lattice positions and also due to the migration of free electrons.

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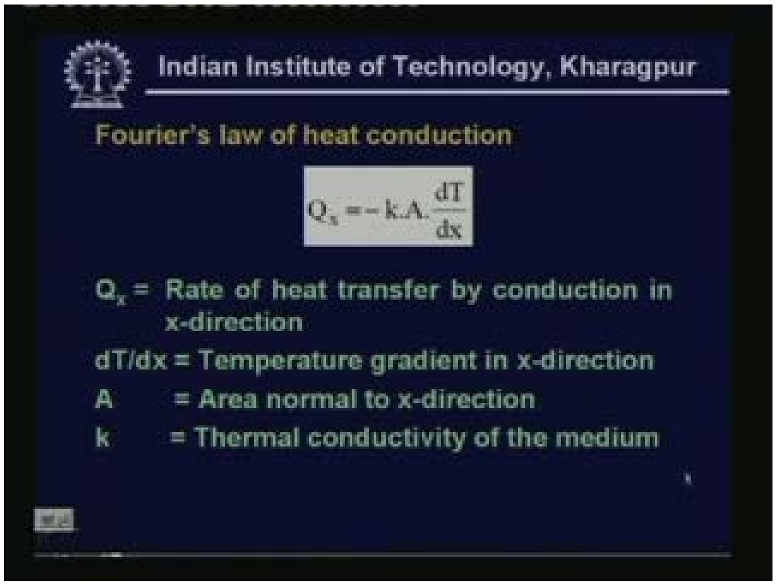

So let us look at the Fourier's law of heat conduction. This is the basic law of heat conduction and it is an empirical equation. So that means you have it is the, it does not have any derivation but it is based on the observations. So this is the fundamental law of heat conduction. Okay. So this law relates the heat transfer rate by conduction with temperature gradient and area of cross section. As you can see that according to Fourier's law of heat conduction, heat transfer rate in a di in x direction is equal to minus k A d T by d x where d T by d x is a temperature gradient in x direction and A is the area normal to x direction and k is the property of the medium and it is called a thermal conductivity.

And if you want find out the heat transfer rate obviously we need to know the temperature gradient. That means we should know the function of temperature I mean temperature as a function of spatial coordinates. Then you can find out the heat transfer rate by conduction provided. You know the thermal conductivity and also the heat transfer area and the negative sign in this equation is a consequence of second law of thermodynamics. As you know very well the second law of thermodynamics says that heat transfer takes place spontaneously from a system of high temperature to the system of at low temperature. That means d T by d x will always be negative as decided by the second law of thermodynamics. So if you want to make Q x as positive you have to have this negative sign. So the negative sign is a consequence of second law of thermodynamics.

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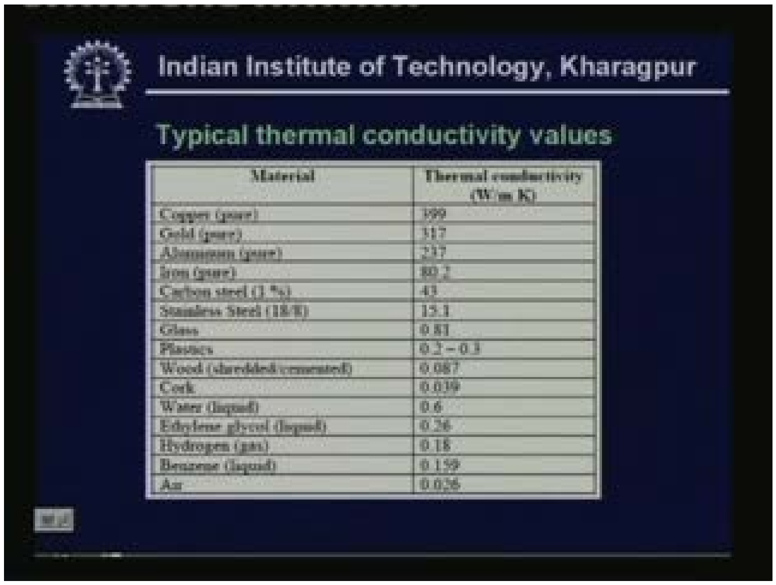

Material	Thermal conductivity (W/m K)
Copper (pure)	399
Gold (pure)	317
Aluminum (pure)	237
Iron (pure)	80.2
Carbon steel (1 %)	43
Stainless Steel (18/8)	15.1
Glass	0.81
Plastics	0.2 – 0.3
Wood (shredded/cemented)	0.087
Cork	0.039
Water (liquid)	0.6
Ethylene glycol (liquid)	0.26
Hydrogen (gas)	0.18
Benzene (liquid)	0.159
Air	0.026

Now let us look at typical thermal conductivity values this table here shows the typical thermal conductivity values for a large number of materials at three hundred Kelvin. That means at a temperature of twenty-seven degree centigrade. So from the table you can notice that all pure metals have very high thermal conductivity copper has a very high thermal conductivity of three ninety-nine. Similarly gold, aluminum etcetera they have very good thermal conductivity that means they are all good conductors of heat. And compared to pure metals alloys have lower thermal conductivity. For example pure irons have a thermal conductivity of eighty point two where as carbon steel has a thermal conductivity of only forty-three. And stainless steel has a thermal conductivity of fifteen point one. That means whenever you have alloys the thermal conductivity will be lower.

And compared to metals non metals have still lower thermal conductivity. For example glass has thermal conductivity of point eight one and plastics have point two to point three and cork has a thermal conductivity of point zero three nine. Typically cork is a bad conductor of heat. So we use it as a insulating medium not as a conducting medium. And another observation is that compared to the solids liquids have much lower thermal conductivity and compared to the liquids gases have much lower thermal conductivity. And among the gases certain gases like hydrogen and helium have reasonably high thermal conductivity values.

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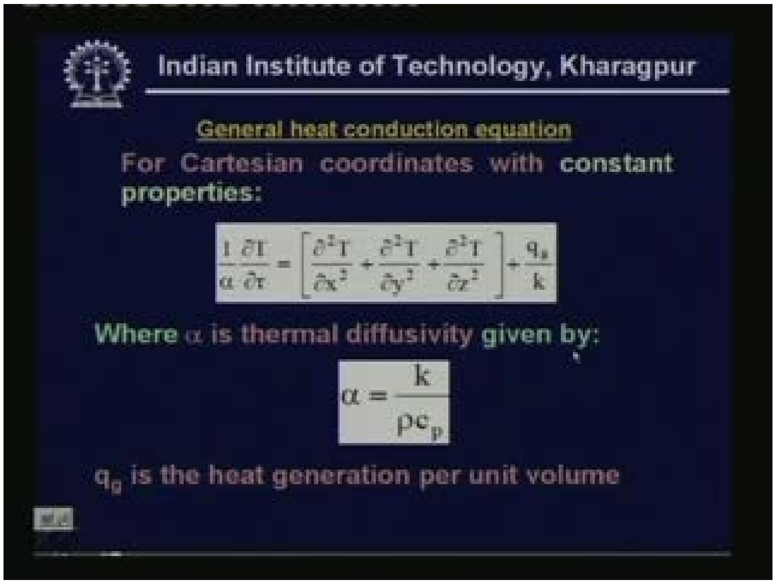

Now I have mentioned that in order to find the heat transfer rate by conduction you have to know the spatial variation of temperature. So to find the spatial variation of temperature we have to solve what is known as general heat conduction equation. So the general heat conduction equation is shown here for Cartesian coordinates with constant thermo physical properties. That means if I am assuming that thermo physical properties such as thermal conductivity, specific heat etcetera are constant.

And if I am applying first law of thermodynamics along with the Fourier's law of heat conduction to Cartesian coordinates system we arrive at this general heat conduction equation.

In this equation alpha, this alpha is your alpha is the thermal, known as thermal diffusivity and it is defined as k by rho c p and q g is the heat generation per unit volume. So if you solve this general heat conduction equation you get the solution gives you the very temperature as a function of this three spatial coordinates x y z and at the time tau.

Of course there are wide variety of ways in by which you can solve this particular equation and you can derive similar equations by applying Fourier's law and first law of thermodynamics to other coordinate systems for example in polar coordinates etcetera. And in order to solve this is a typically, a partially, partial differential equation and if want to solve this equation you need to know certain initial and boundary conditions. So with the help of the initial and boundary conditions you can solve this equation and get a an expression for temperature in terms of x y z and tau.

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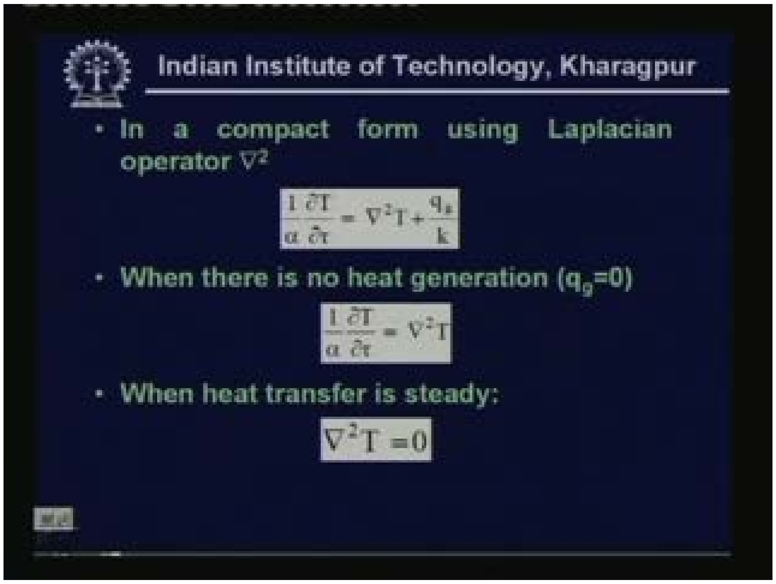

Now we can write this equation in a compact form using Laplacian operator del square. For example if I am using Laplacian operator del square the general heat conductive equation for Cartesian coordinate system becomes one by alpha Do T by Do tau is equal to del square T plus q g by k. And when there is no heat generation obviously q g by k term becomes zero and you have a transient heat conduction equation without heat generation given by one by alpha Do T by Do tau is del square T. And when there is no variation with time Do T by Do tau becomes zero. And you have what is known as a steady state heat conduction equation given by del square T is equal to zero this equation is known as Laplace equation.

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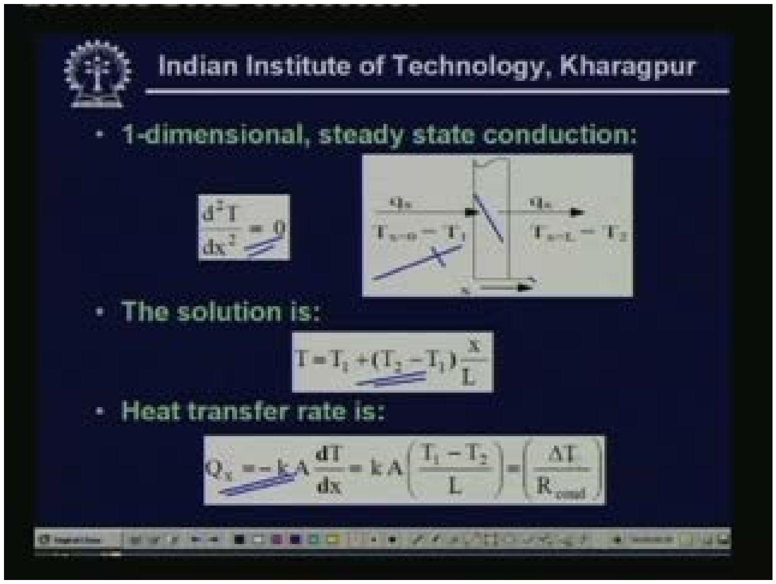

Now let us apply this equation to a simple case of one dimensional steady state conduction. So for one dimensional steady state conduction this is the basic equation and if to solve this equation we need to know two boundary conditions. And this is the typical geometry we have. Let us say wall thin wall whose dimensions in y and z directions are much larger compared to the dimensions in the x direction. And here we have two boundary conditions whether where x is zero that means this thing, we have temperature is equal to T one and x is L. That means the thickness of the plate is L at x is L the temperature is T two.

So these are the two boundary conditions and this is the governing equation d square T by d x square so the solution is very simple. Solution is given by T at x at any x is equal to T one plus T two minus T one into x by L. That means the temperature variation is typically linear so we have a linear variation of temperature. And the heat transfer rate can be obtained by applying the Fourier's law here Q x is minus k A d T by d x. So temperature profile use from this equation and then you get the expression for Q x in terms of the temperature distance delta T where delta T is T one minus T two and the property is k and the thickness L and the cross section area A. So this equation can be written in this form. That means Q x can be written as delta T by R conduction. Where delta T is the temperature potential which is driving the heat transfer and R conduction is the conductive resistance.

So this equation is almost similar to analogous to ohms law Ii mean in ohms law for current we write I as E by R where E is the potential difference and R is the resistance. So this equation also same analogous to ohms law.

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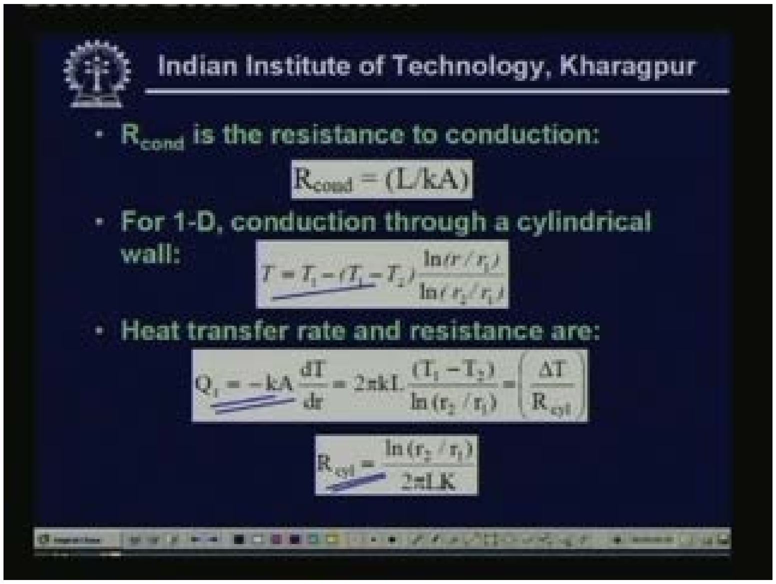

Now this conduction resistance obviously is given by R conduction is L by k A. That means it is a function of the geometry of the system and also with the property of the system that is thermal conductivity. And you can also derive this one dimensional steady state heat conduction equation for a cylindrical wall. Let us say that you have a thin cylindrical wall and if you apply energy balance then you get the basic heat conduction equation and if we solve the heat conduction equation by applying suitable boundary conditions you arrive at the solution for temperature. This is the solution and this solution, this temperature profile is logarithmic in case of Cartesian coordinates we had a linear profile.

But this profile is logarithmic and by differentiating this using the Fourier's law you can get an expression for heat transfer rate in cylindrical coordinates. Again you can write this as delta T by R cylindrical where R cylindrical is the conductive resistance in cylindrical coordinates in cylindrical coordinates the conductive resistance. If you compare this equations is given by L n r two by r one divided by two phi L K. In this equation r two is the outer radius of the cylinder r one is the inner radius of the cylinder K is the thermal conductivity and L is the length of the cylinder.

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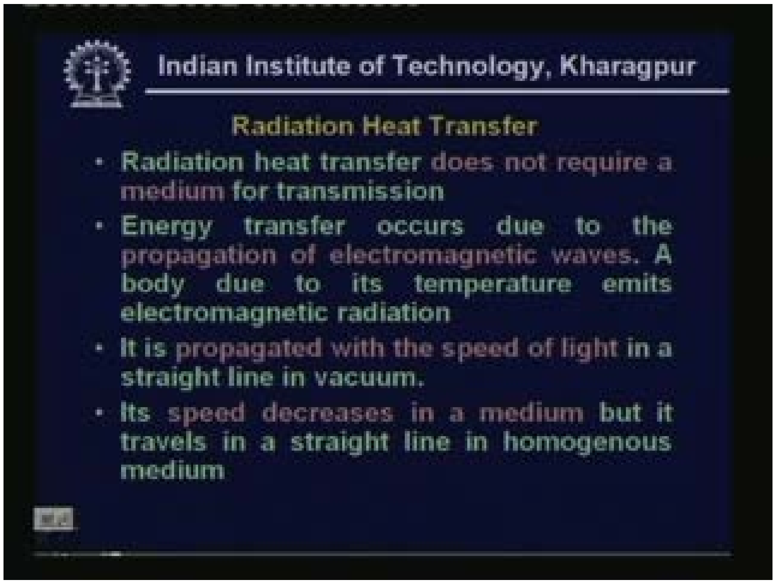

Now let us briefly look at radiation heat transfer. As you know radiation heat transfer does not require a medium for transmission in fact it is very efficient in vacuum so this is unlike the other modes of heat transfer which require a medium and energy transfer in radiation occurs due to the propagation of electromagnetic waves and all bodies having a finite temperature emit electromagnetic radiation. And this electromagnetic radiation propagates with the speed of light in straight line in vacuum. And if you have a medium its speed is reduced but still it travels in a straight line in homogeneous medium.

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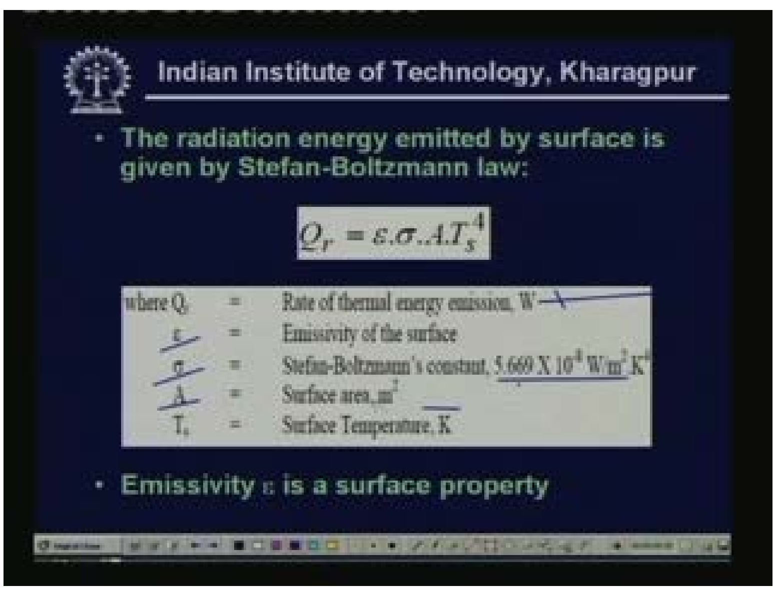

And the basic law for radiation energy emitted by surface is given by Stefan Boltzmann's law and this law is derived by integrating Planks equation okay. So in the this equation is simply given by Q r is equal to epsilon sigma A T s to the power of four where Q r is the rate of thermal energy emission in watts. And epsilon is the emissivity of the surface and sigma is Stefan Boltzmann's constant its value is given here and A is the surface area and T s is the surface temperature in absolute units. Unlike the conduction and convection equations the Stefan Boltzmann's law can be derived from basic thermodynamics. That means it is a derived it is not only an observation not only based on observation.

And here the emissivity is a property of the surface and if emissivity is one we have a surface which is ideal. That means for an ideal surface the emissivity is one and such a surface is known as a black body. A black body has nothing to do with the black colour black body is an ideal emitter that means it emits at a given temperature. A black body emits maximum amount of radiation similarly it absorbs a maximum amount of radiation. So such a body is called as black body and all real bodies have emissivities less than one so all real bodies have emissivity less than one and emissivity. The definition of emissivity itself it is define defined as the emissive power of a real body divided by the emissive power of the black body at a fixed temperature okay.

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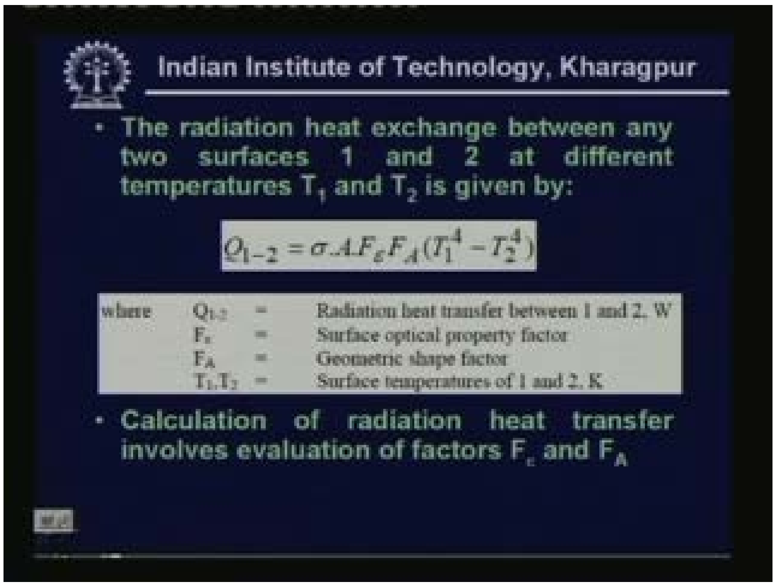

Now let us look at the radiation heat exchange between any two surfaces one and two which are at two different temperatures T one and T two. So this is it can be shown that this is given by Q one two is equal to sigma into A into F epsilon into F A into T one to the power of four minus T two to the power of four. Where Q one two is the radiation heat transfer between surfaces one and two and F epsilon is what is known as a surface optical property factor which depends upon the properties of the surfaces participating in radiation. So basically it is a function of emissivities of the surfaces and you also have a factor F A which is known as geometric shape factor or configuration factor. And T one and T two are obviously surface temperatures of one and two in degrees Kelvin that means in absolute temperature scale so the major problem in radiation is evaluation of the factors F epsilon and F A.

This is the normally we know the temperatures T one and T two and we also know the surface areas etcetera. So we have to find out the factors F epsilon and F A so unlike the other modes of transfer radiation transfer between two surfaces depends upon the orientation of the surfaces. So the factors geometric factor or configuration factor takes care of the orientation of the surfaces.

For example if the surfaces do not see each other then there will not many radiation exchange between them okay.

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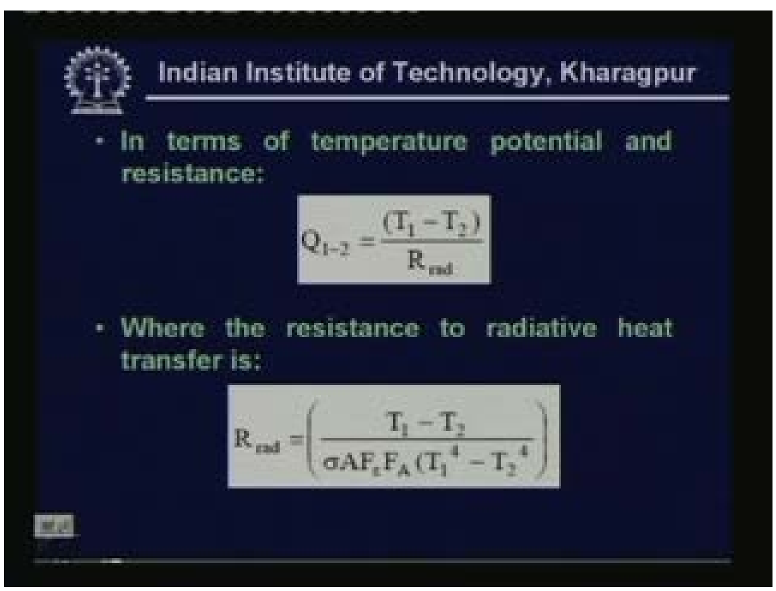

Now we can also write the temperature radiation heat transfer in term in terms of temperature potential and resistance. Of course if we look at the radiation heat exchange equation we have temperature terms not in linear form but in a non linear form that means Q is proportional to T to the power of four. But still you can linearize it and you can write Q radiation as T one minus T two divided by R radiation where R radiation is the radiative heat transfer resistance and define in the in the manner shown here.

And you can see the radiative heat transfer resistance depends not only on the factors F epsilon and F A but it also depends upon the temperatures in a non linear fashion. But it so happens that in most of the practical problems when the temperature difference is moderate then you can assume the radiative heat transfer coefficient to be linear. That means we can linearize the radiative heat transfer and write it as a function of temperature potential and resistance. We shall see later what are the advantages of writing the transfer rate in terms of a potential and resistance. Now

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Let us look at the other very important mode of heat transfer known as convective heat transfer. So convection heat transfer takes place between a surface and a moving fluid when they are at different temperatures. And convective heat transfer resistance consists of two mechanisms operating simultaneously this is important. What is the, what are the two mechanisms? The first mechanism is energy transfer due to conduction through a fluid layer adjacent to the surface.

Now if you remember in the last lecture I was mentioning hydrodynamic boundary layers when a fluid flows over a surface. The fluid layer adjacent to the surface attains the velocity of the surface. If the surface is stationery the fluid layer also becomes stationery. So this is what you known as no slip condition and the boundary layer are known as hydrodynamic boundary layer.

Similar to hydrodynamic boundary layer when a fluid flows over a surface whose temperature is different from the fluid surface then the fluid layer adjacent to the surface attains the temperature of the surface again. This is because of your no slip condition. Okay. That means we have a stationery layer on the surface where the temperature is same as the surface temperature. That means similar to hydrodynamic boundary layer a thermal boundary layer also develops and the temperature varies in this thermal boundary layer from the surface to that of the free. So you can see the similarities between the momentum heat momentum transfer and convective heat transfer and hydrodynamic and thermal boundary layers. And the layer which as I said is stationery the layer that closes to the plate is stationery. So the mode of heat transfer through the stationery to the layer has be has to be obviously conduction okay.

So initially we have conduction heat transfer taking place from the surface to the fluid through a stationery layer by conduction. Then heat transfer rate heat transfer will be by the bulk motion of the fluid particles so the second mechanism E is energy transfer by macroscopic motion of fluid particles by virtue of an external force. So conduction is followed by macroscopic motion of fluid particles and what is causing the macroscopic motion. An external force causes the macroscopic motion of fluid particles and this external force could be generated because of the presence of a fan or pump. For example a fan or pump is driving the fluid over the surface okay. Then that causes the fluid flow and the mixing of the fluid particles such a type of convection is known as force convection that means whenever we are using an external force such as fan or pump we call that a that convection as force convection.

It is also possible to have convective currents in the absence of any external device this is known as a free convection. This free convection takes place because of the buoyancy effects that means when fluid comes in contact with its surface whose temperature is different from the fluid temperature then there will be temperature radiant. And as you know fluid temperature fluid density depends upon temperature. So when the temperature varies density also varies so due to the density variation buoyancy effects are generated and fluid flow is generated this is known as free convection.

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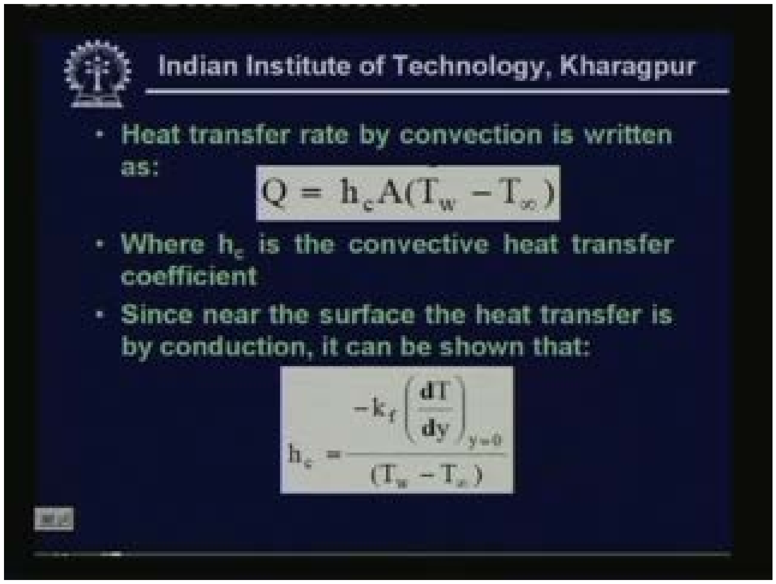

Now the basic heat transfer rate by convection is written in a very convenient fashion as Q is equal to h c A into T w minus T infinity where h c is the convective heat transfer coefficient A is the area of heat transfer T w is the surface temperature and T infinity is the temperature of the fluid in the free stream. This equation which is called as basic equation for heat transfer by convection is also known as Newton's law of cooling. And basically this is a definition of heat transfer coefficient it is not actually a law but it defines heat transfer coefficient. And as I mentioned since near the surface the heat transfer rate is by conduction we can show that h c is nothing but minus k s d T by d y at y is equal to zero divided by T w minus T infinity. By writing the heat transfer rate in terms of conduction for the stationery layer and equating that to Newton's law of cooling you can arrive at this expression.

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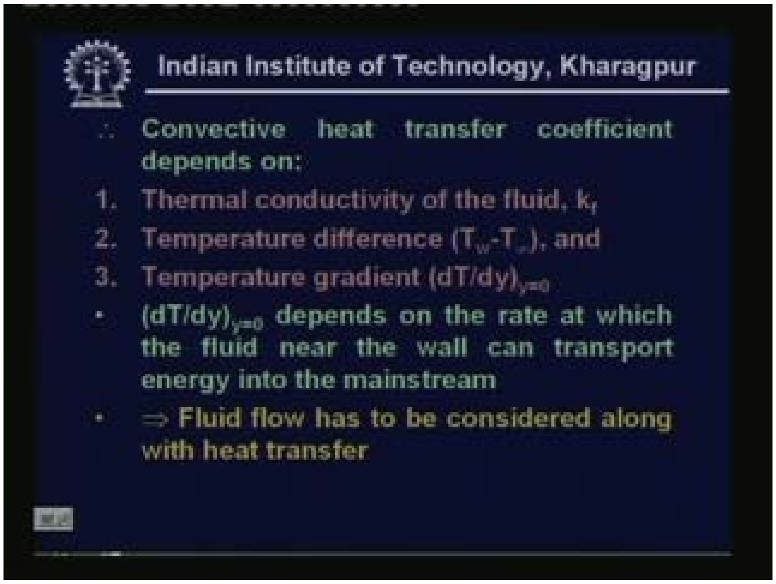

Now the convective heat transfer coefficient from this equation obviously depends upon the thermal conductivity of the fluid the temperature difference T w minus T infinity and the temperature gradient d T by d y at y is equal to zero. That means what is the temperature gradient near the surface. Now this temperature gradient near the surface d T by d y at y is equal to zero y is the direction perpendicular to the surface so I keep it in mind. So d T by d y at y is equal to zero depends on the rate at which the fluid near the wall can transport energy into the main stream.

So it basically depends up on the fluid flow. That means for in convective heat transfer problems we have to consider fluid flow in addition to the heat transfer. That means this mode of heat transfer is governed not only by the heat transfer laws but also by the fluid flow laws. So some people don’t consider convection heat transfer as basic mode because here you have both heat transfers by conduction as well as fluid flow okay. But still for convenience sake we also we considered this also as one of the basic modes of heat transfer.

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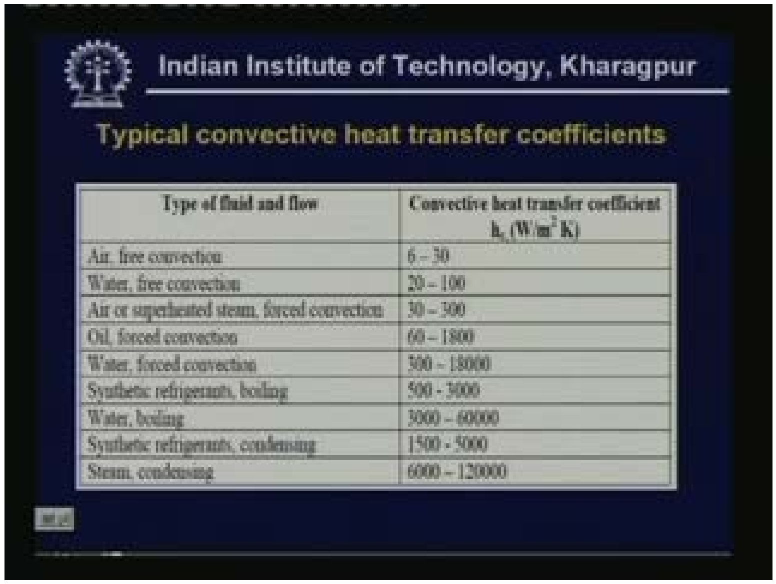

Let me show typical convective heat transfer coefficients. This table shows the type of fluid and flow remember that once again I am repeating it convective heat transfer coefficient depends on the type of the fluid and on the flow and also on the geometry. And if you have air in free convection that means heat transfer is driven by density differences. Then we heat transfer coefficients varies between six to thirty watt per meter square Kelvin. And if you have water again in free convection then you have heat transfer coefficient slightly higher twenty to hundred.

So you can see that water is the gives much higher heat transfer coefficient compare to air this is due to the higher thermal conductivity of liquid. Then if you have force convection then you have higher heat transfer coefficient fourth force convection in the fluid is air or super heated steam. Then the heat transfer coefficient varies from thirty to three hundred. So you have one order of magnitude higher than the free convection. This is because of the vigorous mixing of the fluid when you have force convection. When you have oil in force convection again you have sixty to eighteen hundred. This is higher than the air because you are dealing with liquid and if you have water you get much higher heat transfer coefficient because water has typically higher thermal conductivity compared to oils. And if you have phase changes such as boiling or condensation you get really high heat transfer coefficient For example in case of synthetic refrigerants under boiling condition you have heat transfer coefficient which vary anywhere between five hundred to three thousand watt per meter square Kelvin.

And if you have water then you get really good heat transfer coefficients again because water has excellent thermo physical properties compare to synthetic refrigerants. So you can get heat transfer coefficients from three thousand to sixty thousand. And similarly in condensation generally condensation gives much higher heat transfer coefficients compare to any other mode of heat transfer. So you can see that you get very good heat transfer coefficients when fluids are condensing. Typically with steam you can get heat transfer coefficient as high as one lakhs watt per meter square Kelvin.

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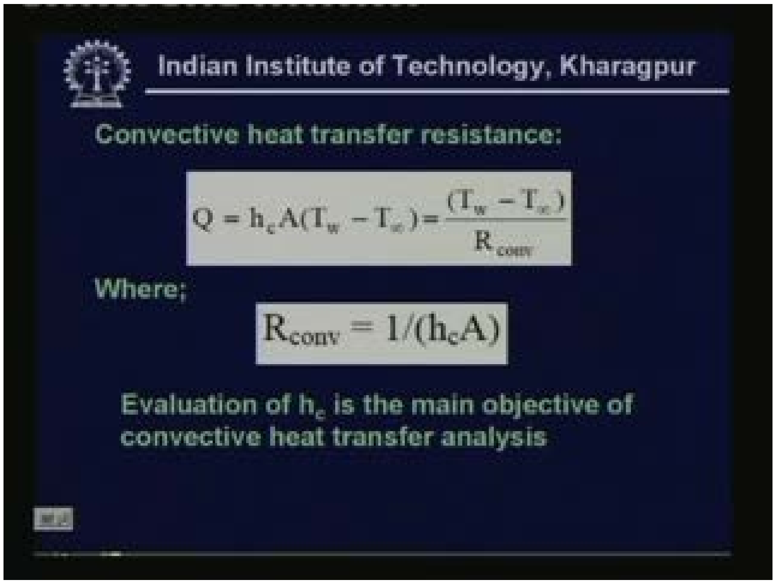

Now similar to conductive and convective heat transfer conductive and radiative heat transfers. We can also write the convective heat transfer rate in terms of the temperature potential and the resistance. So you can write Q as T w minus T infinity divided by R convection where R convection is the heat transfer resistance to convection and if you compare this equation you can easily show that R convection is nothing but one by h c into A. And the major problem in all convective heat transfer problems since the weight has developed is the estimation of heat transfer coefficients. So you can see that all most the entire literature and convective heat transfer coefficient is devoted to evaluation of heat transfer coefficient. Because once you know the heat transfer coefficient you can find out the heat transfer rate by multiplying that into temperature difference and surface area.

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Now how do you evaluate the convective heat transfer coefficient? You can evaluate it analytically for simple cases in if you want evaluated analytically you have to solve mass momentum energy equations. Since this is, this can pretty complicate, this method is possible only for simple situation simple situation means let us say that a laminar fluid flow is taking place over a flat plate. Then you can have analytical solutions and you can find analytical expressions for heat transfer coefficient similarly fluid laminar fluid flow is taking place over a cylinder again you can have close form solution and an analytical solution. But when you have complicated cases for example when you have turbulent flow and when you have complicated geometries then it is very difficult and you cannot have analytical solutions. And in such cases what is done is you have to go either for numerical methods or most popularly people used experimental methods in addition to the dimensional analysis to arrive at expressions for heat transfer coefficients that is what is mentioned here. Most of the convection heat transfer data is obtained through careful experiments.

And equations suggested are mostly empirical once you have empirical equation they are valid for only a set of conditions under which these equations are derived. And they are also applicable to only that particular range of experiment. So you must be very careful when you are using the empirical correlations you must check that your problem falls in the range of that particular correlation only then use it.

And fortunately because of the huge amount of work done in this area you have correlations for all most all practical situations. So you have to look for them in suitable heat transfer data books and text books. And to some extent generalization has been made possible by introducing several non dimensional numbers. Usually you will see that probably you remember from your basic courses on heat transfer that several non dimensional numbers such as Reynolds's numbers Nusselt numbers Prandtl number are introduced and generally the correlations are given in terms of the non dimensional numbers. This will generalized the correlations to a large extent I will show you.

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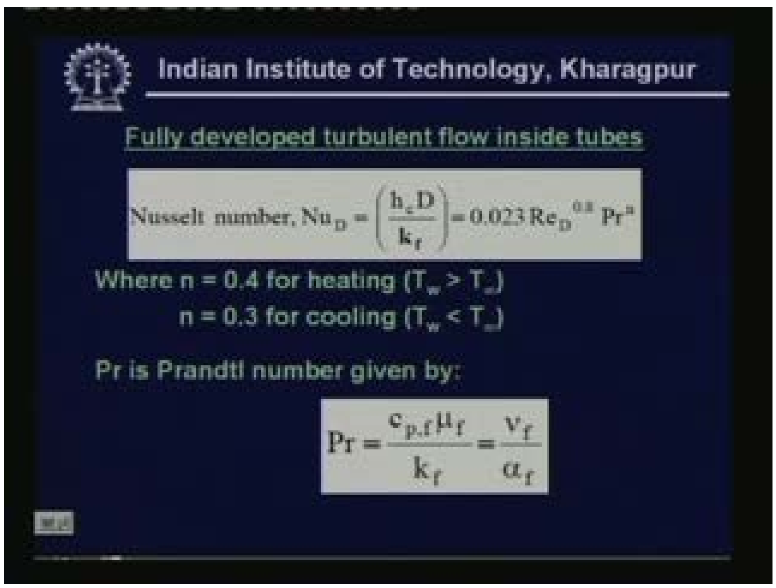

One typical heat transfer correlations this is known as Dittus Boelter equation and this is valid for fully developed turbulent flow inside smooth tubes so this is valid for smooth tubes. And it gives, it relates a non dimensional parameters Nusselt number which is defined as h c D by k f equal to point zero two three R e to the power of point eight and P r to the power of point n. So N u is the Nusselt number and it is equal to h c D by k f where h c is the convective heat transfer coefficient D is the length parameter and k f is the thermal conductivity of the fluid. And on the right hand side you have Reynolds's number R e and also you have another dimensionless number known as Prandtl number Prandtl number is defined as you can see here Prandtl number P r is c p mu f by k f all the properties are that of the fluid that's why the subscript f stands for fluid.

So Prandtl number is c p mu by k which can also be written in terms of kinematic viscosity mu divided by the thermal diffusivity alpha so Prandtl number is basically mu by alpha. And this Dittus Boelter equation there is another parameter n and this n will take the value of point four for heating. That means when the fluid is getting heated you have to use a value of point four for n and if the fluid is getting cool then you must use the value of point three. This is a very popular empirical correlation and very widely used. So as I said for fully developed turbulent flows inside tubes. And if you are using a hydraulic diameter you can also use these two non circular tubes. But this is again valid for certain Reylond's number range and it is also valid for certain Prandtl number range. So when you are using this equation you must know what the range under which this can be used is.

This is just one example of a typical convective heat transfer correlation a large number of correlations. As I mentioned already are available for a wide variety of flow situation. That means you have heat transfer correlations for flow force convection free convection over flat plates inside the tubes and heat transfer correlations for phase change boiling condensation etcetera. So all these things have been derived and they are available so we will be discussing these things in detail when we are designing evaporators and condensers in later lectures. Now let us quickly look at the mass transfer. Mass transfer takes place when a system containing two or more components whose concentration vary from point to point. Then there will be a natural tendency for mass to be transferred before that the concentration difference can be minimized.

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That means when you have a system which consists of two or more constituents or components and if there is a concentration difference then the spontaneous process is to reduce the concentration gradient. That means there will be mixing of the components that means there will be mass transfer. That means transfer of one constituent into other this is what is known as mass transfer. So the mass transfer can be defined as the transport of one constituent from a region of higher concentration to that of the lower concentration is called as mass transfer. Why do we study mass transfer in refrigeration and air conditioning because we in refrigeration and air conditioning, we typically encounter several cases where mass transfer takes place a typical example of mass transfer which we, all of us are familiar with is that of drying. For example when you leave a wet cloth in an unsaturated or dryer then the clothes become dry. So what has happened water vapour or water from the wet cloth is transferred from the cloth to the surrounding air.

So this is one popular case of mass transfer, so we have this typical drying problem in air conditioning because air conditioning latent heat is involved. So we will be applying these principles when we are solving those problems another very familiar case of mass transfer is spread of perfume. For example when you put a perfume in one corner because of the diffusion the perfumes spreads all over the room. So this is another example of mass transfer now let us look at some very basic equations of mass transfer.

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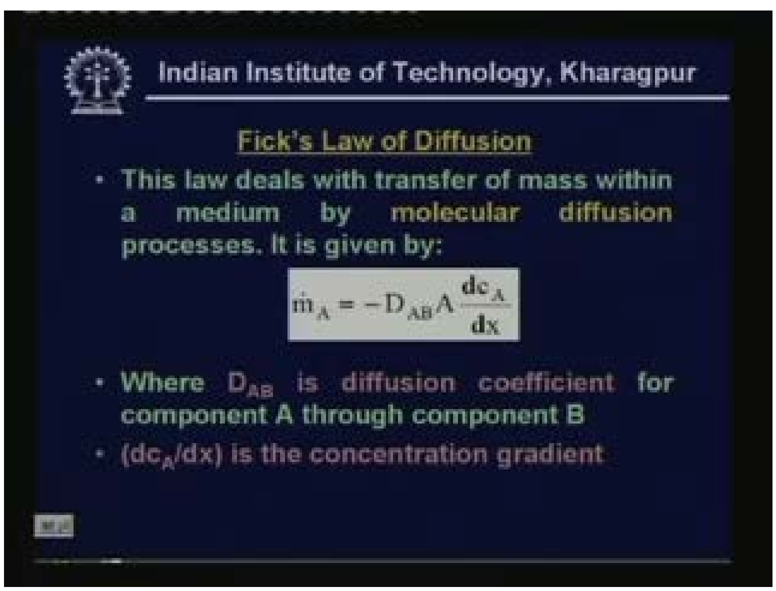

The first basic equation is what is known as Fick's law of diffusion this law deals with transfer of mass within a medium by molecular diffusion process and it is given by m dot A is equal to minus D A B A d c A by d X, where D A B is known as the diffusion coefficient for component A through component B and d c A by d X is the concentration gradient. So you can see the similarity between Fick's law and Fourier's law for heat conduction the similarity arises because both are diffusing processes. So that is why the equations are similar. Again you can see that in an just like Fourier's law of heat conduction you also have a negative sign here. This means that mass transfer always takes place from a region of higher concentration to a region of lower concentration and similar to convective heat transfer.

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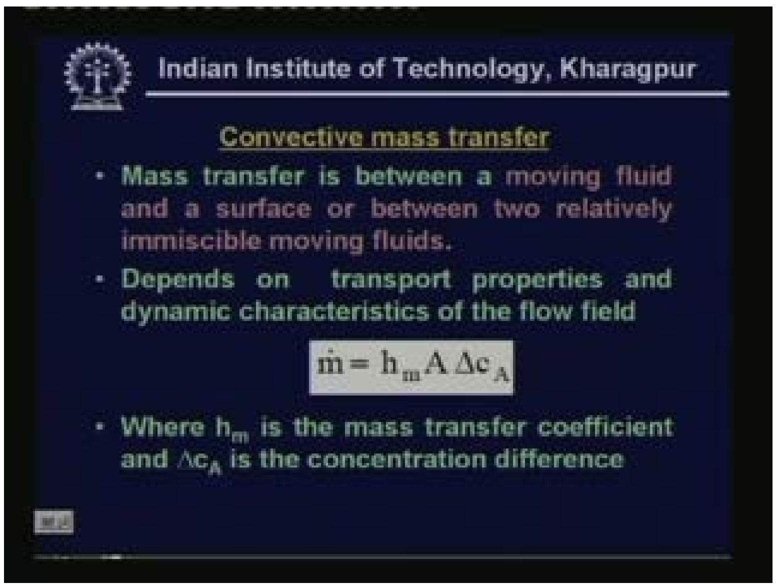

We can also have convective mass transfer this takes place whenever a moving fluid and between the moving fluid and a surface or between two relatively immiscible moving fluids. For example you have let us say that two fluids two different fluids which come in contact with each other. Okay. Then for example you have a concentrated sugar solution and you slowly pour water over that so you have two different fluid layer. But slowly sugar spreads throughout the solution and the entire solution where reaches the uniform concentration. So mass transfer takes place in this process so this is the typical example of convective mass transfer. And similar to Newton's law of cooling for convection you can also write convective mass transfer as m dot is equal to h m A into delta c A where h m is the mass transfer coefficient A is the mass transfer area and delta c A is the concentration difference.

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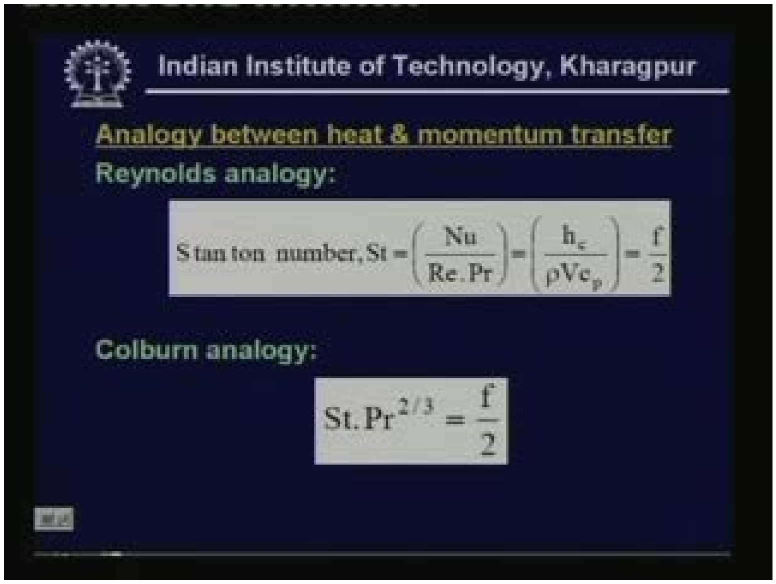

Now let us look at analogy between heat and moments momentum transfer. This is very interesting we have seen that the mass transfer momentum transfer and heat transfer by convection. All appear to be similar because all of them have many peculiarities. For example between momentum and heat transfer you have hydrodynamic boundary layer which takes care of the momentum transfer. And analogous to that you have a thermal boundary layer because of no slip condition velocity becomes zero on the surface.

And similarly the term the fluid temperature becomes that of the surface temperature may be because of the no slip conditions. And mathematically if you look at for example you take a case of laminar fluid flow over a flat plate if you look at the momentum equation and the energy equation you will find that they are exactly identical when Prandtl number is one and when there are no pressure gradients in the direction of flow. And when there is no viscous dissipation and when there are no heat sources then you will find that ma momentum and heat transfer equations are exactly identical and if they have similar boundary conditions the solutions also will be identical.

So that means there is a direct analogy between momentum and heat transfer this is the observation and for this condition it can be easily shown that a non dimensional parameter

Stanton number which is given by N u by R e into P r which is equal to h c by rho V c p where V is the fluid velocity is equal to f by two. So this is known as Reynolds's analogy so what is the use of this Reynolds analogy you can see that Reynolds analogy connects heat transfer coefficient h c with friction factor f. That means if you know the friction factor you can find out heat transfer coefficient by applying this analogy. You do not have to carry out any heat transfer experiments so this is very useful. This Reynolds analogies strictly applicable for the Prandtl number one so Colburn has improved this for different Prandtl numbers and he has arrived at this what is known as Colburn analogy this is given by Stanton number into Prandtl number to the power of two by three is equal to f by two . This is known as Colburn analogy this is applicable to a Prandtl number varying from about point six to fifty. So this is you can see the usefulness of this. Now let us look at analogy between mass and momentum transfer.

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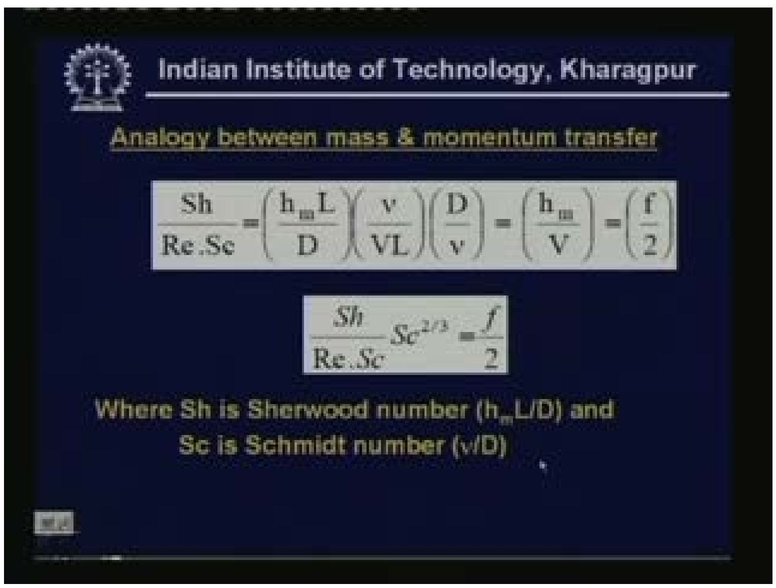

Similar to heat and momentum transfer we can also write analogy between momentum and mass transfer. And here we define another non dimensional number called Sherwood number S h and this Sherwood number is defined as h m into L by D where h m is the mass transfer coefficient and D is the diffusion coefficient and L is the length parameter. So Sherwood number is analogous to Nusselt number and we also define another non dimensional number called a Schmidt number. This Schmidt number is analogous to Prandtl number so when you are applying this analogy you can show that mass transfer coefficient h m divided by the velocity is equal friction factor divided by two this is valid for Schmidt number equal to one. So to care of the Schmidt number other than one we can modify this similar to Colburn analogy and we have the modified analogy given by Sherwood number divided by Reylond number into Schmidt number into Schmidt number to the power two by three equal to f by two. This is the analogy between mass and momentum transfer.

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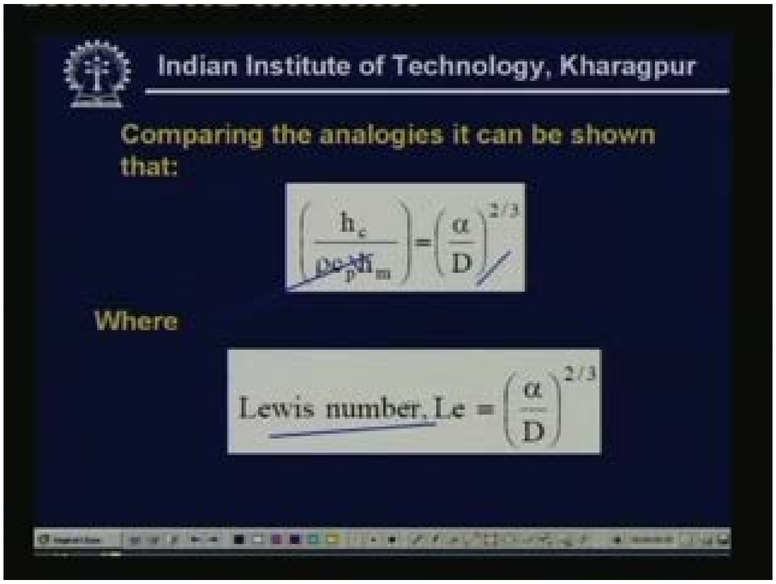

Analogy between mass and momentum heat transfer and momentum and mass transfer you can arrive at this important expression. You can look at this you can show that the heat transfer coefficient divided by the density into specific heat at constant pressure and h m is equal to alpha by D to the power of two by three okay. So this is from the comparison of the two analogies.

This is a very useful expression particularly for air conditioning calculations because for air conditioning calculations. This parameter alpha by D to the power of two by three called as Lewis number L e this takes a value of one for air water mixtures not exactly one but it is close to one.

So when this is close to one then your mass heat transfer coefficient is the in nothing but a product of density into specific heat into mass transfer coefficient. So if you know the heat transfer coefficient directly you can find the mass transfer coefficient. So this is very useful and we will be applying this when we do the air conditioning calculations. Now let us look at multimode heat transfer.

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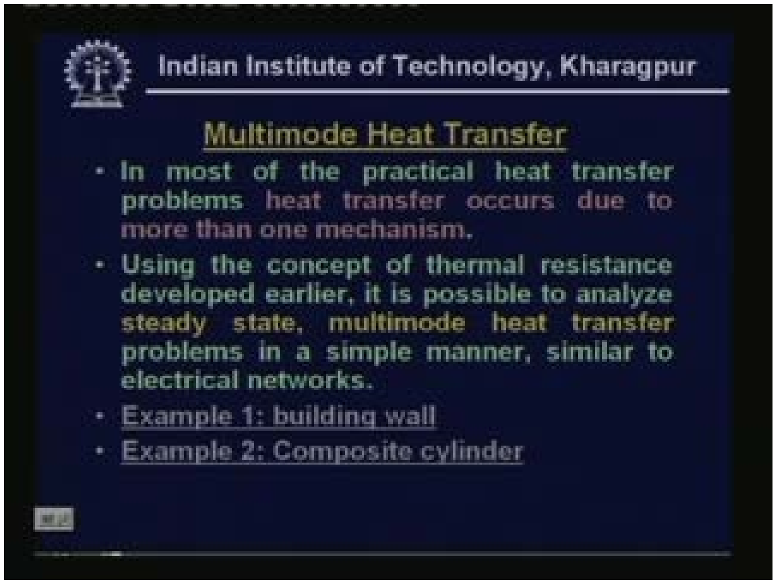

So far we have been discussing and we have been describing the different modes of heat transfer separately. First we have given equations for conduction heat transfer then convection heat transfer then radiation heat transfer. That means we have dealing with the different modes. But as I mentioned in most of the engineering problems the heat transfer takes place by more than one mode at the same time. That means you have what is known as a multimode heat transfer.

So let us see how we look at the how we solve the multimode heat transfer problems. As I said in most of the practical heat transfer problems heat transfer occurs due to more than one mechanism and using the concept of thermal resistance which we have developed earlier it is possible to analyze steady state multimode heat transfer problem in simple manner similar to electrical net works.

So remember that this concept of thermal resistance and network is applicable only to steady state problems if you have unsteady state problems you cannot directly apply the concept of thermal resistance and networks okay. Now let me give an example of a building wall okay therefore you have yeah stop recording for a moment please. Okay. So let me show an example of multimode.

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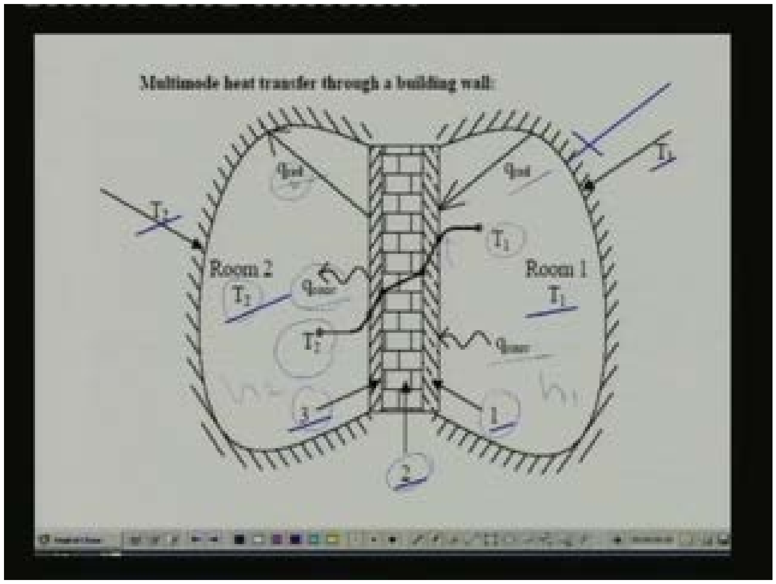

Heat transfer applied to a building so here we have two rooms one and room two there at two different temperatures. For example in this particular case room one is at higher temperature compared to room two. So there will be heat transfer between room one to room two and the surroundings of the room one are also and this particular this thing at the same temperature as the that of the room temperature. That means the air and the surrounding surfaces are of room one are at temperature T one similarly the room two has surface temperature at T two and air temperature is also at T two. So you have two different temperatures and these two rooms are separated by a multi layered wall okay.

So this wall is the multi layered wall that means it consists of two three layers layer one layer two and layer three okay. And here the heat transfer is also by multimode for example look at here the heat transfer heat transfer takes place first by radiation from the surface surrounding surfaces to the wall and also by convection from the air to the wall. So you have radiation heat transfer taking place and convection heat transfer taking place from surroundings and the air of room one to the wall okay. So the radiation and convection will be happening simultaneously okay.

Then from this point onwards the heat transfer to the through this wall is by conduction so you have initially radiation and convection then conduction through the wall and from the wall to the room to which is at lower temperature again the heat transfer is by radiation and by convection okay. Because you have radiative heat transfer here because the surface temperature of the wall is different from the surface temperature of the surroundings of room two so you have radiation okay. Similarly this air temperature T two is different from this surface temperature so again you have convection okay. So this is a very peculiar and typical example of multimode heat transfer which we will be dealing with while doing air conditioning calculations okay. So this is look at the picture carefully. Now we can also draw the temperature profile for example if this is the temperature T one of room one then let's assume that this temperature is uniform in the room.

Then there will be a temperature drop at this point because of the resistances convective and radiative resistance there will be temperature drop here and there will be further temperature variation within the wall because of the conductive resistance.

So the temperature profile varies like this again from the wall to this room two you have again the temperature variation because of the convective and radiative resistances of this room okay. So this is a typical temperature variations of the, for this particular problem. Normally we know these two temperatures and we also know the properties. For example let us say that we know the properties of the walls one two three. That means thermal conductivity lengths areas etcetera. And we also know for the time being let us say that we know what is the heat transfer coefficient here what is the heat transfer coefficient here what the radiative heat transfer here is and what is the radiative heat transfer here. So the basic objective here is to calculate the heat transfer rate from this room to the other room.

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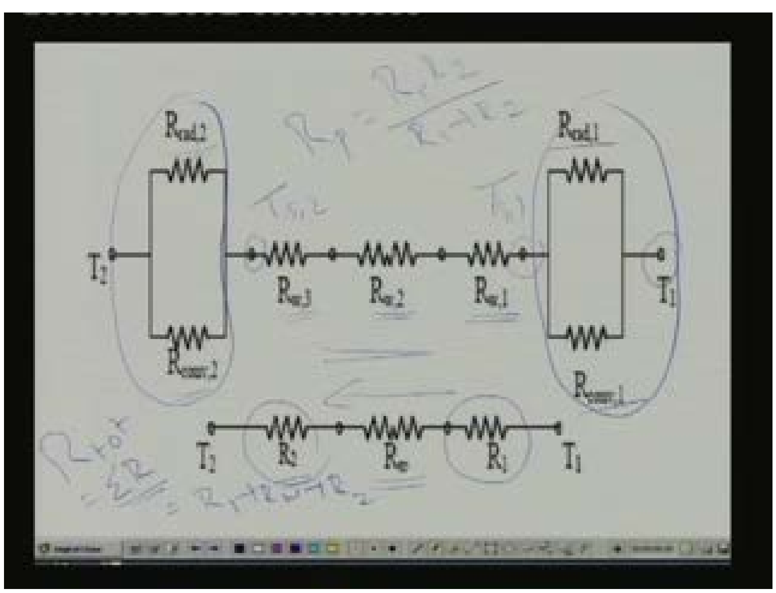

So we can write a radiation network now okay. You I hope you remember the physical model. We can write the radiation network initially we have the temperature T one of room one then two modes of heat transfer taking place simultaneously one is the radiation the other one is convection. So you have radiative heat transfer and convective heat transfer we write it in the form of parallel a network with parallel connection. Because that is happening simultaneously so you have two resistances in parallel one is radiative resistance other one is convective resistance.

So this is the temperature of the surface of the wall inside the room okay. This is T s one and from this point to this point heat transfer is taking place through the wall so you have three different layers this is the conductive resistance of layer one conductive resistance of layer two conductive resistance of layer three okay. So the mechanism is conduction and all the resistances are in series so you have a series resistance in series here.

So this is the temperature of the surface of the wall inside room two so remember that at this point again the heat transfer rate heat transfer takes place parallel by radiation to the surrounding surfaces and by convection. So again you have a parallel network here. So this, the whole thing is the, a typical heat transfer network for the problem discussed now okay. And this radiation network as you remember from your electrical basic electrical technology this can be reduced to this form. So what we have done here is this resistance which is the resistance offered by the radiation. And radiation convection of room two can be clubbed together because they are in parallel so you can find out the equivalent resistance R two. As you know parallel resistance means if the resistance is as R one and R two. So you know that R parallel is equal to R one into R two by R one plus R two okay.

So this is nothing but this, okay. Here R one and R two refer to radiative resistance and convective resistance. So what I have done is i have reduced this to an equivalent resistance R two. Similarly this portion can be reduced to an equivalent resistance R one so we have now three resistances in series R one R w and R two R w is nothing but the equivalent resistance for the composite wall okay. So this is the resistance simplified in the resistance network for the given problem. So now what is the total resistance as you know the total resistance are total is nothing but sigma R so here it is simply equal to R one plus R wall plus R two okay. So we can find out what are the individual resistances because we have already given the expressions for radiative resistance convective resistance conductive resistance etcetera. And if you have the property data and other data you can find out individual resistances and find the total resistance and once you know the total resistance you can find out the total heat transfer rate. Because as you know heat transfer rate is nothing but T one minus T two divided by the total resistance okay. So you can see the usefulness of the network analogy okay. The complicated problems can be easily broken down into simple problems right. And here we have shown the conductive resistances in series it is also possible to have conductive resistances in parallel. A very typical case is heat transfer through a hollow brick when you have a hollow brick you find that you inside the brick the heat transfer is in a parallel mode because it is not homogeneous okay.

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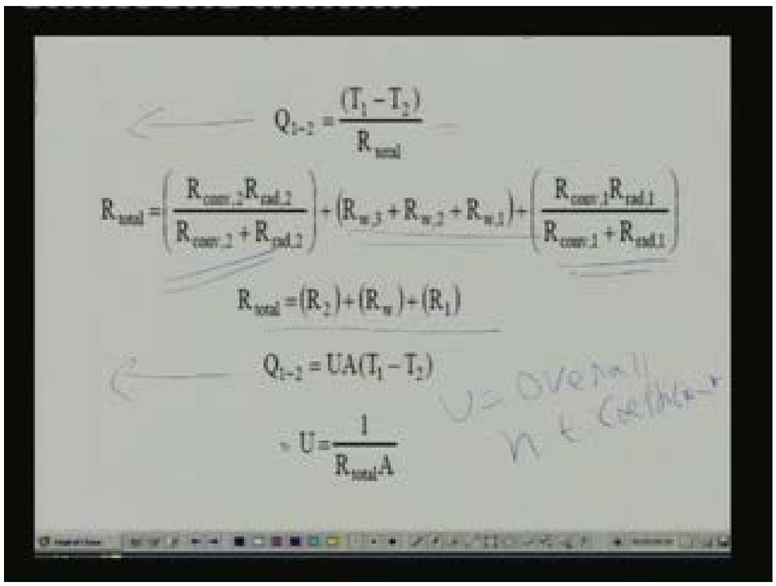

So this is the mathematical, this thing whatever have discussed just now. You can write for this multi layered wall Q one to two. That means from room one to room two as T one minus T two divided by R total where R total consists of these resistances. This is the this is the equivalent resistance of the two parallel radiative and convective resistances in parallel for room two and this is for the room one and this is the resistances in series for the wall and this is the total resistance and this is the heat transfer rate. Now you can write also write the heat transfer rate in terms of what is known as over all heat transfer coefficients.

So you can write either like this or you can also write Q one to two as U A into T one minus T two where U is what is known as over all heat transfer coefficient. You probably might have of this when you are doing heat transfer calculations and when you are, when you when I am comparing this equation with this equation you find that over all heat transfer coefficient is nothing but one by R total into A. So if you know the resistances you can calculate the overall heat transfer coefficient. The concept of overall heat transfer coefficient will be used very widely when we are designing the heat exchangers okay.

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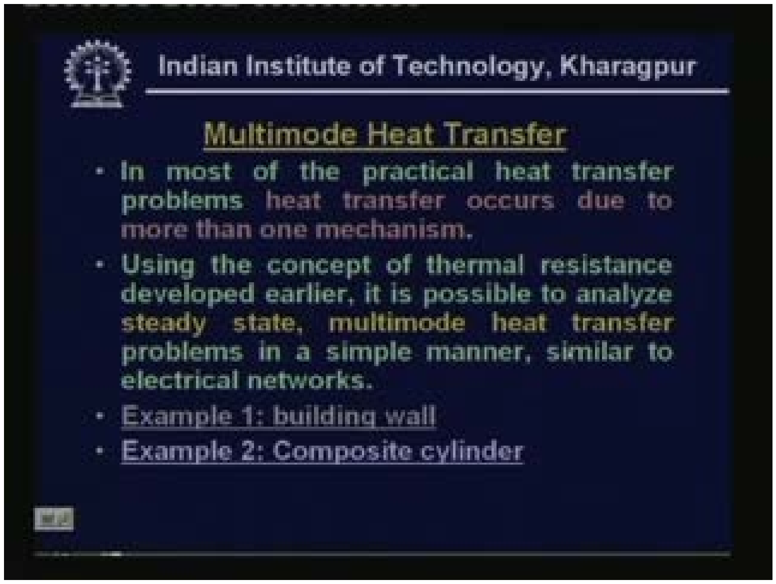

Now let me give another example that of a composite cylinder.

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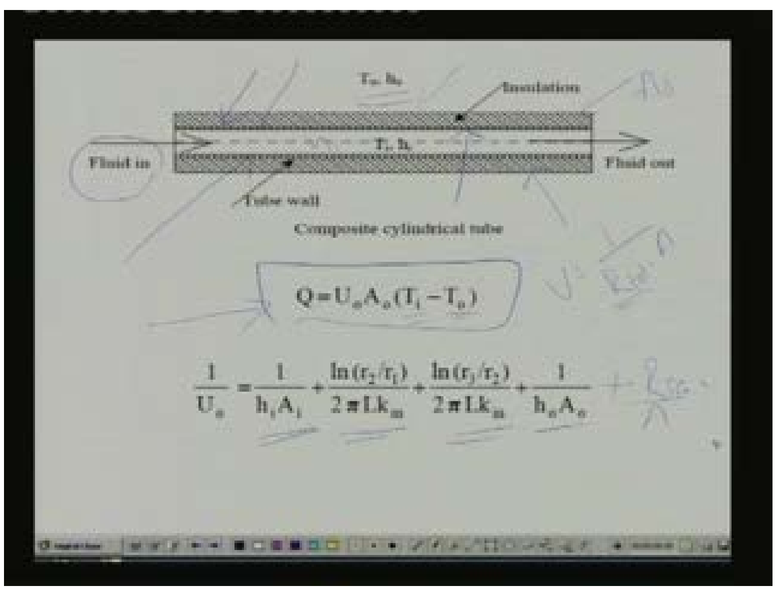

This also very commonly encountered. So here what we have is a metallic tube okay. This is the metallic tube through which a fluid is flowing okay. And this is an insulated tube so outside you have insulation right so in insulated tube through which a fluid is flowing and let us say that the fluid temperature is different from the surrounding temperature. So surroundings have a temperature of T naught where as the fluid has a temperature of Ti okay. Then there will be obviously heat transfer depending upon whether T naught is greater than Ti or Ti is greater than T naught. There will be heat transfer from the fluid to the outside or from the outside to the surface outside to the fluid sorry. And what is the heat transfer rate the heat transfer rate can be written like this Q is equal to U naught A naught into Ti minus T naught where Ti is the fluid temperature inside the tube and T naught is the outside surrounding temperature. And where A naught is the surface outside surface area of the tube that means surface area refer to the outside surface okay this is A naught okay. Typically phi T naught into L where T naught is the outside diameter so i can write Q as UA into Ti minus T naught. And what is U as you know just now we have shown that U is nothing but one by R total into A okay.

So what are the different resistances here we have one resistance that is convective heat transfer resistance inside the tube because of the fluid flow and we have one resistance big offered by the tube wall. And then we have another resistance offered by the insulation finally we have another resistance offered by the outside convective heat transfer okay. So basically we have the four resistances in series okay. So you can easily find out what is the R total because R total is nothing but summation of inside convective resistance of conductive resistance offered by the tube wall conductive resistance offered by the insulation and convective resistance offered by the outside surrounding air okay.

So you can find out R total and from R total you can find out U naught once you know U naught you can find out Q okay. So again you can see, what is the advantage of applying resistance network in the concept of thermal resistances. Okay. Sometimes what happens is you can have additional resistances. For the example when a fluid is flowing through a tube let us say that the flow is not very clean. So it can form a scale inside the tube, okay that means there can be scale formation here okay. So what is the effect of the scale formation there will be another resistance term here because of the scale formation okay. There be a resistance term here because of scale formation here and if you know what is the resistance offered by the scale you can find out the new overall heat transfer coefficient right. So this what we have seen is multimode heat transfer.

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Now let us look at very briefly about heat exchangers. A heat exchanger is a device in which heat is transferred from one fluid stream to a another across all it surface basically most of the common heat exchangers have two fluid streams one hot stream and the other cold stream. They come in contact with solid surface there will heat transfer between the hot stream to the cold stream through the solid surface this is the typical example of a commonly used what is known as recuperative type of heat exchangers right. And so as you can see a typical heat exchanger involves both conduction and convection heat transfers.

And there are the wide variety of heat exchangers used in practice in fact there are many types of heat exchangers available and you can classify them in wide variety of ways. So we will look at the classification and different types of heat exchangers. Then again we deal with the design of evaporators and condensers at this point remember that large numbers of different types of heat exchangers exist.

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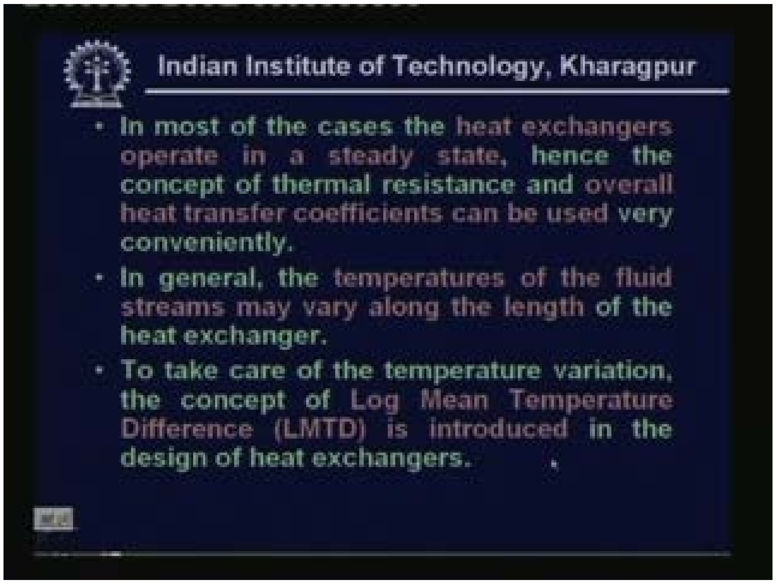

In most of the cases the heat exchangers operate in steady states. So we can apply the concept of thermal resistance and the overall heat transfer coefficients very conveniently. And in general the temperatures of the fluid streams vary along the length of the heat exchanger, the, in the example of the multimode heat transfer for a composite cylinder the temperatures remain constant. That means outside temperature T naught and inside temperature Ti remains constant you have a very simple expression Q is equal to U A into delta T. But in a typical heat exchanger as the fluids flow through the heat exchanger their temperature varies along the length okay. So you do not have a fixed temperature. So to take care of this temperature variation along length means, temperature is defined this is known as log mean temperature difference or LMTD.

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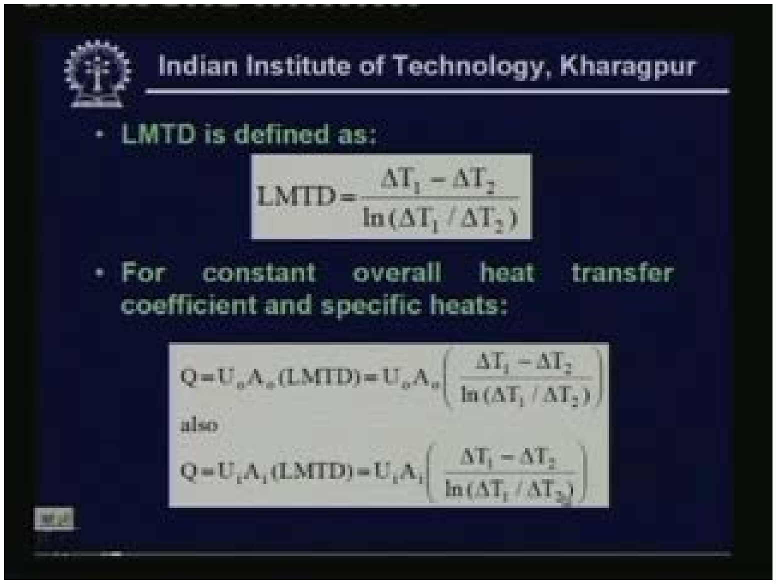

So we have LMTD introduced and it is very widely used in heat exchanger design. So this LMTD is defined as LMTD is equal to delta T one minus delta T two divided by l n delta T one by delta T two where delta T one and delta T two are the temperature differences between the hot and cold streams at the inlet and outlet respectively. So one can be inlet then two will be outlet or vice versa okay.

So they are the basically the terminal temperature differences between the two fluids streams.

So if you are using LMTD then the heat transfer rate is simply given by Q is equal to U A into LMTD and this U A you can write with reference to the outside area. That means you can write it as U naught A naught or you can also write with reference to inner area. That means U i A i so this is a typical expression for heat transfer in a heat exchanger and this expression given here that is Q A is equal to Q is equal to U A into LMTD is applicable for pure parallel flow type of heat exchanger and pure counter flow type of heat exchanger. That means when the fluid flows in parallel flow or in counter flow when they flow in cross wise manner then it is not applicable then we have to add another factor which will consider the other flow direction okay. These aspects again we will discuss when we are discussing the design of evaporators and condensers.

So let me quickly summarize what we have learned in this lesson.

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In the present lesson we have looked at the basic modes of heat transfer. And we have discussed basic governing equations. And we have introduced the concepts of thermal resistance and networks to solve steady state multimode heat transfer problems. And then we have developed analogies between heat mass and momentum and we have also looked at the consequences and usefulness of these analogies. Then we have looked at the basics of heat exchangers. We will be discussing and we will be applying these fundamentals when we do the design of heat exchangers in later chapters okay.

Thank you.