Refrigeration and Airconditioning

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Lecture No. # 41
Cooling & heating Load Calculations (Contd.)

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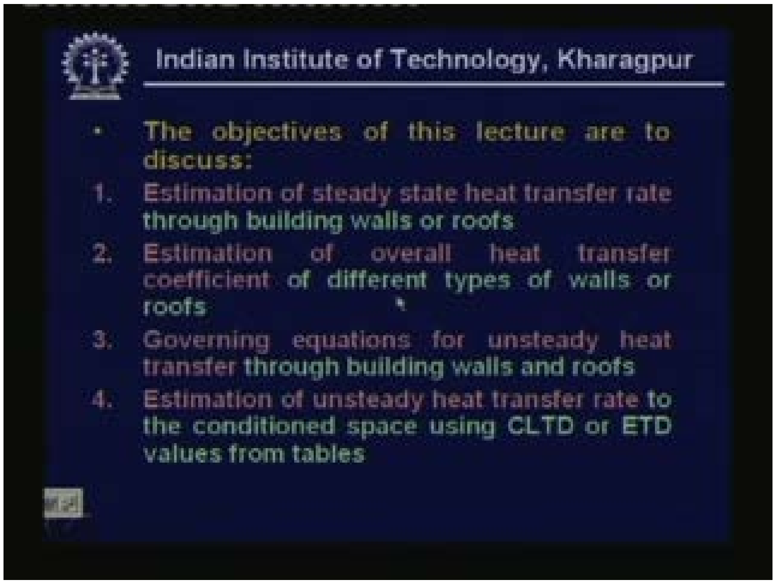

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- The objectives of this lecture are to discuss:
1. Estimation of steady state heat transfer rate through building walls or roofs
2. Estimation of overall heat transfer coefficient of different types of walls or roofs
3. Governing equations for unsteady heat transfer through building walls and roofs
4. Estimation of unsteady heat transfer rate to the conditioned space using CLTD or ETD values from tables

Welcome back, the objectives of this particular lecture are to on discuss estimation of steady state heat transfer rate through building walls or roofs, discuss estimation of overall heat transfer coefficient of different types of walls and roofs then discuss governing equations for unsteady state heat transfer through building walls and roofs and finally estimation of unsteady heat transfer rate to the conditioned space using CLTD or ETD values from tables.

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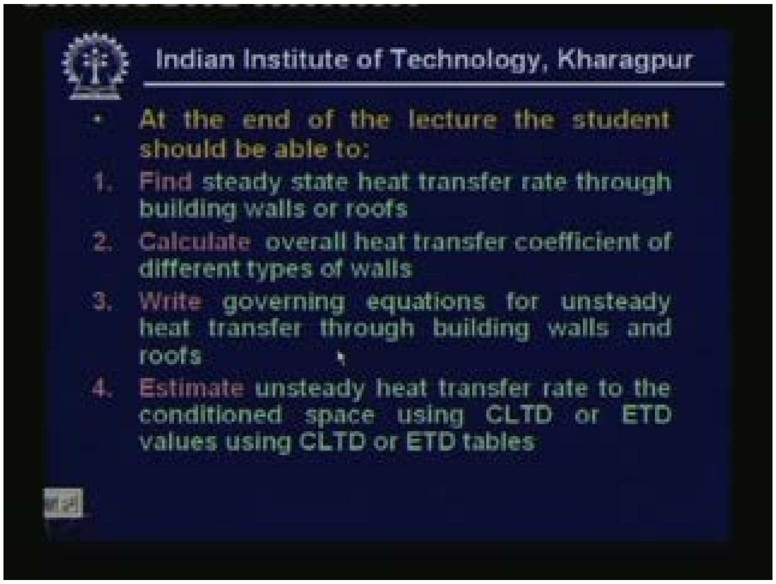

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- At the end of the lecture the student should be able to:

1. Find steady state heat transfer rate through building walls or roofs
2. Calculate overall heat transfer coefficient of different types of walls
3. Write governing equations for unsteady heat transfer through building walls and roofs
4. Estimate unsteady heat transfer rate to the conditioned space using CLTD or ETD values using CLTD or ETD tables

At the end of the lecture you should be able to find steady state heat transfer rate through building walls and roofs, calculate overall heat transfer coefficients of different types of walls, write governing equations for unsteady state heat transfer through building walls and roofs and finally estimate unsteady heat transfer rate to the conditioned space using CLTD or ETD values from the tables.

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Heat transfer through building structure

- Due to temperature difference between indoor and outdoors, heat transfer takes place through the walls and roof of the building
- This is known as fabric heat gain/loss
- Fabric heat gain/loss is sensible heat transfer
- Exact analysis of buildings to estimate fabric heat transfer is very complicated due to:
- Continually changing indoor & outdoor conditions
- Buildings of diverse shape and orietation
- Wide variety of materials used in construction

Let me give a brief introduction to heat transfer through building structures due to temperature different between indoors and outdoors.Hheat transfer takes place through the walls and roof of the building this type of heat transfer is known as fabric heat gain or loss. If the building is gaining heat you call it as heat gain, if it is losing heat it you call it as fabric heat loss. The fabric heat gain or loss is sensible heat transfer. That means it does not involve any latent heat transfer process and the exact analysis of buildings to estimate fabric heat transfer is very complicated. Because of the fact that the outdoor and indoor conditions change continually and buildings are of diverse shape and orientation and a wide variety of materials are used in construction. So because of these factors exact analysis of buildings is very difficult.

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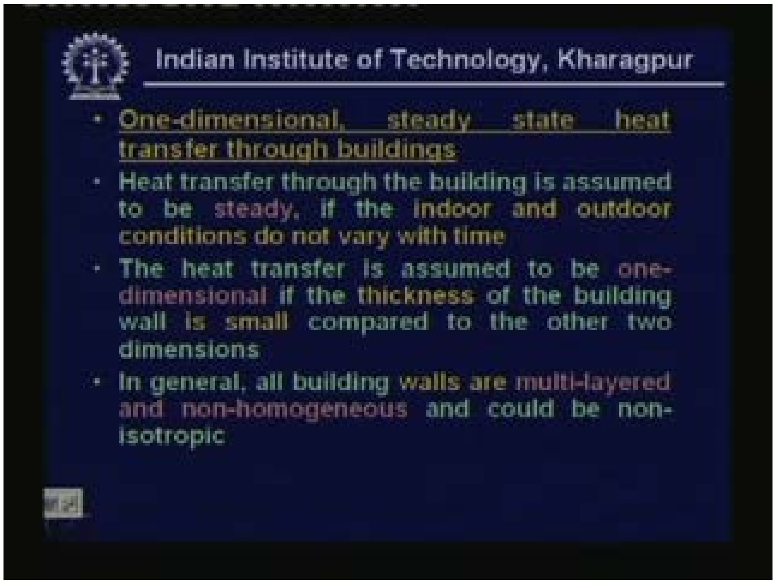

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- One-dimensional, steady state heat transfer through buildings
- Heat transfer through the building is assumed to be steady, if the indoor and outdoor conditions do not vary with time
- The heat transfer is assumed to be one-dimensional if the thickness of the building wall is small compared to the other two dimensions
- In general, all building walls are multi-layered and non-homogeneous and could be non-isotropic

First let us look at one dimensional steady state heat transfer through buildings heat transfer through the building is assumed to be steady if the indoor and outdoor conditions do not vary with time. So these are the assumptions under which you can apply one dimensional steady state heat transfer though the buildings first requirement is that the outdoor and indoor conditions should not vary with time. And the heat transfer is assumed to be one dimensional if the thickness of the building wall is small compared to the other two dimension that means the wall thickness is small compared to its width and height then you can treat it as one dimensional steady state heat conduction problem. In general all building walls are multi layered and non homogeneous and could be non isotropic. Also first let us look at homogeneous walls then we'll we shall discuss non homogeneous walls.

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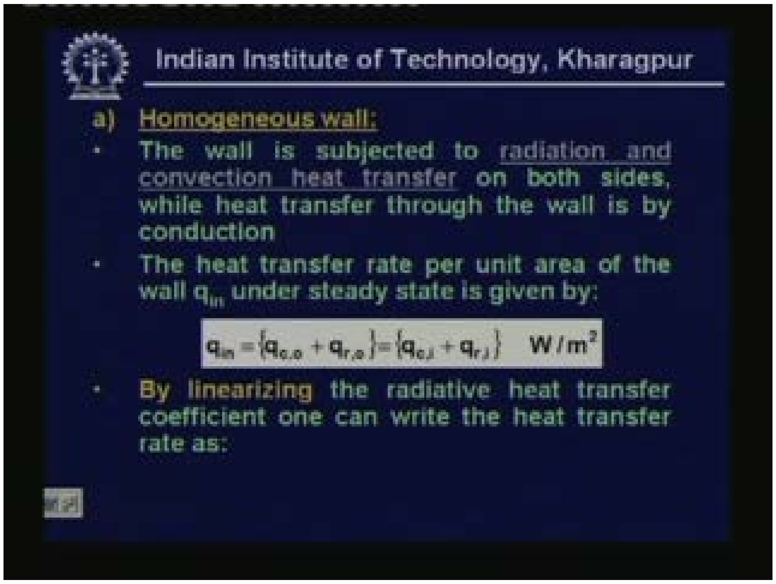

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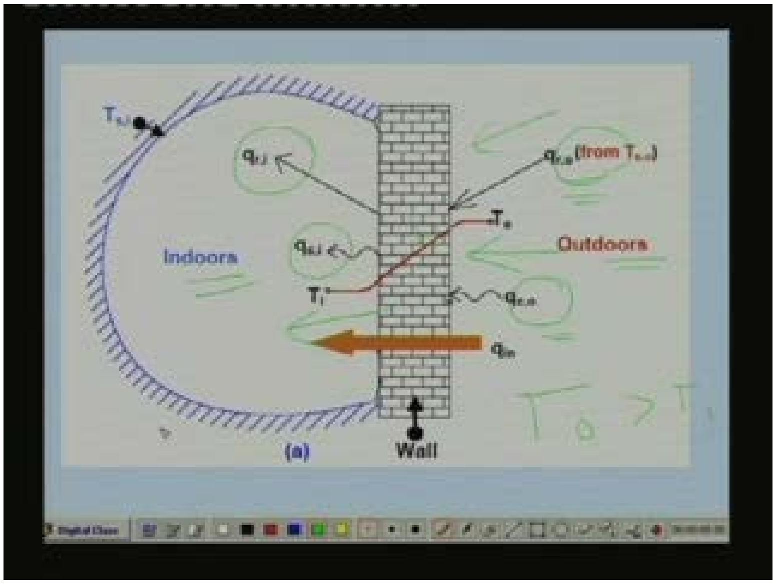
a) Homogeneous wall:

- The wall is subjected to radiation and convection heat transfer on both sides, while heat transfer through the wall is by conduction
- The heat transfer rate per unit area of the wall q_{in} under steady state is given by:

$$q_{in} = \{q_{c,o} + q_{r,o}\} = \{q_{c,i} + q_{r,i}\} \quad W/m^2$$

- By linearizing the radiative heat transfer coefficient one can write the heat transfer rate as:



So homogeneous wall is subjected to radiation and convection heat transfer on both sides while heat transfer through the wall is by conduction. So let me show a picture of this. So this a homogeneous wall okay. So this is a wall and these are the outdoors and these, the indoors and just for an example let us assume that the outdoor temperature T naught is greater than indoor temperature Ti okay. And you have outdoor surface I mean the outer surface of the wall is subjected to radiation heat transfer and it is also subjected to convective heat transfer. So heat transfer takes place from the outdoor to the outer surface of the wall by radiation and by convection.

Then heat transfer through the wall takes place by conduction. Then heat transfer from the wall to the indoors from the inner surface of the wall takes place again by radiation and by convection okay. And since we are talking about steady state heat transfer problem whatever heat enters the wall from the outside should be equal to heat leaving the wall from the inner surface okay. So heat transfer at the outer surface is always equal to heat transfer to the from the inner surface okay, that is why it is steady state.

Now the heat transfer rate per unit area of the wall under steady state is given by q subscript in is equal to q subscript co plus q subscript ro which is equal to q subscript ci plus q subscript ri what is q subscript co q subscript co is nothing but the convective heat transfer from the outdoor air to the outer surface of the wall. And q subscript ro is the radiation radiative heat transfer from the outer surface to the outer surface and q ci is the convective heat transfer from the inner surface to the conditioned space and q ri is the radiant heat transfer from the inner surface to the conditioned space.

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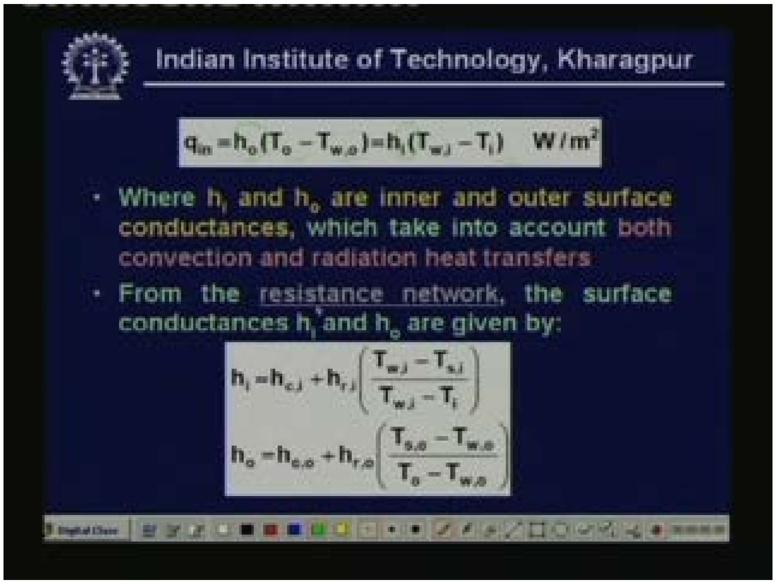

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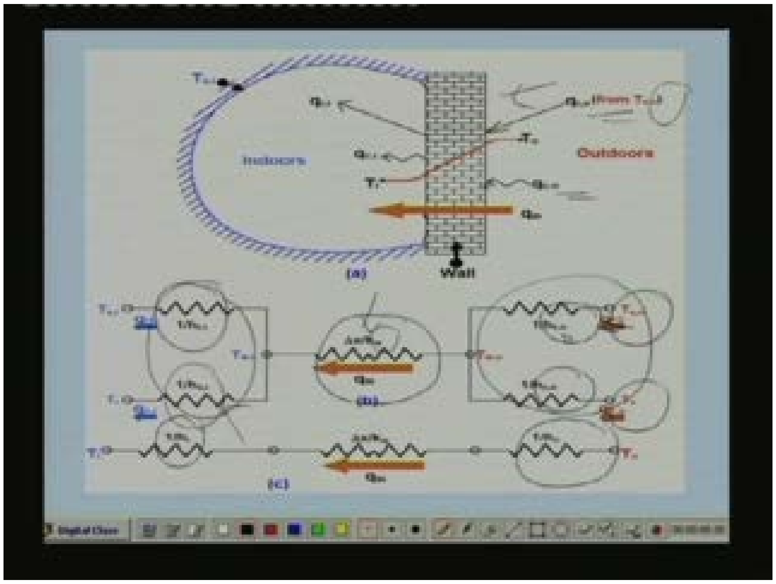
$$q_{in} = h_o(T_o - T_{w,o}) = h_i(T_{w,i} - T_i) \quad W/m^2$$

- Where h_i and h_o are inner and outer surface conductances, which take into account both convection and radiation heat transfers
- From the resistance network, the surface conductances h_i and h_o are given by:

$$h_i = h_{c,i} + h_{r,i}\left(\frac{T_{w,i} - T_{s,i}}{T_{w,i} - T_i}\right)$$

$$h_o = h_{c,o} + h_{r,o}\left(\frac{T_{s,o} - T_{w,o}}{T_o - T_{w,o}}\right)$$



By linearising the radiative heat transfer coefficient we can write the heat transfer rate as, q in is equal to h naught into t naught minus T wo which is equal to hi into Twi minus Ti where hi and hr h naught are inner and outer surface conductance's okay. So these are this is known as outer surface conductance and this is known as inner surface conductance and T naught and Ti are the outer and inner dry bulb temperatures and T subscript wo and T subscript wi are the temperatures of the outer surface of the wall and inner surface of the wall respectively and from the resistance network the surface conductance's hi and h naught are given by; let me show the resistance network here.

Okay. So this again shows the wall and as I have mentioned this is the outer surface of the wall and here you have radiation and you also have convection okay. So and these two heat transfer modes takes place parallely okay. So you have one parallel path by which radiation is taking place and another path through which convection is taking place. So radiation is taking place form a radiant source at temperature T so and convection is taking place from the outdoor dry bulb temperature T subscript o and one by h ro. This is your radiative resistance to radiative heat transfer and this is a resistance to convective heat transfer on the outer surface side. And through the wall the heat transfer is by conduction. So this is the conduction resistance where delta x is thickness of the wall and kw is the thermal conductivities of all material and again from the inner surface to the conditioned space. That means to the indoors you have heat transfer by radiation and convection. So you have radiation heat transfer and convection heat transfer. So you can see here that again one by h subscript ri is a resistance to radiation heat transfer inside the conditioned space and this is resistance to convective heat transfer okay.

So now we can write an equivalent circuit by combining these two parallel resistances into a single resistance one by h naught and similarly for the inside surface side we can combine these two resistances into a single resistance one by hi so this h naught and hi are the equivalent resistances which consider both radiation as well as convection heat transfer on the outer surface side as well as the inner surface side. So you can easily show from the network that h subscript i. That is the inner surface conductance is equal to h subscript ci plus h subscript ri into Twi minus Tsi divided by Twi minus Ti okay, where as I said this is your inner convective heat transfer coefficient. This is the inner linearised radiative heat transfer coefficient this is the temperature of the wall on the inner side and this is the temperature of the conditioned space surface temperature of the conditioned space okay.

So this is the dry bulb temperature of the conditioned space similarly for the outside surface conductance you can write an equation of the which is of the similar form and you see here that if, for example, if the inside surface temperature is same as the inside dry bulb temperature then hi is simply equal to hci plus hri. Similarly for the outside if the outside surface temperature t subscript s o is equal to outdoor dry bulb air temperature then you will find that h naught is equal to simply hco plus hro.

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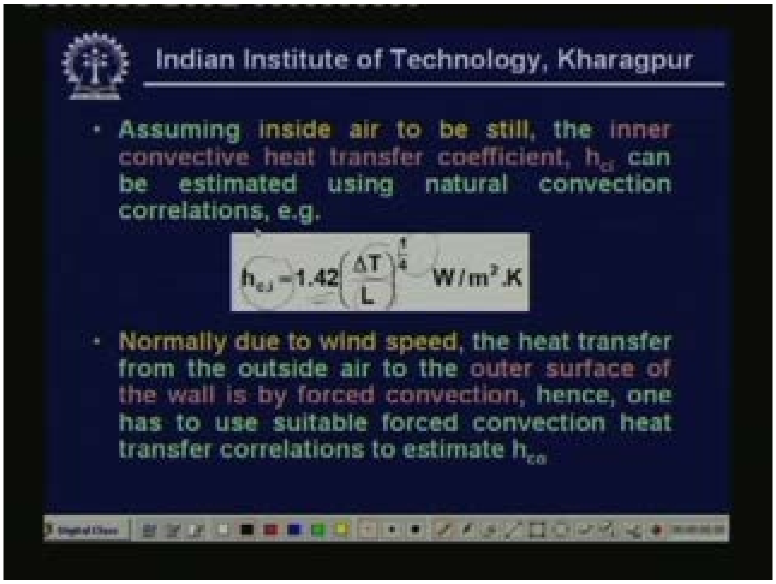

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- Assuming inside air to be still, the inner convective heat transfer coefficient, h_{ci} can be estimated using natural convection correlations, e.g.

$$h_{ci} = 1.42\left(\frac{\Delta T}{L}\right)^{\frac{1}{4}} \quad W/m^2.K$$

- Normally due to wind speed, the heat transfer from the outside air to the outer surface of the wall is by forced convection, hence, one has to use suitable forced convection heat transfer correlations to estimate h_{co}

Assuming inside air to be still normally in the conditioned space we have to maintain very low temperatures, very low air velocities to avoid the problem of draft. So typically the air velocities are of the order of point one five to four point two five meter per second. So for all practical purposes you can treat air inside a conditioned space to be still air. So if the air is still air then the heat transfer between the air and the surface will be because of natural convection okay. So if want to estimate the convective heat transfer coefficient in the condition inside the conditioned space you have to apply suitable natural convective heat transfer correlations okay. A simple correlation is given here for example h subscript ci is the natural convection heat transfer coefficient inside the conditioned space. This is equal to one point four to multiplied by delta T by L to the power of one by four where delta T is a temperature different between the surface and the air and L is the length or height of the surface okay.

So this generally valid for atmospheric air okay. So if you know the surface temperature and the air temperature and the dimensions of the wall you can calculate the heat transfer coefficient and as for as the outside heat transfer coefficient is concerned normally due to wind speed the heat transfer from the outside air to the outer surface of the wall is by force convection okay. So once, hence one has to use suitable force convection heat transfer correlation to estimate hco okay. So you have to use hm if it is horizontal wall then you have to use force convection heat transfer coefficient for flow over horizontal wall like that.

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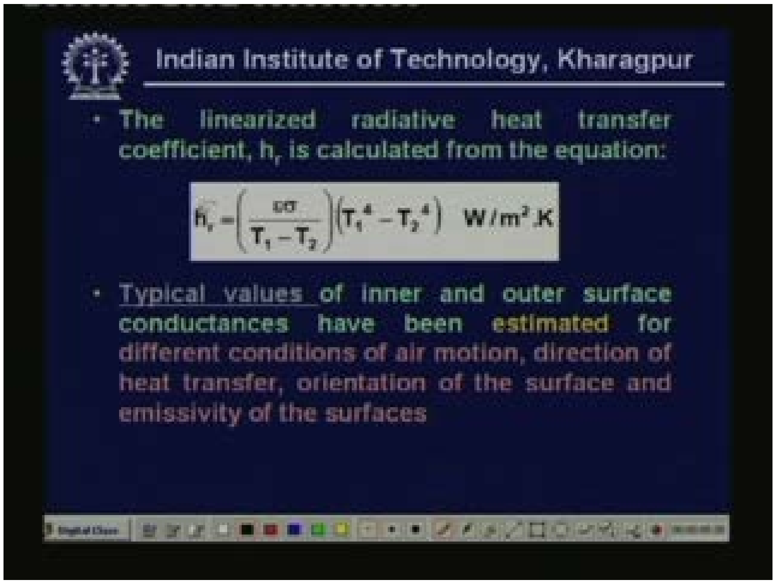

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- The linearized radiative heat transfer coefficient, h_r is calculated from the equation:

$$h_r = \left(\frac{\varepsilon\sigma}{T_1 - T_2}\right)\left(T_1^4 - T_2^4\right) \quad W/m^2.K$$

- Typical values of inner and outer surface conductances have been estimated for different conditions of air motion, direction of heat transfer, orientation of the surface and emissivity of the surfaces

And the linearized radiative heat transfer coefficient hr is calculated from the equation. This we have discussed while discussing fundamentals of heat transfer the linearized heat transfer coefficient hr okay. So this is equal given by this expression where t one and t two are the two surface temperatures between which radiation heat transfer is taking place and epsilon is the absorbsity of the wall and this sigma is the Stefan Boltzmann constant right. And the temperature should be in absolute scale okay. And typical values of inner and outer surface conductances have been estimated for different conditions of air motion direction of heat transfer orientation of the surface and emissivity of the surface. Let me show you some typical values.

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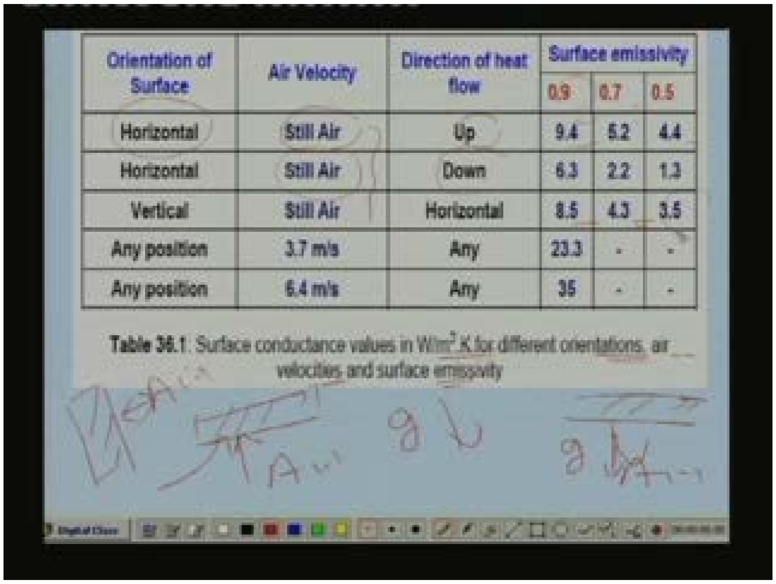

Orientation of Surface	Air Velocity	Direction of heat flow	Surface emissivity		
			0.9	0.7	0.5
Horizontal	Still Air	Up	9.4	5.2	4.4
Horizontal	Still Air	Down	6.3	2.2	1.3
Vertical	Still Air	Horizontal	8.5	4.3	3.5
Any position	3.7 m/s	Any	23.3	-	-
Any position	6.4 m/s	Any	35	-	-

Table 36.1: Surface conductance values in W/m^2.K for different orientations, air velocities and surface emissivity

Okay. So this table shows as I said surface conductance values in watt per meter square Kelvin for different orientations okay. Different air velocities and surface emissivity, for example, take this is the orientation of the surface is horizontal and the air velocity is still air. That means you have to you can apply this still air condition to the conditioned space inside the building okay. And if the direction of the heat flow is upwards and if the surface emissivity is point nine then the heat transfer coefficient is nine point four watt per meter square Kelvin if the surface emissivity is point seven. Then the heat transfer coefficient is five point two watt per meter square Kelvin and if the emissivity if point five this is the heat transfer coefficient.

What you mean by horizontal and direction of heat flow is of you have a wall like this okay. This is a horizontal wall right and you have air here and direction of heat transfer is upward that means heat transfer taking place form the air to the wall in this direction okay, where the gravity is in this direction okay. For this condition you can take these values and as I said epsilon is the emissivity of this surface okay. And for the next condition again you have the still air and the direction of heat flow is downwards that means you have again the wall okay. And let us say that the air is here and heat transfer is taking place from the wall to the air okay, in this direction okay. And g is acting in this direction in downwards direction again for different values of surface emissivity you have the values of heat transfer coefficient okay. Next comes vertical wall and still air that means you have a vertical wall like this okay. And you have air and heat transfer is taking place between the wall to the air okay.

And again if the emissivity is point nine this is the heat transfer coefficient if emissivity is point seven this is the heat transfer coefficient and for point five emissivity this is the heat transfer coefficient okay. So as I said these three conditions are applicable for conditioned space. That means inside the building okay, and next two conditions where the air velocity is given as three point seven meter per second and six point four meter per second here the this is applicable to any position because here the heat transfer rate is mainly by force convection okay. One thing you can notice here is that when the air is still for example for these conditions heat transfer rate is by natural convection and also by radiation.

So emissivity is coming into picture okay, and typically the heat transfer coefficient values are small right because of the convective heat transfer coefficient is generally small in case of natural convection whereas when you have force convection. That means when you have velocity of air at the rate of three point seven meter per second or six point four meter per second heat transfer is mainly by force convection. When it is by force convection the orientation of the surface is not very important okay. Similarly the emissivity of the surface is also not very important because compared to the force convection heat transfer the radiation heat transfer is negligible. So you can see that the, for this case the heat transfer coefficient depends only on the velocity if the velocity is three point seven meter per second. Then the heat transfer coefficient is twenty-three point three watt per meter square Kelvin if it is six point four meter per second it is thirty-five watt per meter square Kelvin okay.

So these are the typical values in absence of any correlations or any better data you can use this data for estimating the inside and outside surface conductance’s. You must keep in your mind that the surface conductance includes both a convective as well as radiative heat transfer coefficients okay.

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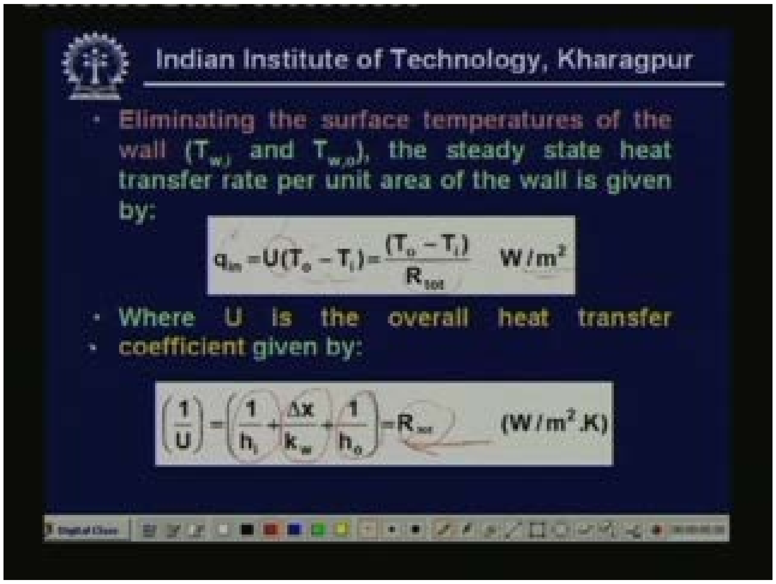

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- Eliminating the surface temperatures of the wall ($T_{w,i}$ and $T_{w,o}$), the steady state heat transfer rate per unit area of the wall is given by:

$$q_{in} = U(T_o - T_i) = \frac{(T_o - T_i)}{R_{tot}} \quad W/m^2$$

- Where U is the overall heat transfer
- coefficient given by:

$$\left(\frac{1}{U}\right) = \left(\frac{1}{h_i} + \frac{\Delta x}{k_w} + \frac{1}{h_o}\right) = R_{tot} \quad (W/m^2.K)$$

Now you can eliminate the surface temperature of the wall. That means T subscript wi and T subscript wo and write the steady state heat transfer equation in this form using the overall heat transfer coefficient U okay. If you are using overall heat transfer coefficient U you can write the steady state heat transfer rate per unit area this is heat flux basically watt per meter square that is equal to overall heat transfer coefficient multiplied by the temperature difference between the outdoor air and indoor air okay. T naught minus Ti so U is nothing but one by total resistance right so this is nothing but all the resistance are summed up okay.

And the inverse of the resistance is your overall heat transfer coefficient okay. And the we have seen that the expression for overall heat transfer coefficient for this homogeneous wall is given by this is the resistance inner convective and radiative resistance this is a resistance offered by the wall this is outer convective and radiative resistance these three resistances are in series. So you add them up find out the r total and inverse of r total will give you the value of U okay. Once you know the value of U and outer and inner dry bulb temperatures you can calculate what is the steady state heat transfer rate.

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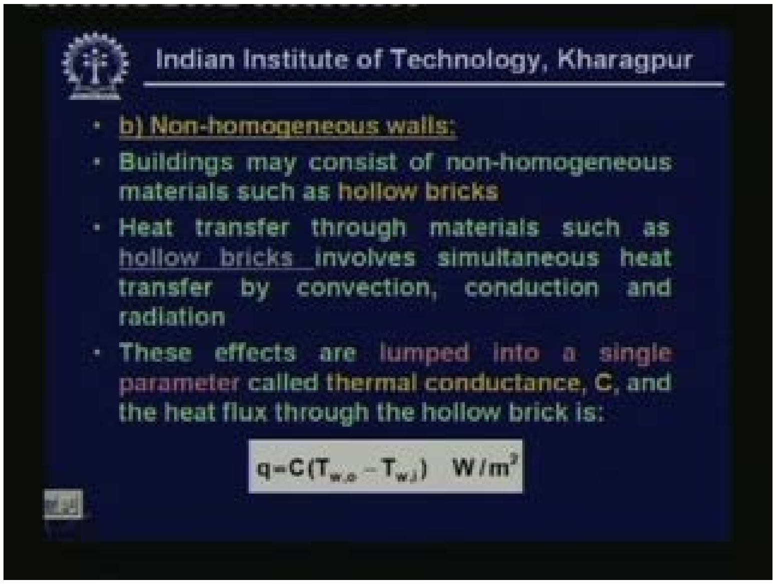

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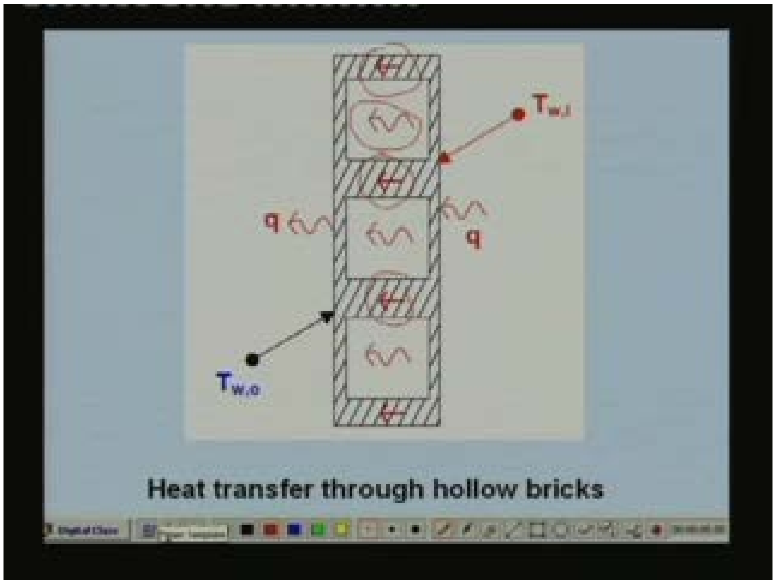
- b) Non-homogeneous walls:
- Buildings may consist of non-homogeneous materials such as hollow bricks
- Heat transfer through materials such as hollow bricks involves simultaneous heat transfer by convection, conduction and radiation
- These effects are lumped into a single parameter called thermal conductance, C, and the heat flux through the hollow brick is:

$$q = C(T_{w,o} - T_{w,i}) \quad W/m^2$$



Heat transfer through hollow bricks

Now let us look at non-homogeneous walls buildings may consist of non homogeneous materials such as hollow bricks hollow bricks are quiet a very widely used in buildings. Because hollow bricks are have better insulation properties compared to solid bricks okay. That is the reason why hollow bricks are quite widely used the heat transfer through materials such as hollow bricks involve simultaneous heat transfer by convection conduction and radiation. So let me show a picture of hollow brick okay. So this shows a picture of a hollow brick. So you can see here that in this case heat transfer takes place by conduction here okay. Through the material of the wall this is by conduction heat transfer through the solid material and through the air space you have heat transfer take taking place by radiation as well as convection as well as conduction okay. So you have a multi mode heat transfer problem here okay. Conduction convection and radiation okay. So for such problems what is done is all these affects like convection conduction and radiation they are lumped into a single parameter and this single parameter is called as thermal conductance c and the heat flux through the hollow brick is simply given as q is equal to C into T w o minus T w i where T w o and T w i are the outer and inner surface temperatures of the hollow brick and C is the conductance.

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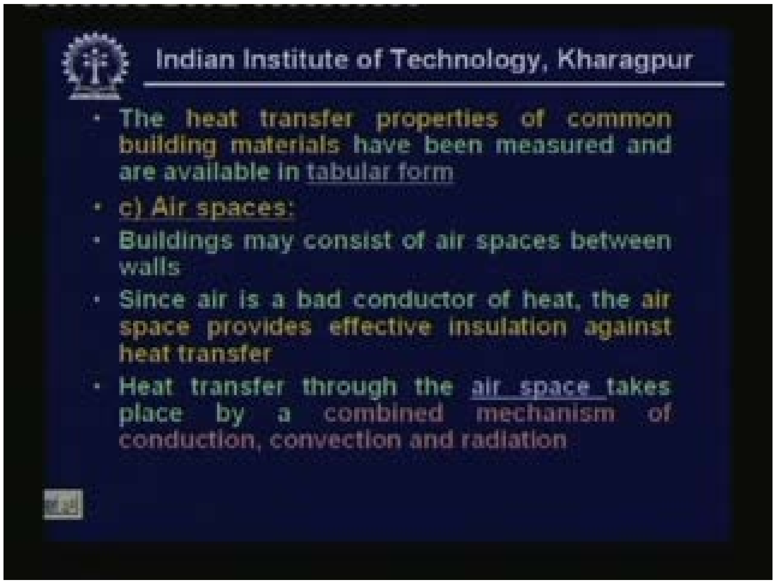

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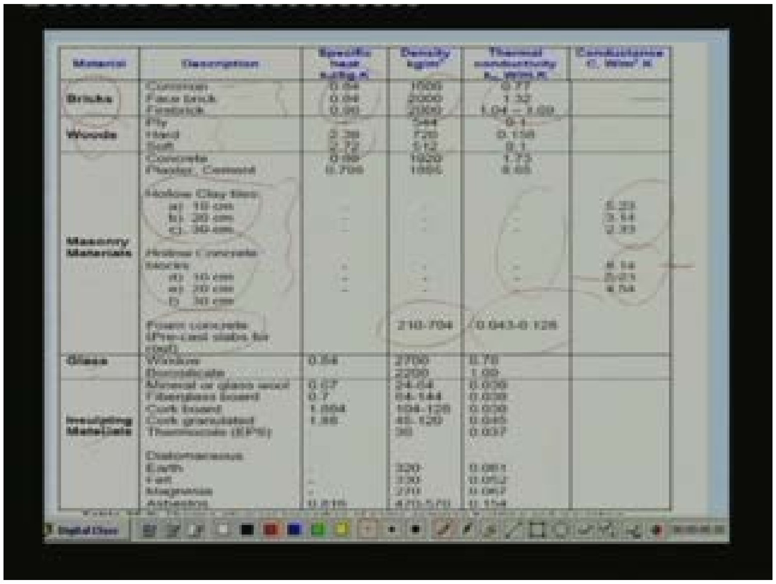
- The heat transfer properties of common building materials have been measured and are available in tabular form
- c) Air spaces:
- Buildings may consist of air spaces between walls
- Since air is a bad conductor of heat, the air space provides effective insulation against heat transfer
- Heat transfer through the air space takes place by a combined mechanism of conduction, convection and radiation



Material	Description	Specific heat kJ/kg K	Density kg/m³	Thermal conductivity k, W/m K	Conductance C, W/m² K
Bricks	Common	0.84	1600	0.77	
	Face brick	0.84	2000	1.32	
	Firebrick	0.96	2000	1.04 – 1.09	
Woods	Ply	–	544	0.1	
	Hard	2.39	720	0.159	
	Soft	2.72	512	0.1	
Masonry Materials	Concrete	0.88	1920	1.73	
	Plaster, Cement	0.706	1885	8.65	
	Hollow Clay tiles				
	a) 10 cm	–	–	–	5.23
	b) 20 cm	–	–	–	3.54
	c) 30 cm	–	–	–	2.33
	Hollow Concrete blocks				
	a) 10 cm	–	–	–	8.14
	b) 20 cm	–	–	–	5.21
	c) 30 cm	–	–	–	4.54
	Foam concrete (Pre-cast slabs for roof)		210-704	0.043-0.128	
Glass	Window	0.84	2700	0.78	
	Borosilicate		2200	1.09	
Insulating Materials	Mineral or glass wool	0.67	24-64	0.039	
	Fiberglass board	0.7	64-144	0.038	
	Cork board	1.884	104-128	0.039	
	Cork granulated	1.88	45-120	0.045	
	Thermocole (EPS)		30	0.037	
	Diatomaceous				
	Earth	–	320	0.061	
	Felt	–	330	0.052	
	Magnesia	–	270	0.067	
	Asbestos	0.816	470-570	0.154	

The heat transfer properties of common building materials have been measured and they are available in tabular form okay let me show a typical values. You can see here that for wide variety of common commonly used materials you have the property. For example for bricks okay, again under bricks you have common brick you have face brick you have fire brick. So for all these types of bricks these are the specific heat values this is the these are densities and these are the thermal conductivity values since these materials are homogeneous materials you need not give conductance value thermal conductivity value is enough.

And from the thickness of the brick and the thermal conductivity you can find out what is the resistance next comes woods. So you have plywood hard wood soft wood and these are the specific heat values these are the densities again these are the thermal conductivity values because these are also homogeneous. When it comes to hollow clay tiles or hollow concrete blocks the thermal conductivity values are not given. Because here the heat transfer rate as I have discussed just now is by multi mode convection conduction and radiation. So for these materials the conductance values are given these values are generally obtained from experimental measurements.

So for different types of for example hollow concrete block of ten centimeter thick this is your conductance value for twenty centimeter thick this is the conductance value for thirty centimeter that is the conductance value. Similarly for foam concrete okay, this is the density value and this is the thermal conductivity value similarly for glass and similarly for insulting material okay. So this kind of properties is available in air conditioning design data books such as ASHRAE data books or other air-conditioning books. So looking at the tables you can take the properties like specific heat density thermal conductivity or conductance and you can calculate if, for example if you are calculating the overall heat transfer coefficient then you can use the either the conductance value or thermal conductivity and thickness. And you can find out what is the overall heat transfer coefficient and from the overall heat transfer coefficient and the temperature difference you can find out what is the heat flux through the wall okay.

Now let us look at air spaces what is the air space buildings may consists of air spaces between walls and air spaces may also be there. For example in the fall ceiling or in attic space okay. And since air is a bad conductor of heat the air space provides effective insulation against heat transfer. So this is one of the reasons why air spaces are used in buildings okay. It provides good insulation against heat transfer so the load on the building gets reduced. And heat transfer through the air space takes place by a combined mechanism of conduction convection and radiation. So again you have a multi mode heat transfer in an air space okay.

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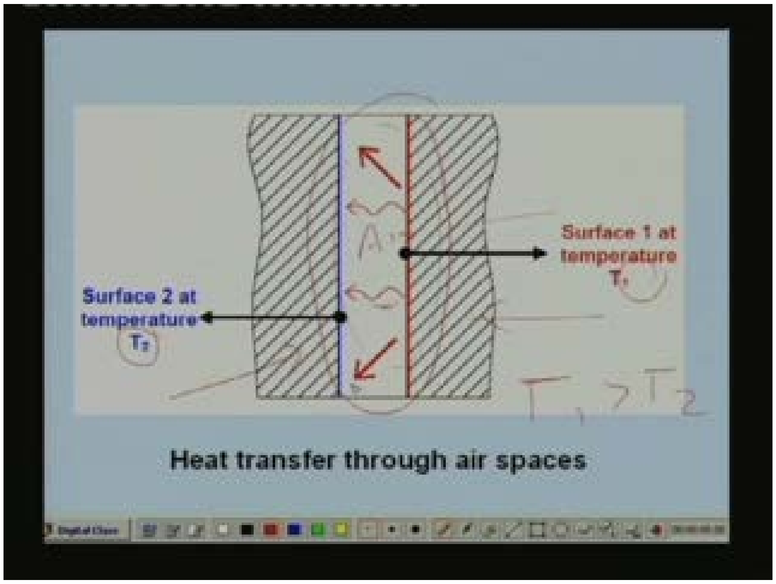

Heat transfer through air spaces

So let me explain that, so you have this is a wall and this is the wall and been in between these two walls you have the air space okay. So this is the air space, let us say that this surface is at a temperature T one and this surface is at temperature T two okay. And for the time being let's assume that T one is greater than T two okay. So heat transfer takes place from this surface to this surface. So since you have air here you have air here, so heat transfer takes place by conduction through the air by convection from the surface to the air and from the air to the surface and directly by radiation from this surface to this surface. So you have all three heat transfer modes taking place between one surface to the other surface through the air film. So this is the air gap okay. So for this kind of air spaces how do we calculate the heat transfer rate.

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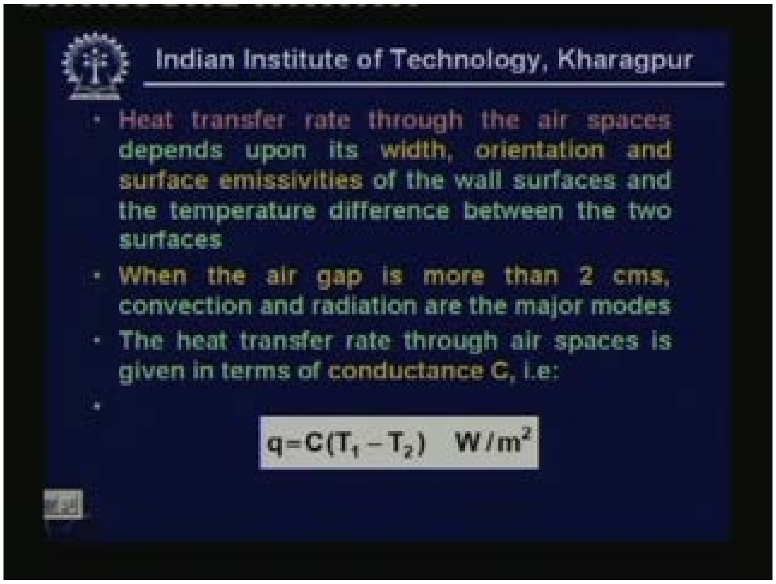

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- Heat transfer rate through the air spaces depends upon its width, orientation and surface emissivities of the wall surfaces and the temperature difference between the two surfaces
- When the air gap is more than 2 cms, convection and radiation are the major modes
- The heat transfer rate through air spaces is given in terms of conductance C, i.e:

$$q=C(T_1-T_2)\quad W/m^2$$

Now heat transfer rate through the air spaces depends upon its width orientation and surface emissivity’s. Because radiation is involved so surface emissivity is also come into picture and also the temperature difference between the two surfaces when the air gap is more than two centimeters it is observed that the conduction heat transfer is negligible and generally the convection radiation are the major modes by which heat is transferred okay. When the gap is more than two centimeters and the heat transfer rate through air spaces is given in terms of again we use conductance okay. So heat transfer rate q is equal to C into T one minus T two per unit area. So watt per meter square where C is the conductance of the air gap and T one and T two are the two surface temperatures.

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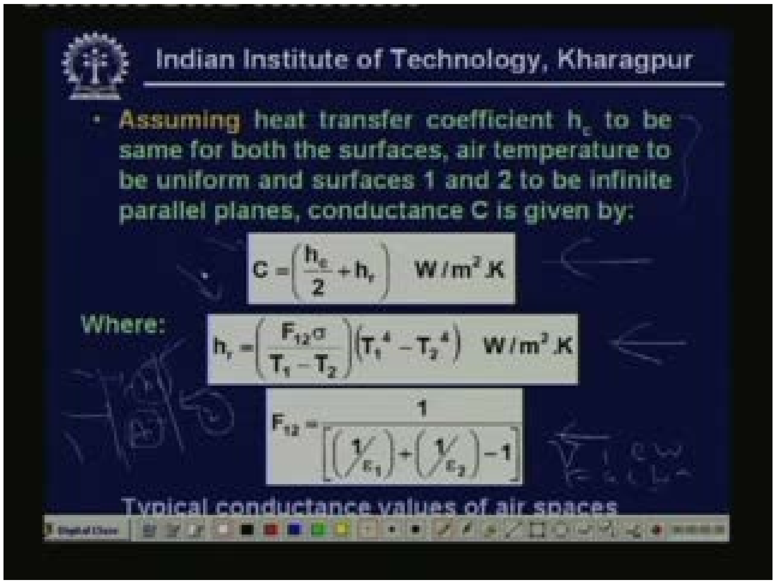

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- Assuming heat transfer coefficient h_c to be same for both the surfaces, air temperature to be uniform and surfaces 1 and 2 to be infinite parallel planes, conductance C is given by:

$$C=\left(\frac{h_c}{2}+h_r\right)\quad W/m^2.K$$

Where:

$$h_r=\left(\frac{F_{12}\sigma}{T_1-T_2}\right)\left(T_1^4-T_2^4\right)\quad W/m^2.K$$

$$F_{12}=\frac{1}{\left[\left(1/\varepsilon_1\right)+\left(1/\varepsilon_2\right)-1\right]}$$

Typical conductance values of air spaces

And assuming heat transfer coefficient hc to be same for both the surfaces okay. So what is the meaning of that so you have two surfaces okay. This is surface one and this is surface two let us say, so you have air here so there is a heat transfer coefficient between this surface and air and there is heat transfer coefficient between this surface and air. So if you assume that this heat transfer coefficient between the air and surface one and air and surface two are same okay, which is equal to hc right and the temperature is uniform. That means there is no temperature gradient inside the air space right and these two plates are infinite parallel plains.

Then the conductance is given by C is equal to hc by two plus hr you can derive this very easily this expression under these assumptions okay. So the conductance value can be obtained if you know the convective heat transfer coefficient and linearised radiative heat transfer coefficient and the linearised radiative heat transfer coefficient is given by this expression where F subscript one two this one this is called as view factor okay. View factor or configuration factor or geometry factor okay. This we have discussed again while discussing radiation heat transfer. So you can see that the view factor is a function of emissivity of surface one epsilon one and emissivity of surface two epsilon two.

So if you know the emissivity of the surfaces one and two you can calculate the view factor and if you know the surface temperatures T one and T two you can calculate radiative heat transfer coefficient. And if you calculate the convective heat transfer coefficient you can find out what is the conductance of the air space okay. And again typical conductance values of air spaces are given in this table.

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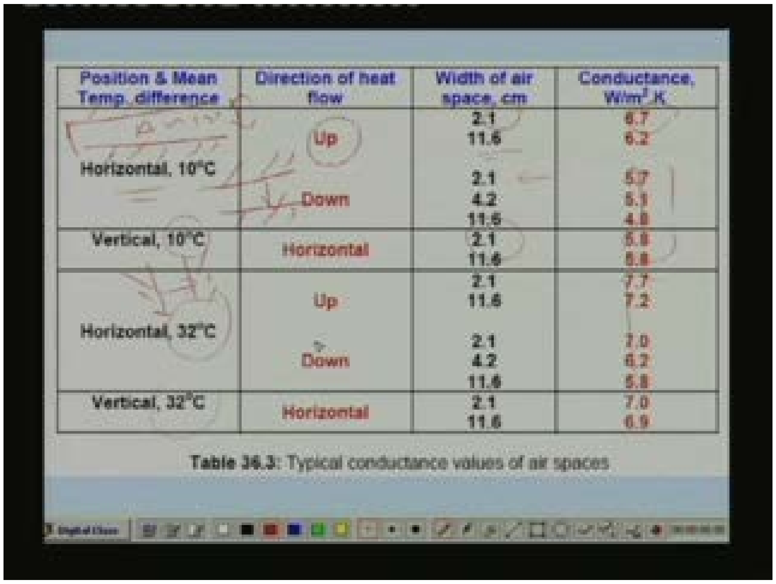

Position & Mean Temp. difference	Direction of heat flow	Width of air space, cm	Conductance, W/m^2.K
Horizontal, 10°C	Up	2.1 11.6	6.7 6.2
	Down	2.1 4.2 11.6	5.7 5.1 4.8
Vertical, 10°C	Horizontal	2.1 11.6	5.8 5.8
Horizontal, 32°C	Up	2.1 11.6	7.7 7.2
	Down	2.1 4.2 11.6	7.0 6.2 5.8
Vertical, 32°C	Horizontal	2.1 11.6	7.0 6.9

Table 36.3: Typical conductance values of air spaces

Okay. So these are the typical conductance values of air spaces again you can see here that since you have convection as well as radiation the orientation places a major role because inside the air space convection heat transfer is by natural convection. So the orientation and temperature difference become important for example for horizontal air space that means you have air space like this okay. So this is your air space okay. And if the heat transfer is upward that means heat transfer taking place from the bottom surface to the top surface and if the air gap. That mean this gap is two point one centimeters this is the conductance value if it is eleven point six centimeters the conductance value six point two and the other hand for the temperature difference of ten degree centigrade. That means T one minus T two of ten degree centigrade if the heat flow direction is downwards that means you have two surfaces like this and heat is flowing in this direction.

Then for different air gaps you have the conductance values five point seven five point one four point eight okay. These things and for vertical that means you have surfaces like this okay. And the temperature difference between these two surfaces is ten degrees and the heat flows in the horizontal direction. That means in this direction then depending upon the air gap you have the conductance value five point eight five point eight four air gap of two point one and eleven point six centimeters okay. Similarly for thirty-two degree centigrade these are the conductance values and if it is vertical these are the conductance values in general you can see that when the temperature difference increases the conductance values increases okay.

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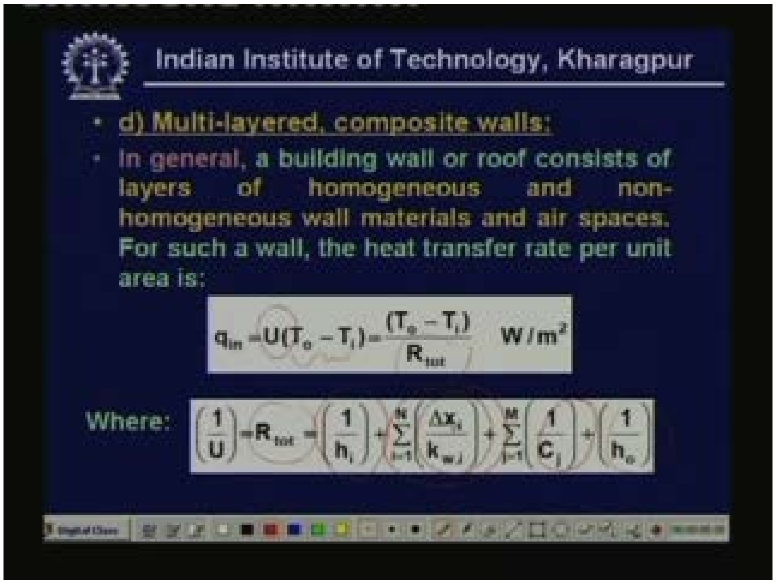

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- d) Multi-layered, composite walls:
- In general, a building wall or roof consists of layers of homogeneous and non-homogeneous wall materials and air spaces. For such a wall, the heat transfer rate per unit area is:

$$q_{in} = U(T_o - T_i) = \frac{(T_o - T_i)}{R_{tot}} \quad W/m^2$$

Where: $\left(\frac{1}{U}\right) = R_{tot} = \left(\frac{1}{h_i}\right) + \sum_{i=1}^{N}\left(\frac{\Delta x_i}{k_{w,i}}\right) + \sum_{j=1}^{M}\left(\frac{1}{C_j}\right) + \left(\frac{1}{h_o}\right)$

Now let us look at a combined wall a multi layered composite wall so in general a building wall or a roof consists of layers of homogeneous and non homogeneous wall materials and air spaces. That means the same wall may consists of several layers one layer may consist of a homogeneous material second layer may consists of a non homogeneous material third layer may consist of an air space and so on okay. So this kind of a wall is known as a composite wall or a multi layered wall. So for composite wall or a multilayered wall the heat transfer rate per unit area are the heat flux is given by q subscript in okay.

So this is equal to overall heat transfer coefficient U into temperature difference across the wall T naught minus T i okay. T naught is the outdoor temperature T i is the indoor temperature okay. Which is equal to T naught minus T i by R total with where R total is the total resistance to heat transfer. So total resistance heat transfer for a multilayered composite wall is given by this expression here this factor one by h subscript i is the internal resistance due to inner conductance and this factor sigma i is one to n delta x by kwi is the sum total of the conductance resistances offered by all the homogeneous walls okay. So this holds for all homogeneous walls and this one takes care of all non homogeneous wall as well as air spaces okay.

And finally one by h naught this takes care of the outer resistance okay. Outer resistance due to conduction and a convection and radiation okay. So if you know the individual resistances or if you know the properties of the individual materials right then you can calculate the individual resistance and from the individual resistances you can calculate the total resistance and from the total resistance you can calculate the overall heat transfer coefficient and from the overall heat transfer coefficient and temperature difference you can find out what is the steady state heat transfer rate through a multi layered or composite wall.

Sometimes a multi layered or composite wall may have parallel paths okay. Then you have to draw a equivalent resistance network and from the resistance network find out what is the total resistance and from the total resistance find the overall heat transfer coefficient and so on okay. So it is always very useful to draw the resistance network first and then evaluate each individual resistance and then add them up and find the total resistance okay. That way you can find out the heat transfer rate under steady state conditions okay.

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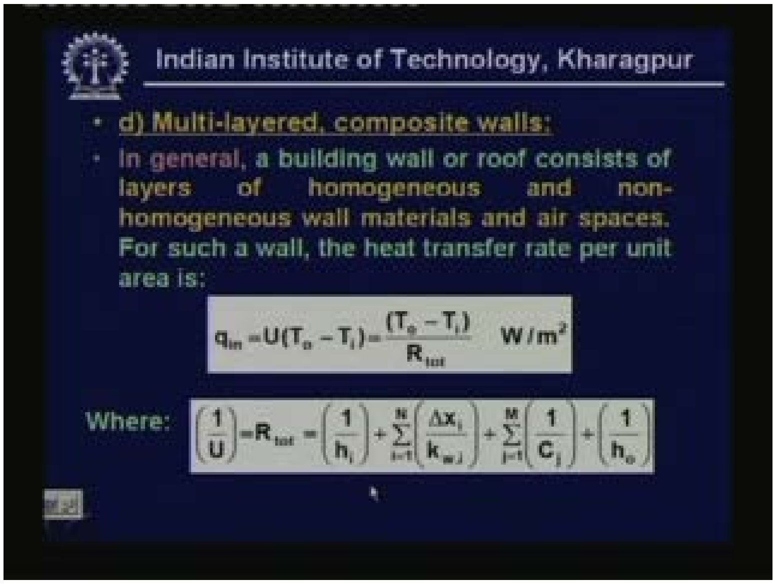

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- **d) Multi-layered, composite walls:**
- In general, a building wall or roof consists of layers of homogeneous and non-homogeneous wall materials and air spaces. For such a wall, the heat transfer rate per unit area is:

$$q_{in} = U(T_o - T_i) = \frac{(T_o - T_i)}{R_{tot}} \quad W/m^2$$

Where: $$\left(\frac{1}{U}\right) = R_{tot} = \left(\frac{1}{h_i}\right) + \sum_{i=1}^{N}\left(\frac{\Delta x_i}{k_{w,i}}\right) + \sum_{j=1}^{M}\left(\frac{1}{C_j}\right) + \left(\frac{1}{h_o}\right)$$

Now let us look at unsteady state heat transfer through walls and roofs in general heat transfer through building walls and roofs is unsteady due to variation solar radiation and varying temperatures even though we have discussed. So far we have discussed steady state heat transfer and how to calculate heat transfer rate under steady state condition you find that most of the times the heat transfer is not under steady state okay. Most of the time heat transfer through the buildings is in an unsteady state okay. This is mainly because of the variations in the solar radiation and variations in the outdoor and indoor temperatures. If the building is air conditioned then the indoor indoor temperature may remain constant. But the outdoor temperature will vary continuously throughout the day and again it will vary from day form day right.

Similarly the solar radiation varies throughout the day. So because of the variation of the solar radiation and outdoor temperature with time you have a problem where the heat transfer is not steady. But it is unsteady okay here the unsteady state arises because of the time varying boundary conditions and also because of the thermal storage properties of the walls and roof okay in general the building walls and roofs have very large but finite thermal capacity okay. Because the thermal capacity they store energy and similarly they release energy. So this thermal storage effect gives rise to unsteady effects okay. For example let me show a solar radiation and how the solar radiation varies.

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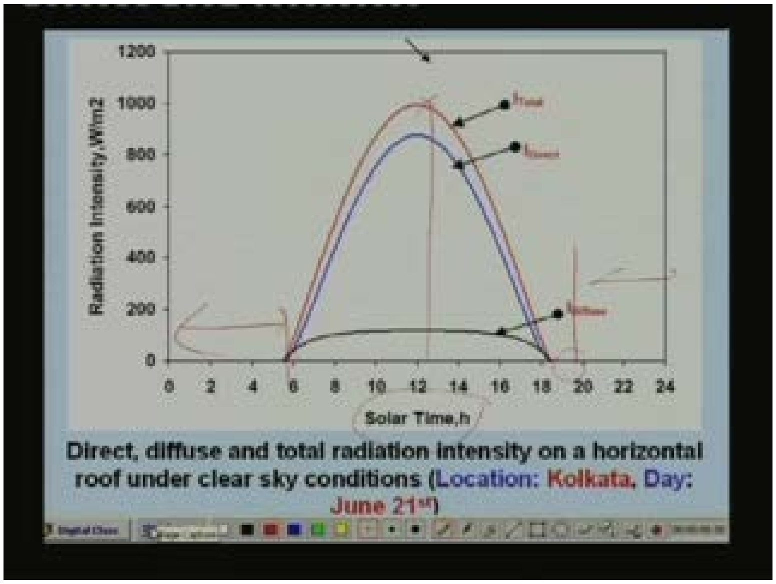

Direct, diffuse and total radiation intensity on a horizontal roof under clear sky conditions (Location: Kolkata, Day: June 21st)

Okay. So this is a typical variation of direct diffuse and total radiation incident intensity on a horizontal roof under clear sky conditions and the data is for holds good for Kolkata and the day is June twenty-first okay. It is a horizontal roof under clear sky conditions. So you can see that it is zero from and these point it is zero because this before sunrise and this is after sun set so solar radiation will be there only during the sun okay, during that day, so at this point sun rises. So gradually the diffuse radiation and direct radiation increase with solar time they reach a peak at solar noon okay. Then again they gradually decrease and again they gradually become zero at sunset. So it is zero at sunrise and zero at sunset so it is continuously varying throughout the day. Because of this the outdoor boundary condition the radiative boundary condition also varies continuously right which time.

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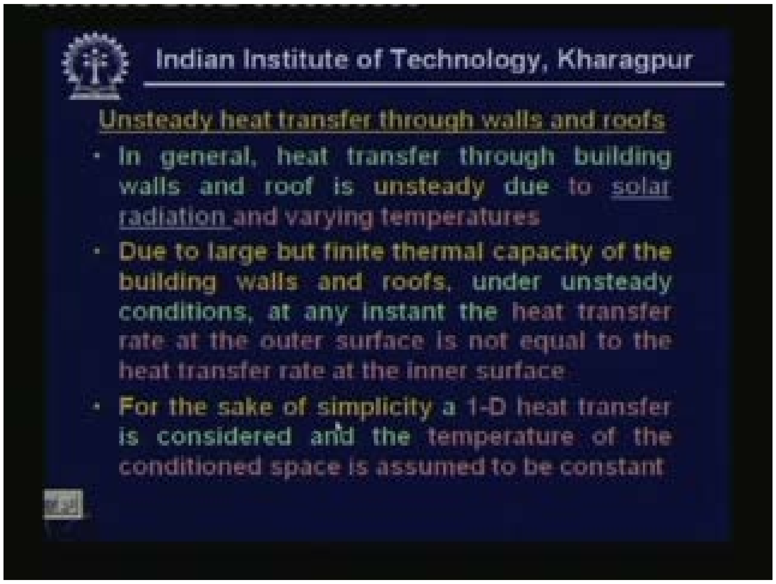

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Unsteady heat transfer through walls and roofs

- In general, heat transfer through building walls and roof is unsteady due to solar radiation and varying temperatures
- Due to large but finite thermal capacity of the building walls and roofs, under unsteady conditions, at any instant the heat transfer rate at the outer surface is not equal to the heat transfer rate at the inner surface
- For the sake of simplicity a 1-D heat transfer is considered and the temperature of the conditioned space is assumed to be constant

Similar to solar radiation the outdoor temperature also varies with time Noise due to as I said due to large but finite thermal capacity of the building walls and roofs under unsteady conditions at any instant the heat transfer rate at the outer surface is not equal to the heat transfer rate at the inner surface. This is very important what it mean is, if I have the wall let us say okay, this is outdoor okay this is in door. So heat transfer is taking place to the outer surface of the wall by radiation okay. And also by convection let us say similar heat transfer taking place from the inner surface of the wall by radiation and convection you find out whatever heat transfer is taking place here okay, is not same as whatever heat transfer taking place from inner surface to the, a conditioned space. That means if here if this is q in and if this is q out then q in is not equal to q out okay.

This comes into picture because of the thermal storage capacity of the walls okay. And what we do here is for the sake of simplicity we assume one dimension heat transfer and we also assume that the temperature of the conditioned space remains constant that means typically we are carrying out this analysis for a building which is air conditioned. Because it is possible to maintain the conditioned space temperature at a constant value only by using an artificial method such as an air conditioning system okay. If you do not have any air conditioning then inside temperature also will vary along with the outside temperature okay. So for the sake of simplicity we assume that the building is air conditioned so inside temperature remains constant whereas the outside temperature that means surface temperature on the outer wall varies continuously okay.

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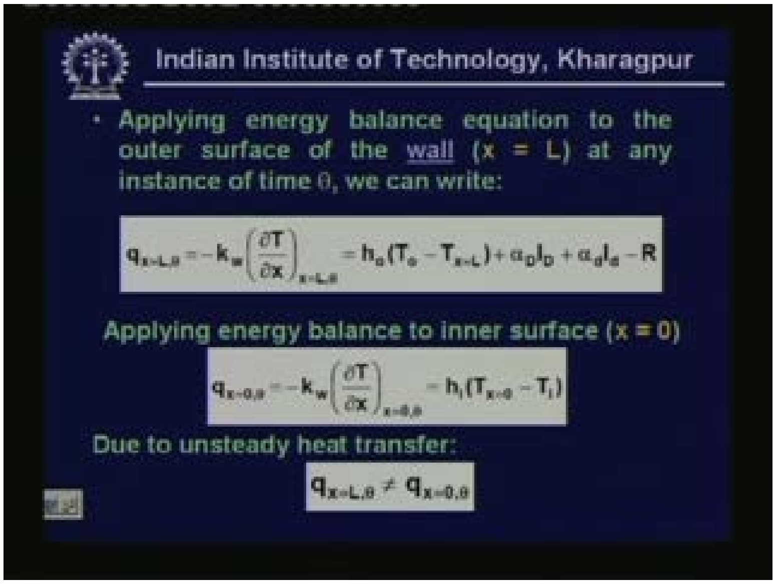

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- Applying energy balance equation to the outer surface of the wall (x = L) at any instance of time θ, we can write:

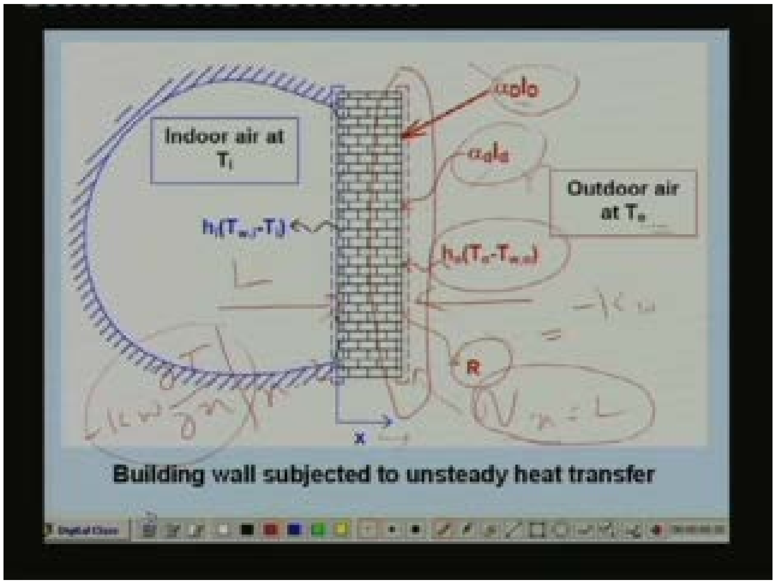
$$q_{x=L,\theta} = -k_w\left(\frac{\partial T}{\partial x}\right)_{x=L,\theta} = h_o(T_o - T_{x=L}) + \alpha_D I_D + \alpha_d I_d - R$$

Applying energy balance to inner surface (x = 0)

$$q_{x=0,\theta} = -k_w\left(\frac{\partial T}{\partial x}\right)_{x=0,\theta} = h_i(T_{x=0} - T_i)$$

Due to unsteady heat transfer:

$$q_{x=L,\theta} \neq q_{x=0,\theta}$$



Building wall subjected to unsteady heat transfer

Now what we do is we apply energy balance equation to the outer surface of the wall at any instance of time theta okay. So let us take the outer surface of the wall okay. So this is your wall and this is the outer surface okay. So this is outer surface shown by this dash line and we apply energy balance to the outer surface. So energy balance to the outer surface since surface does not have any mass whatever energy enters the surface must leave the surface whatever what is the energy entering the surface energy is entering the surface by way of direct radiation okay. I subscript capital D multiplied by alpha d where alpha d is your absorptivity of the surface for direct radiation and id is the intensity of direct radiation.

Similarly you also have radiation reaching the surface because of diffuse radiation. So I subscript small d is a diffuse radiation and alpha subscript small d is the absorptivity for diffuse radiation and heat transfer also takes place from the outdoor air to the outer surface of the wall by convection. So you also have convective heat transfer and heat transfer may also take place by long wave radiation either from the wall to the surrounding surfaces or from the surrounding surfaces to the wall that is given by this r okay. So these are all the heat transfer rates from the outside to the surface of the wall and this should be equal to the heat transfer from the surface to the wall okay. That is given by okay, if since you are assuming that heat transfer through the wall is by conduction this should be equal to q at x is equal to L L increases, x increases in this direction and the thickness of the wall. Let us say that the thickness of the wall is l when x is zero that means the inner surface of the wall x is L means outer surface of the wall.

So q subscript x is L is equal to sum total of all these things that should be equal to minus k wall okay. Let me write here minus k wall dhow t by dhow x at x is equal to L where this is the conductive heat transfer from the outer surface of the wall to the wall okay. So this is the heat balance equation for the outer surface that is what is shown here q at x is equal to L and any theta is equal to minus kw dhow t by dhow x this is nothing but your Fourier's law of heat conduction which is equal to heat transfer by convection heat transfer by direct radiation diffuse radiation and long wave radiation okay. So this is the energy balance for outer surface similarly you can write an energy balance for the inner surface inner surface does not have any solar radiation. So you do not have these terms are not there. So simply whatever heat is transferred from the inner surface is, because of combined effects of convection and internal radiations which are clubbed in hi so that is equal to minus kw dhow t by dhow x at x is equal to zero and theta which is equal to hi into Tx is equal to zero minus Ti okay.

And as I said due to because of the capacity of effect of the wall q at x is equal to L and theta is not equal to q at x is equal to zero and theta. That means q in is not equal to q out okay and ultimately what is the load on the building load on the building is nothing. But what is the heat transferred from the wall to the conditioned space that is given by this. So this is very important as far as the building cooling load is concerned okay.

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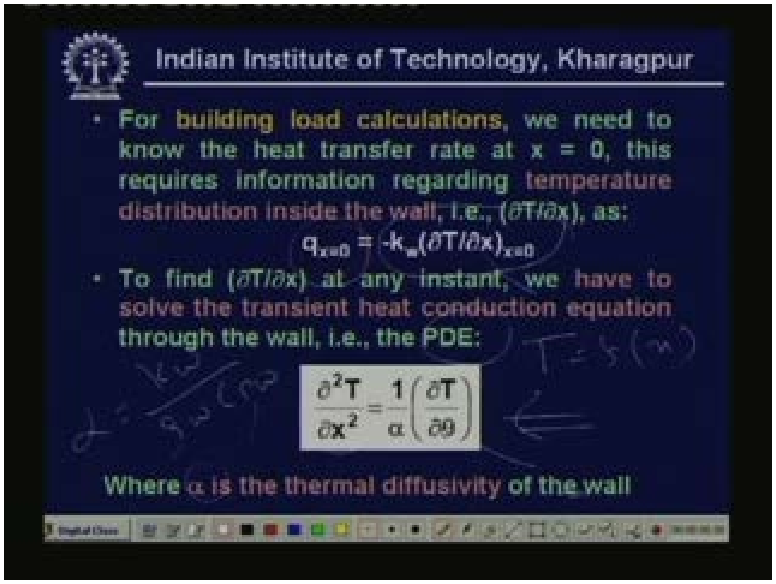

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- For building load calculations, we need to know the heat transfer rate at x = 0, this requires information regarding temperature distribution inside the wall, i.e., $(\partial T/\partial x)$, as:

$$q_{x=0} = -k_w(\partial T/\partial x)_{x=0}$$

- To find $(\partial T/\partial x)$ at any instant, we have to solve the transient heat conduction equation through the wall, i.e., the PDE:

$$\boxed{\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha}\left(\frac{\partial T}{\partial \theta}\right)}$$

Where α is the thermal diffusivity of the wall

$T = f(x)$

$\alpha = \frac{k_w}{\rho_w C_{pw}}$

Now for building load calculations we need to know the heat transfer rate at x is equal to zero as I have already explained to you we need to know what is the heat transfer rate from the inner surface of the wall to the conditioned space. That means from x is equal to zero to the conditioned space this requires information regarding temperature distribution inside the wall. That means we need to know how the temperature we distribution is there inside the wall that is dhow T by dhow x. Because the heat transfer to the conditioned space as I have said is given by this expression minus kw dhow T by dhow x at x is equal to zero.

So if know T as a function of x okay then you can find out dhow T by dhow x at any theta okay. Taking the value of x as zero so from this you can find out this parameter okay. So how do you find the temperature distribution inside the wall. As I said for the sake of simplicity let us assume that the wall is a homogeneous wall okay. If it the wall is homogeneous then heat transfer is by conduction okay. So if you want to find out what is the heat transfer what is the temperature distribution inside the wall you have to solve the conduction unsteady state conduction equation okay and for a plain wall.

We are talking about plain wall for the plain wall the unsteady state heat conduction equation is given by this partial differential equation PDE the partial differential equation dhow square T by dhow x square is equal to one by alpha dhow T by dhow theta where T as you know is the temperature x is the space coordinate theta is the time coordinate and alpha. As you know is the thermal diffusivity of the wall that is alpha is equal to k wall divided by rho wall into Cp wall okay. K is the thermal conductivity rho is the density of the wall Cp is the specific heat of the wall. So this is the equation that governs the heat conduction equation through the wall under unsteady state conditions okay. So we have to solve this equation you can see that this is a partial differential equation and it is second order in space and first order in time. So you have to specify two boundary conditions for space and one boundary condition for time okay, if you want to solve the equation.

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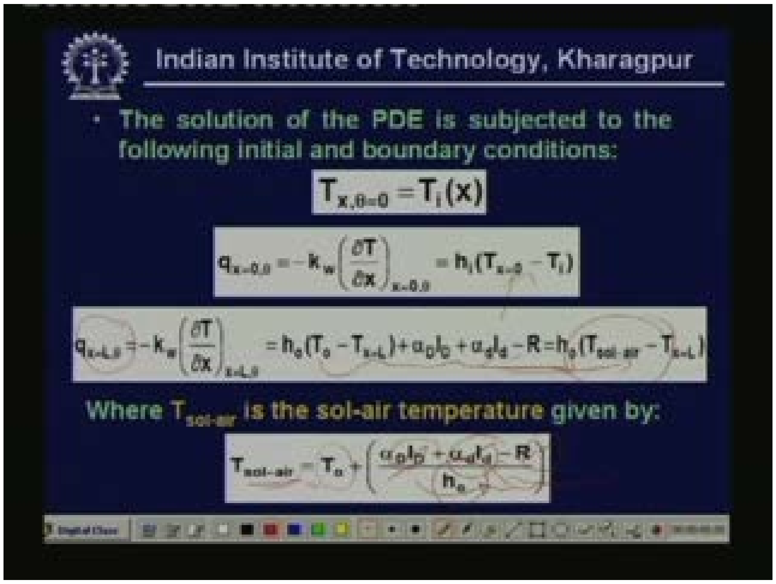

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- The solution of the PDE is subjected to the following initial and boundary conditions:

$$\boxed{T_{x,\theta=0} = T_i(x)}$$

$$\boxed{q_{x=0,\theta} = -k_w\left(\frac{\partial T}{\partial x}\right)_{x=0,\theta} = h_i(T_{x=0} - T_i)}$$

$$\boxed{q_{x=L,\theta} = -k_w\left(\frac{\partial T}{\partial x}\right)_{x=L,\theta} = h_o(T_o - T_{x=L}) + \alpha_D I_D + \alpha_d I_d - R = h_o(T_{sol\text{-}air} - T_{x=L})}$$

Where $T_{sol\text{-}air}$ is the sol-air temperature given by:

$$\boxed{T_{sol\text{-}air} = T_o + \left(\frac{\alpha_D I_D + \alpha_d I_d - R}{h_o}\right)}$$

And the solution of the PDE subjected to the following initial and boundary conditions as I said you have to specify these conditions only then you can solve the equation. So this is your initial condition that means at some theta arbitrary value of time theta is zero the temperature distribution inside the wall is given by this and we should we should know this. That means this is known okay and this is specified as known boundary condition for time or an initial condition okay.

Then you have to specify two boundary conditions. Because you have dhow square T by dhow x square term. So two boundary conditions are for the inner surface that is x is equal to zero one boundary condition is this minus kw dhow T by dhow x at x is equal to zero into theta is hi into Tx is equal to zero minus Ti this is the boundary condition of the inner surface. Similarly the boundary condition at the outer surface that is my x is equal to L is given by this okay qx is equal to L theta is minus kw dhow T by dhow x at x is equal to L theta. Which is equal to the heat transfer rate by conduction by I am sorry convection heat transfer rate by direct radiation heat transfer rate by diffuse radiation this is the long wave radiation right what is done here is the boundary condition at the outer surface that means this one is written in terms of an effective or equivalent temperature called as sol-air temperature.

Okay. So this is known as sol-air temperature so what we do is we club all these factors and we write this boundary condition also similar to this boundary condition by introducing a fictitious equivalent temperature called as T sol-air temperature. And if you compare these two equations you find that the sol-air temperature T subscript sol-air is given by T subscript o which is the dry bulb temperature of outdoor air plus this factor okay. See you can see there when there is no radiation that means when there is no direct radiation when there is no diffuse radiation when there is no long wave radiation sol-air temperature is simply equal to outdoor dry bulb temperature of the air okay. On the other hand when you have radiation when you have sun you may have solar direct radiation you will have diffuse radiation.

Then the sol-air temperature can be much higher than the outdoor dry bulb temperature okay. And during the night this will be zero and this will be zero whereas this can be positive then it is possible that the sol-air temperature can be smaller than the outdoor dry bulb air temperature and you can also see here that the sol-air temperature also depends upon the outdoor surface conductance h naught okay. So the advantage of defining sol air temperature is that you can write the outdoor boundary condition also as h naught into T sol-air minus T wall temperature okay so the form looks simple but the sol air temperature depends upon several factors like the radiation solar geometry and outdoor convection and all that okay.

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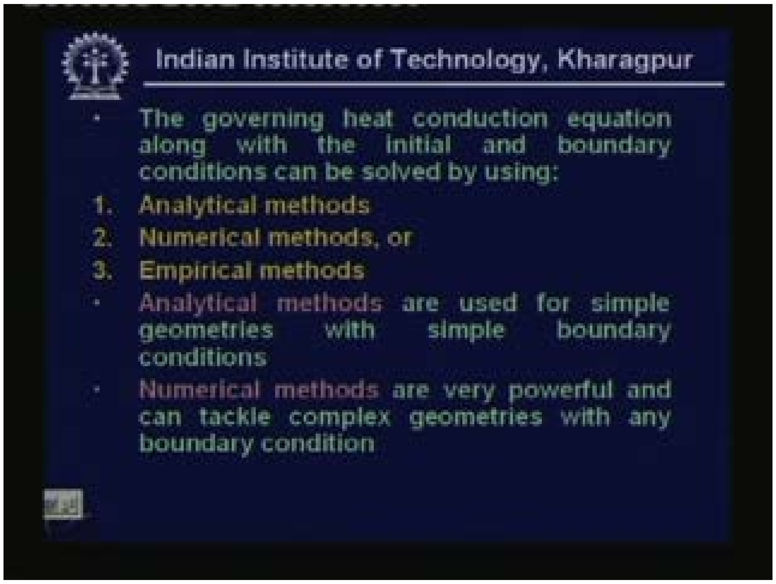

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- The governing heat conduction equation along with the initial and boundary conditions can be solved by using:

1. Analytical methods
2. Numerical methods, or
3. Empirical methods

- Analytical methods are used for simple geometries with simple boundary conditions
- Numerical methods are very powerful and can tackle complex geometries with any boundary condition

The governing heat can now how do we solve now we have define the governing equation as we have seen for simple plane wall okay. Plane homogeneous wall the governing equation is a partial differential equation and you let us say that we have also specified the required initial and boundary conditions. So the problem is fully defined now the question is how do we solve it you can solve this governing differential equation either by using an analytical method or by using numerical methods or by using empirical methods. So what are the typical characteristics of these methods analytical methods are used for simple geometries with simple boundary conditions okay.

Simple geometries means you have a plane wall okay. Simple boundary conditions means outside temperature or outside radiation varies as a simple harmonic okay. For this kind of simple geometries and simple boundary conditions you can derive an analytical expression or you can get an analytical solution okay. Whereas the numerical methods are very powerful and they can tackle complex geometries with any boundary conditions. So these advantages of numerical methods you can use the numerical method for any type of any shape of the building or for any type of boundary conditions okay. However numerical methods are in general more time consuming and accuracy also they are not percent accurate unlike analytical methods.

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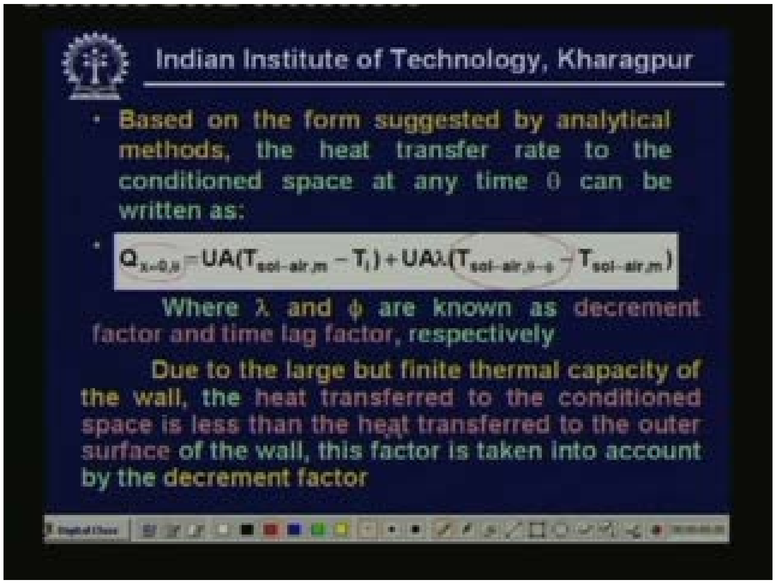

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- Based on the form suggested by analytical methods, the heat transfer rate to the conditioned space at any time θ can be written as:
- $Q_{x=0,\theta} = UA(T_{sol-air,m} - T_i) + UA\lambda(T_{sol-air,\theta-\phi} - T_{sol-air,m})$

Where λ and φ are known as decrement factor and time lag factor, respectively

Due to the large but finite thermal capacity of the wall, the heat transferred to the conditioned space is less than the heat transferred to the outer surface of the wall, this factor is taken into account by the decrement factor

And based on the form suggested by analytical methods the heat transfer rate to the conditioned space at any time theta can be written as, so this, as I said, this is the form suggested by the analytical method okay. By the analytical method you can write at any time the heat transfer rate to the conditioned space that is Q x is equal to zero and theta these, the transfer rate to the conditioned space. As I have said that is equal to UA where U is the overall heat transfer coefficient of the wall A is the surface area of the wall multiplied by T sol-air subscript m minus Ti plus UA into lambda into T sol-air theta minus five minus T sol-air subscript M. So what are all these things this one T sol air subscript m is what is known as mean sol air temperature. Let us say that you find the sol air temperature for the twenty-four hours you calculate the hourly sol air temperature and find an average of that, so that is the mean sol air temperature T sol air subscript m okay. Then T i is the temperature of the conditioned space which we are assuming to be constant right and this lambda okay, is what is known as decrement factor right I will explain what it is and then this phi is what is known as phi is what is known as time lag factor okay. And here T sol air look at this temperature what is this I am calculating heat transfer rate at some time theta okay. So this is written as in terms of temperature at time theta minus phi okay, where phi is the time lag. That means that let us say that I am calculating heat transfer rate at six pm okay. On a particular wall I want to know what is the heat transfer rate from the wall to the conditioned space at six pm and let the wall as a time lag of five hours okay.

Then T sol air subscript theta minus phi is the temperature of the wall or the sol air temperature of the wall at six minus phi that is one pm okay so that is the meaning of theta minus phi okay. And now coming to decrement factor what is the decrement factor due to the large but finite thermal capacity of the wall the heat transfer to the conditioned space is less than the heat transfer to the outer surface of the wall okay. As I have already explained to you because of the thermal capacity of the wall Qin is not equal to Q out and it may. So happen that Qin is much larger than the Q out so this introduces a factor called as decrement factor okay. Similarly you have what is known as the time lag factor and what is the time lag factor.

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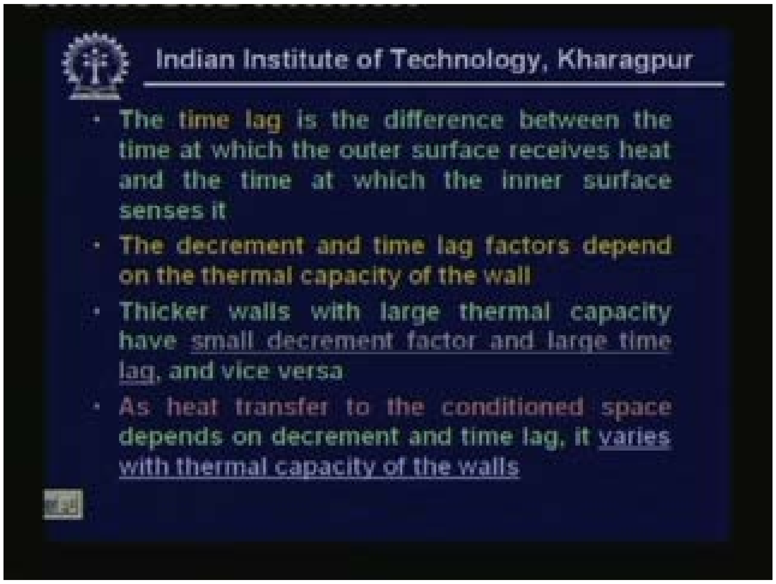

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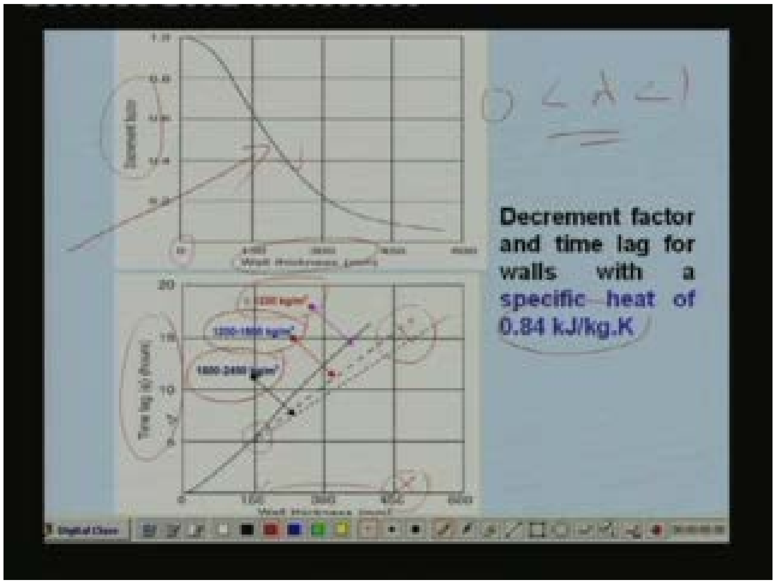
- The time lag is the difference between the time at which the outer surface receives heat and the time at which the inner surface senses it
- The decrement and time lag factors depend on the thermal capacity of the wall
- Thicker walls with large thermal capacity have small decrement factor and large time lag, and vice versa
- As heat transfer to the conditioned space depends on decrement and time lag, it varies with thermal capacity of the walls



$0 < \lambda < 1$

Decrement factor and time lag for walls with a specific heat of 0.84 kJ/kg.K

The time lag is the difference between the time at which the outer surface receives heat and the time at which the inner surface senses it. So let me give an example let us say that you have a wall here okay. Let say that this is the wall and this is the outdoor and this is the indoor. Let us say that suddenly this wall experiences some heat transfer okay. Let say that at this time, let say time is four pm okay at four pm this wall outer surface of the wall is suddenly exposed to some heat transfer Qin okay. And because of the thermal capacity of the wall you find that the inner surface does not sense this immediately okay. Some time is required for the inner surface to sense this heat transfer let say that the time lag is three hours okay.

Then you will find that this inner surface senses this heat transfer at four plus three that is seven pm okay. So this is what is known as time lag this is the reason why if the outside temperature is maximum say at three pm we find that the indoor temperature in an unconditioned room is maximum at say seven pm or eight pm okay. For example at mid noon at twelve o'clock outside may be the hottest but inside the inside the room temperature will be very high not at twelve of clock but may at three o'clock or four clock okay. So this is because of the thermal capacity of the wall okay. And this factor is known as time lag factor right and the decrement and time lag factors depend on the thermal capacity of the wall.

Obviously what is the thermal capacity of the wall the thermal capacity of the wall depends upon the density of the wall thickness of the wall and specific heat of the wall thicker walls with large thermal capacity have small decrement factor and large time lag and vice versa okay. Let me show that variation of decrement and time lag factor. This graph here shows the decrement factor as a function of wall thickness okay. These are calculated for buildings material having a specific heat of eight forty joule per kg Kelvin okay. So you can see that the decrement factor is one when the thickness is zero okay.

That means there is no wall and the decrement factor is one and as the wall thickness increases the decrement factor reduces okay. So in general the decrement factor varies between zero to one okay, thicker walls have lower decrement factors thinner walls have higher decrement factors okay. Next this graphs show the variation of time lag with wall thickness and for different types of walls having different densities okay. So you can see that as the wall thickness increases the time lag increases okay. For example for four fifty mm thick wall the time lag would be fifteen hours okay. Similarly for one fifty mm wall the time lag is five hours like that okay.

As heat transfer to the conditioned space depends on time decrement and time lag it varies with thermal capacity of the wall okay. So obviously the heat transfer rate as we have seen depends upon the sol air temperature which in turn depends upon the decrement and time lag factor and decrement and time lag factor depend upon the thermal capacity of the wall. So finally you find that the heat transfer to the conditioned space depends among other factors on the thermal capacity of the wall okay. So let me show a typical variation of heat transfer rate okay this graph here

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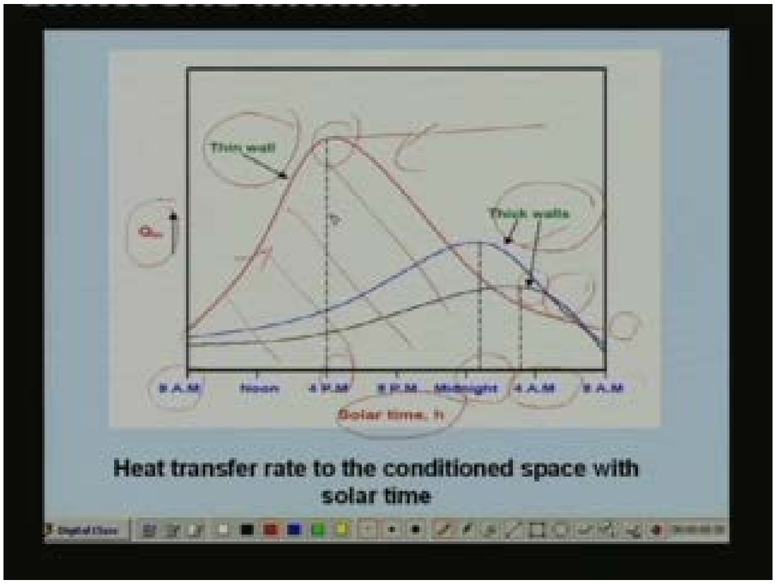

Heat transfer rate to the conditioned space with solar time

Shows the heat transfer to the conditioned space okay, not heat flux but heat total heat transfer to the conditioned space as a function of solar time okay. For a thin wall a thick wall okay, and a thicker wall. So you can see that the heat transfer rate increases from about eight am that means slightly one or two hours after the sun rise for a thin wall the heat transfer rate increases in this manner and it reaches the peak at about four pm and then again it starts decreasing okay and it reaches a minimum at about eight am okay. And for a thick wall again it starts increasing from about eight am it reaches a peak you can see that around at mid night okay, not during the day time but during the night and again it decreases and for still thicker wall you find that the peak heat transfer rate takes place not at not during the day time at all. But it takes place at about four am that means in the morning oaky.

So this is the effect of the thickness of the wall on the heat transfer to the conditioned space at different times and you can also see that the total heat transfer rate that is nothing but the area under this curve is much higher for the thin wall compared to the thick wall okay. So one thing is that the peak heat transfer rate for the thin wall is very high and the total heat transfer rate for the thin wall is also high compared to the thick walls.

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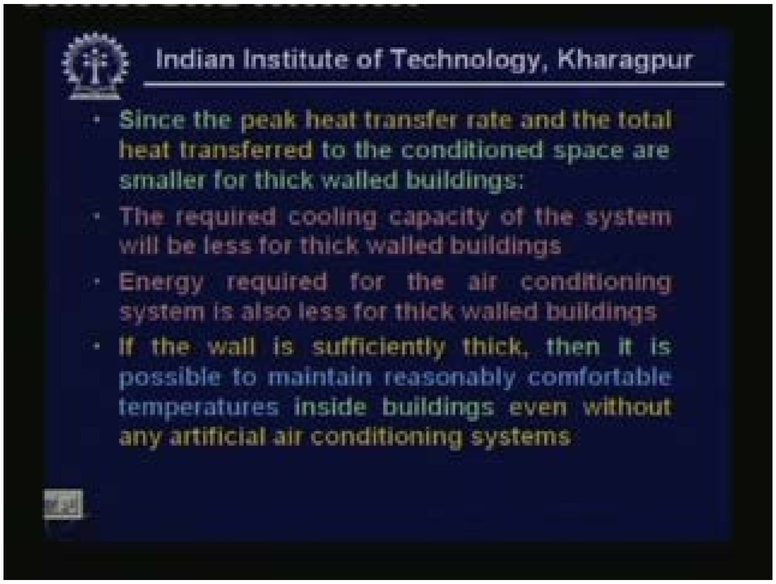

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- Since the peak heat transfer rate and the total heat transferred to the conditioned space are smaller for thick walled buildings:
- The required cooling capacity of the system will be less for thick walled buildings
- Energy required for the air conditioning system is also less for thick walled buildings
- If the wall is sufficiently thick, then it is possible to maintain reasonably comfortable temperatures inside buildings even without any artificial air conditioning systems

So since the peak heat transfer rate and the total heat transfer to the conditioned space are smaller for thick wall buildings the required cooling capacity of the system will be less for thick wall building. So it is an advantage and energy required for the air conditioning system is also less for thick walled buildings okay. So this also an advantage and you will find that if the wall is sufficiently thick then it is possible to maintain reasonably comfort temperatures comfortable temperatures inside buildings even without any artificial air conditioning systems okay. Because of the small decrement factor and large time lag in fact this is the principle behind the old temples and old forts or old buildings which have very thick walls okay. You find that these buildings even without any air conditioning are very comfortable even during peak summer okay. So this is because of the large thermal capacity of the building which introduces small decrement factor and a large time lag okay.

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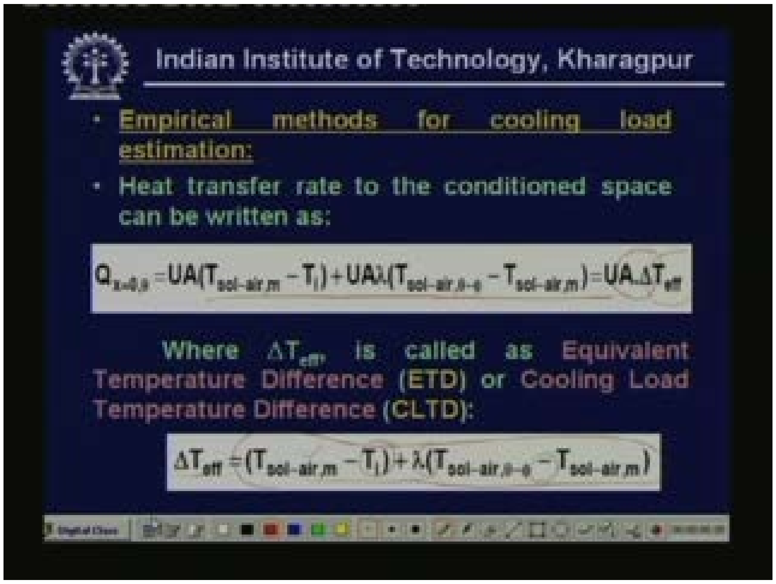
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- Empirical methods for cooling load estimation:
- Heat transfer rate to the conditioned space can be written as:

$$Q_{x=0,\theta} = UA(T_{sol-air,m} - T_i) + UA\lambda(T_{sol-air,\theta-\phi} - T_{sol-air,m}) = UA.\Delta T_{eff}$$

Where ΔT_{eff}, is called as Equivalent Temperature Difference (ETD) or Cooling Load Temperature Difference (CLTD):

$$\Delta T_{eff} = (T_{sol-air,m} - T_i) + \lambda(T_{sol-air,\theta-\phi} - T_{sol-air,m})$$

And now let us look at empirical methods for cooling load estimation heat transfer rate to the conditioned space can be written as we have seen by this expression okay. And this is written in terms of UA into some delta T effective where this delta T effective is called as equivalent temperature difference ETD or cooling load temperature differences CLTD and from this expression you can easily find that the equivalent temperature difference or cooling load temperature difference is given by this expression. So it includes the sol-air mean sol-air temperature the time lag and the decrement and it also includes the inside temperature okay. So all these factors are included.

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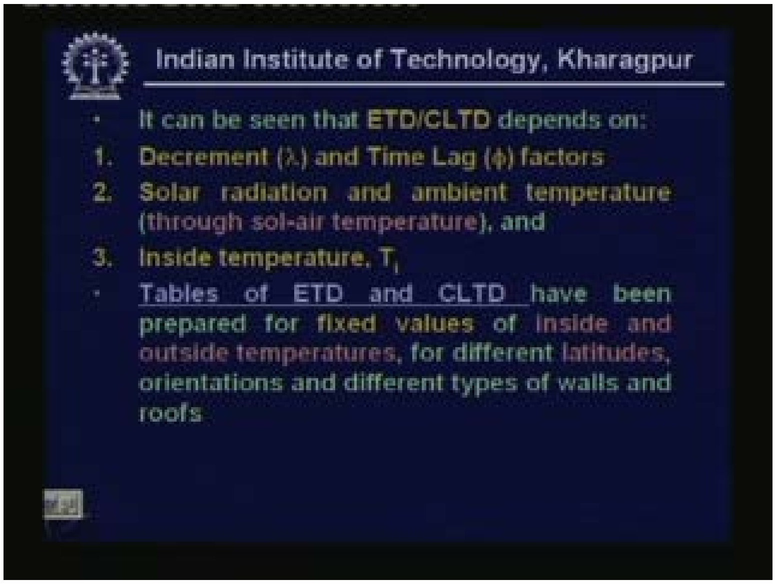
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- It can be seen that ETD/CLTD depends on:

1. Decrement (λ) and Time Lag (ϕ) factors
2. Solar radiation and ambient temperature (through sol-air temperature), and
3. Inside temperature, T_i

- Tables of ETD and CLTD have been prepared for fixed values of inside and outside temperatures, for different latitudes, orientations and different types of walls and roofs

So you can find that the ETD or CLTD depends on decrement and time lag factors solar radiation and ambient temperature through sol-air temperature and inside temperature Ti okay. And tables of ETD and CLTD have been prepared for fixed values of inside and outside temperatures. For example they are available in ASHRAE hand books for different latitudes orientations and different types of walls and roofs okay. So let me show typical tables.

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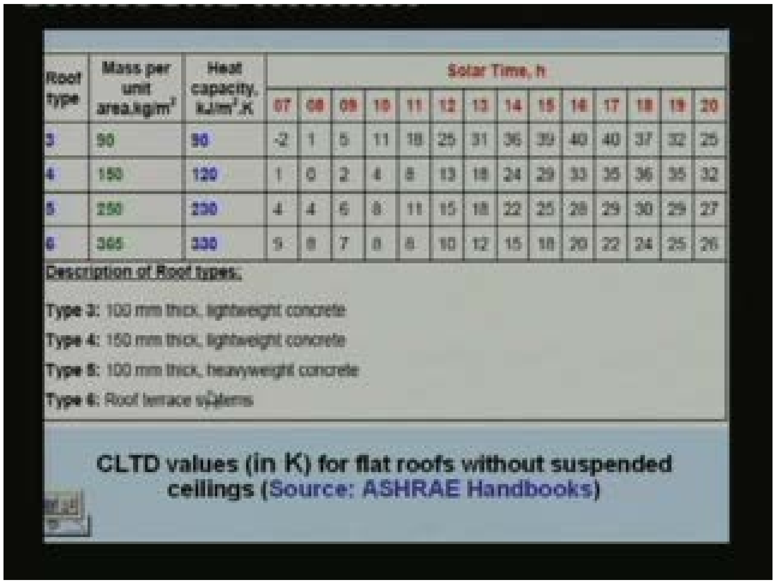

Roof type	Mass per unit area,kg/m^2	Heat capacity, kJ/m^2.K	Solar Time, h													
			07	08	09	10	11	12	13	14	15	16	17	18	19	20
3	90	90	-2	1	5	11	18	25	31	36	39	40	40	37	32	25
4	150	120	1	0	2	4	8	13	18	24	29	33	35	36	35	32
5	250	230	4	4	6	8	11	15	18	22	25	28	29	30	29	27
6	365	330	9	8	7	8	8	10	12	15	18	20	22	24	25	26

Description of Roof types:

Type 3: 100 mm thick, lightweight concrete

Type 4: 150 mm thick, lightweight concrete

Type 5: 100 mm thick, heavyweight concrete

Type 6: Roof terrace systems

CLTD values (in K) for flat roofs without suspended ceilings (Source: ASHRAE Handbooks)

Okay. So this is the CLTD table for a flat roof without suspended ceilings. And this is taken from ASHRAE hand books and here you have four different types of roofs three four five six and the description of the roofs are given here type three is hundred mm thick light weight concrete type four is one fifty mm thick light weight concrete type five is hundred mm thick heavy weight concrete type six is roof terrace system and the properties are given here mass per unit area. Okay and the heat capacity and the CLTD values are given as function of solar time we can see that for this wall. For example type three wall at seven solar time minus two is the CLTD value at eight am this is one degree at nine am this is five degrees and this is at ten am eleven degrees like that okay. Similarly for different times of different types of roof at different solar times.

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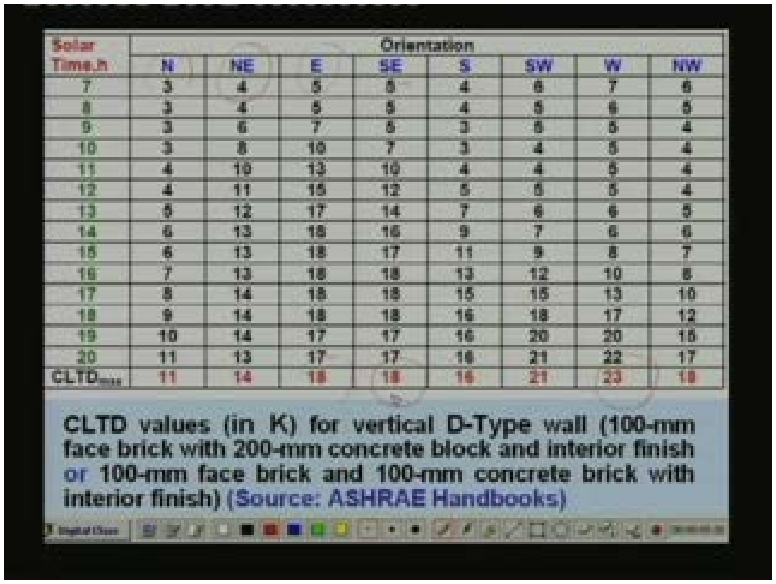

Solar Time,h	Orientation							
	N	NE	E	SE	S	SW	W	NW
7	3	4	5	5	4	6	7	6
8	3	4	5	5	4	5	6	5
9	3	6	7	6	3	6	5	4
10	3	8	10	7	3	4	5	4
11	4	10	13	10	4	4	5	4
12	4	11	15	12	5	5	5	4
13	5	12	17	14	7	6	6	5
14	6	13	18	16	9	7	6	6
15	6	13	18	17	11	9	8	7
16	7	13	18	18	13	12	10	8
17	8	14	18	18	15	15	13	10
18	9	14	18	18	16	18	17	12
19	10	14	17	17	16	20	20	15
20	11	13	17	17	16	21	22	17
$CLTD_{max}$	11	14	18	18	16	21	23	18

CLTD values (in K) for vertical D-Type wall (100-mm face brick with 200-mm concrete block and interior finish or 100-mm face brick and 100-mm concrete brick with interior finish) (Source: ASHRAE Handbooks)

And this table gives the CLTD values for vertical D type wall and the description of the D type wall is given D type wall means hundred mm face brick with two hundred concrete block and interior finish or hundred mm face brick and hundred mm concrete block with interior finish. Since it is a vertical wall the orientation comes into picture where it is north facing or north east facing right this north facing north east facing east facing south east facing like that okay. And at different solar time right so these are the temperatures in Kelvin and you can also see here the maximum CLTD value. For example for east facing wall eighteen degrees Kelvin is the maximum CLTD and for south east wall also it is eighteen degrees and for the west facing wall it is twenty-three degrees like that okay. So this kind of tables are available in ASHRAE hand books now what is the validity of ASHRAE hand books.

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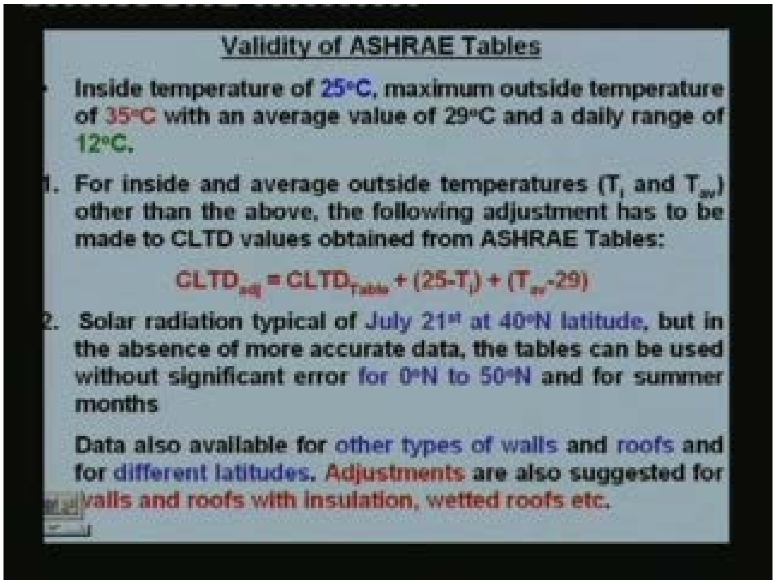

Validity of ASHRAE Tables

- Inside temperature of 25°C, maximum outside temperature of 35°C with an average value of 29°C and a daily range of 12°C.

1. For inside and average outside temperatures (T_i and T_{av}) other than the above, the following adjustment has to be made to CLTD values obtained from ASHRAE Tables:

$$CLTD_{adj} = CLTD_{Table} + (25-T_i) + (T_{av}-29)$$

2. Solar radiation typical of July 21st at 40°N latitude, but in the absence of more accurate data, the tables can be used without significant error for 0°N to 50°N and for summer months

Data also available for other types of walls and roofs and for different latitudes. Adjustments are also suggested for walls and roofs with insulation, wetted roofs etc.

The ASHRAE hand books have ASHRAE hand books have ASHRAE tables have been obtained for inside temperature of twenty-five degree centigrade and maximum outside temperature of thirty-five degree centigrade with an average value of twenty-nine centigrade and a daily range of twelve degree centigrade. What is daily range daily range means, maximum outdoor temperature minus minimum outdoor temperature okay. The so that value is taken as twelve degree centigrade now for inside and average outside temperatures other than the above the following adjustment has to be made to CLTD values obtained from ASHRAE tables okay. So if you are your values are different, for example the inside temperature okay is not twenty-five degrees but something else okay.

Similarly the outside temperature average temperature not twenty-nine but let us say thirty-two. Then you have to make an adjustment to the values obtained from the table that adjustment is given by this equation the adjusted CLTD values is equal to tabular values plus twenty-five minus Ti plus T average minus twenty-nine. So as I said let us say that your Ti value is twenty-five then this will this adjustment will not be there but if the average temperature is higher than twenty-nine then you have to add that to the values that you obtained from the table so that is why you get the adjusted CLTD values okay.

And solar this data is also applicable to solar radiation typical of July twenty-first at forty degree north latitude but in the absence of more accurate data the tables can be used without significant error for zero degrees to fifty degrees north latitude for summer months okay. And data also available for other types of walls and roofs and for different latitudes and adjustments are also suggested for walls and roof with insulation wetted roofs etcetera okay. So if you look at the ASHRAE hand books or other air-conditioning hand book all these tables are given either CLTD tables if you look at other hand books they give what is known as effective temperature difference tables okay. As function of the type of the wall orientation solar time and all that for a fixed conditions. And they also suggest adjustments for other conditions. So if you have the table and your specific conditions then you can get the tabular value applied the adjustment and get the adjusted value of CLTD or ETD okay. That one must use for calculating the heat transfer rate okay.

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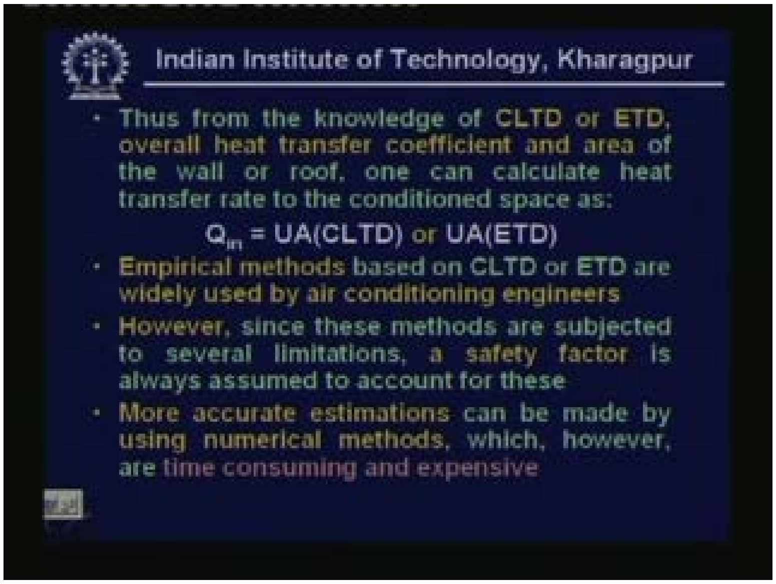

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- Thus from the knowledge of CLTD or ETD, overall heat transfer coefficient and area of the wall or roof, one can calculate heat transfer rate to the conditioned space as:

$$Q_{in} = UA(CLTD) \text{ or } UA(ETD)$$

- Empirical methods based on CLTD or ETD are widely used by air conditioning engineers
- However, since these methods are subjected to several limitations, a safety factor is always assumed to account for these
- More accurate estimations can be made by using numerical methods, which, however, are time consuming and expensive

And thus from the knowledge of CLTD or ETD overall heat transfer coefficient and area of the wall or roof one can easily calculate the heat transfer rate of the conditioned space as Qin is equal to UA into CLTD or UA into ETD so CLTD value get from the table U value calculate from the specifications of the wall and A is the surface area of the wall okay. Now the empirical methods based on CLTD or ETD are widely used by air conditioning engineers however since these methods are subjected to several limitations a safety factor is always assumed to account for these okay. So they are not hundred accurate all these empirical method. So to take care of this a safety factor is always assumed more accurate estimates can be made by using numerical methods which however are time consuming and expensive okay.

If your building is having a different shape or if you want more accurate results you have to apply the numerical methods numerical methods the advantage is that you can take care of any shape or any boundary condition but the problem is that they are expensive and they are also time consuming. So that is the reason why most of the time the air conditioning engineers use the empirical methods and provide a safety factor to take care of the inaccuracies okay. So at this point I end this lecture and in the next lecture I shall discuss the actual estimation of cooling loads on the buildings.

Thank you.