Basics of Mechanical Engineering-3

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Week 05

Lecture 23: Heat Transfer

Welcome to the next lecture on Heat Transfer. Until now, we have covered the zeroth law, first law, second law, and the application of P-V diagrams and T-S diagrams. Then we moved into cycles, different types of cycles, such as the Otto cycle, Diesel cycle, Rankine cycle, and Brayton cycle. We have studied all these cycles. We also determined how to find the thermal efficiency of the process in all these cycles. And friends, in this entire course, there are only two things. One is how we apply heat or extract heat, or how we apply work or extract work.

These are the two things. If we want to understand that, we have to go step by step and grasp the fundamentals. Then we move to the technology associated with that. From that understanding, we will now move toward a new topic: heat transfer.

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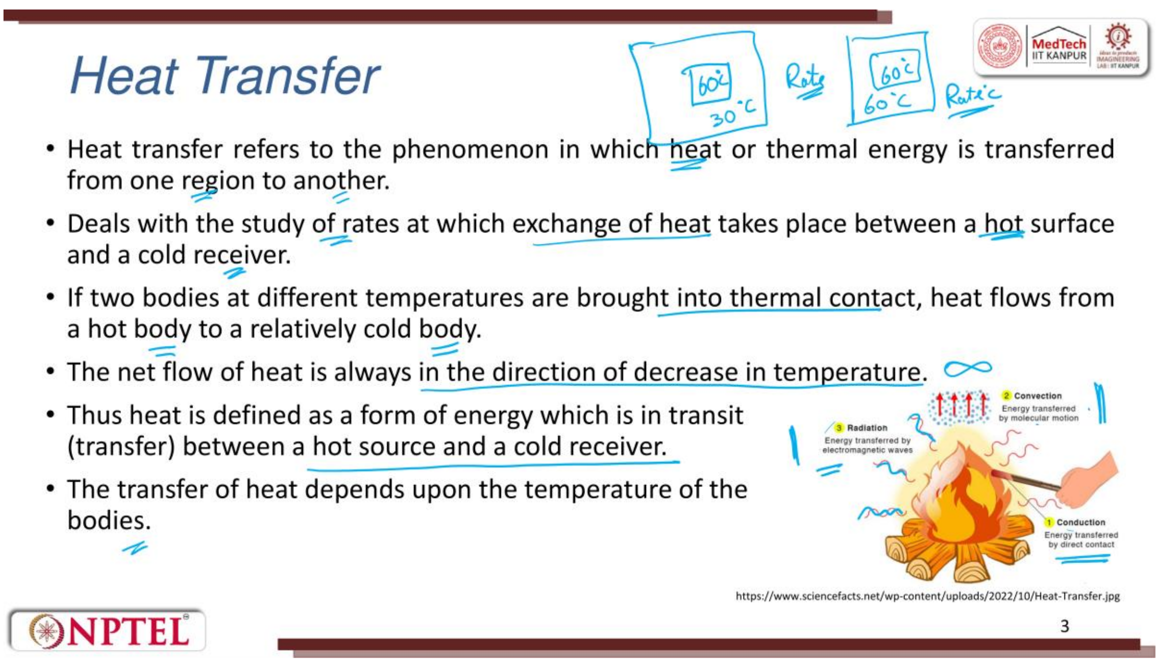
In this topic, we will cover what heat transfer is, the different modes of heat transfer, conduction, Fourier's law, and thermal conductivity. Then we will examine plane wall conduction, composite wall conduction, and cylinder conduction. So by giving the shape. How does conduction happen? Then comes convection, free convection, and forced convection. Finally, we will examine radiation.

Many times, if you see when the heat has to be removed faster, we try to put a fan very close to it and extract the heat. Isn't it? So that is forced convection. Free convection is when you leave it in the open atmosphere. Yesterday, when we were trying to feed our pet, we cooked food, and it was very hot.

He was very hungry. So we had to find ways and means to cool it so that our pet could eat the food. That is where the concept of free convection and forced convection comes in.



Heat transfer refers to a phenomenon in which heat or thermal energy is transferred from one region to another. It can be from higher to lower or lower to higher, whatever the case may be.

So it is only heat transfer or thermal energy transfer happening between two regions. It deals with the study of rate. For example, I gave you the scenario of cooling food for my pet. I wanted to do it faster. So, I have to work with time now.

So, the transfer of heat is 1, and the rate of transfer of heat is 2. So, it deals with the study of rates at which the exchange of heat takes place between a hotter surface and a cold receiver. See, if you take an example, you take a box which is at 60 degrees Celsius. And you have an atmosphere which is around 30 degrees Celsius. You see what happens with the heat transfer.

One, you see the rate at which the heat transfer happens. That means, when does 60 degrees become 30 degrees? Then you try to have a 60-degree vessel and also have an outside temperature of 60 degrees. Now you see the rate. So you see there will be a different phenomenon.

The object you kept here may be cooked food in a steel vessel in a room where the atmospheric temperature is 30 degrees or where the atmospheric temperature is 60 degrees. The food is the same, the steel vessel is the same, the surroundings are the same, the air is constant, and it is not moving. You see there will be a difference in the exchange of heat. So the rate is very important. If two bodies at different temperatures are brought into thermal contact, the heat flows from a hot body to a cold body or a relatively cold one.

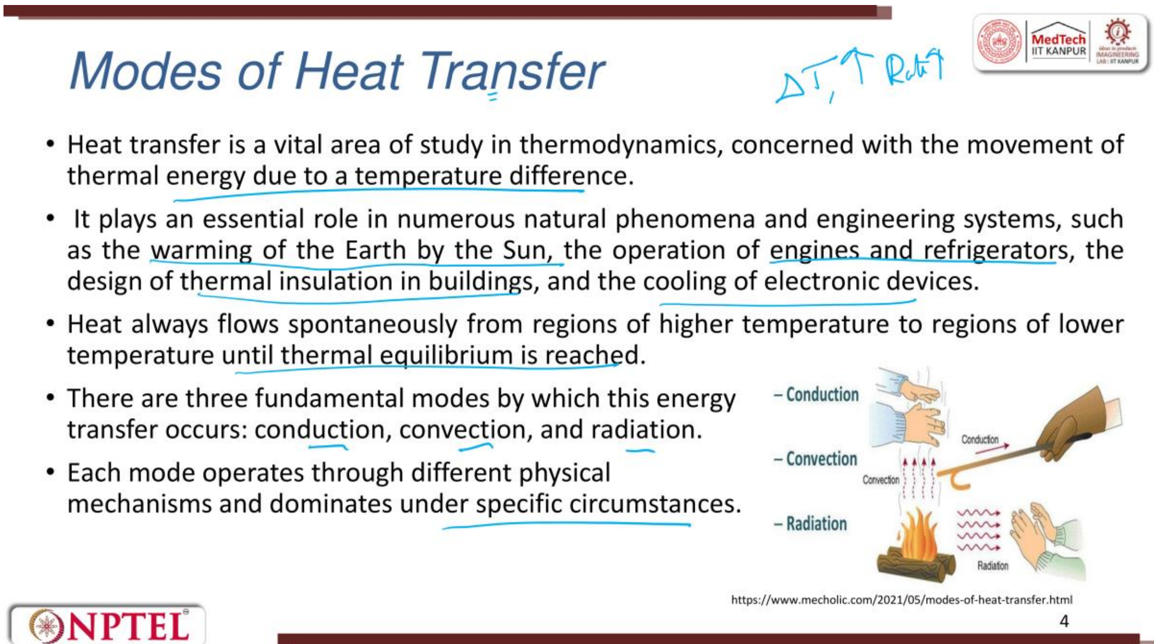
So it can be 60 degrees, or it can be 50 degrees. So there will be a heat transfer from 60 to 50. The net flow of heat is always in the direction of decreasing temperature. Thus, heat is defined as a form of energy that is transferred between a hot source and a cold receiver. Can we do it, Ulita, from cold to hot?

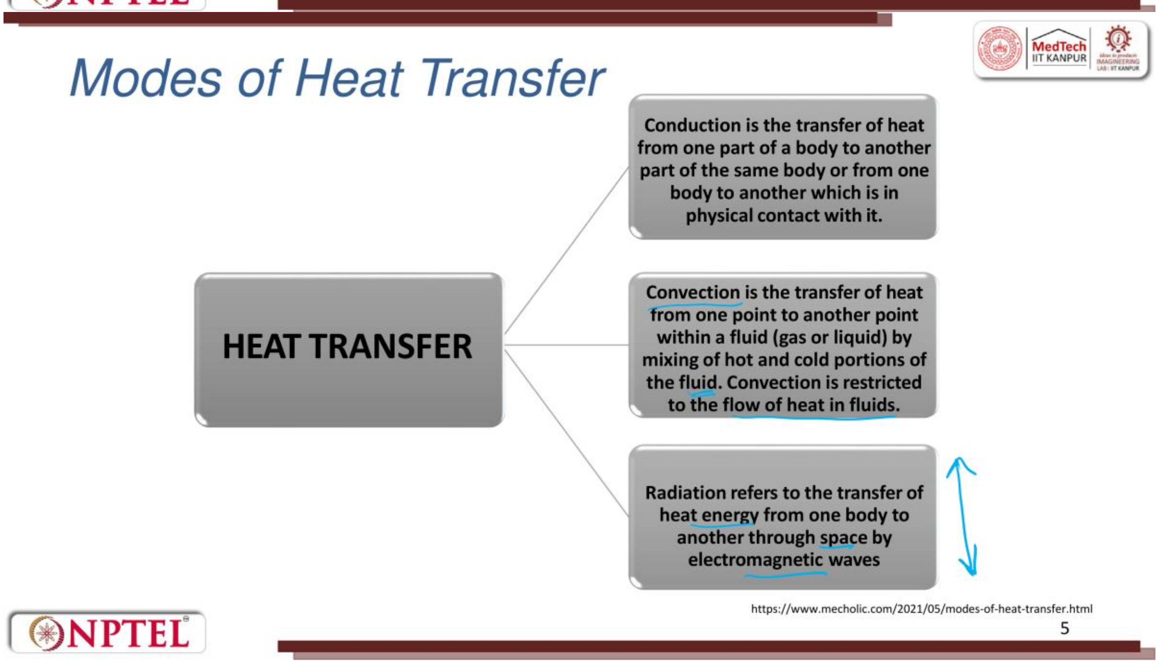
Yes, you can do it. But hot to cold happens naturally. If you want to reverse it, you have to apply energy. The transfer of heat depends on the temperature of the body. So you can see here, there is a log that is set on fire.

So just outside the fire, you can see the waves, the electromagnetic waves. So these waves represent radiation, the energy transferred by electromagnetic waves. So here it is convection, energy transferred by molecular motion. So from here it can radiate, and then what you do is operate a fan on top of it. So here, what happens is the energy transfer is done by molecules.

And then the third one is you keep a red-hot rod which is attached to your hand. You see conduction; the energy transfers by direct contact. So this is the difference between convection, conduction, and radiation. So thermal imaging cameras work on IR, which is electromagnetic waves they try to capture. That is what is used in your airports.

When the passenger keeps moving, there will be an IR camera which tries to check what the body temperature is from a very far-off distance. So that is done by radiation. The next thing is convection is the molecular transfer. The energy transfers by molecular motion. The conduction is this.





Modes of Transfer. Heat transfer is a vital area of study in thermodynamics concerned with the movement of thermal energy due to a temperature difference. Δ T difference plays an important role in the rate. If the δ T is high, the rates also, majority of the time, can be high. The rate of heat transfer can be high.

It plays an essential role in numerous natural phenomena and engineering systems, such as the warming of the earth by the sun, the operation of engines and refrigerators, the design of thermal insulation in buildings, and the cooling of electronic devices. So, all these things are examples where heat transfer is very important. Friends, the IC chip used today in processors always imposes a restriction. It's not because the feature size cannot be made smaller. It's because, for that feature size, the heat rejection and cooling present a challenge.

So, people are looking forward to developing cooling methods that are very efficient at small scales. Thus, microscale heat transfer is a major research topic in the field of heat transfer. Heat always flows spontaneously from a higher-temperature region to a lower-temperature region until equilibrium is reached. We have seen the three modes of heat transfer, and each mode operates through a physical mechanism and dominates under specific circumstances. So, conduction is the transfer of heat from one part of a body to another part of the same body or from one body to another body that is in physical contact with it.

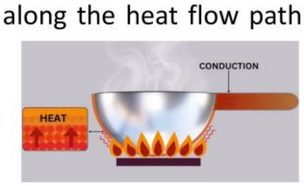
So, that is conduction. Convection is the transfer of heat from one point to another within a fluid. It can be a gas or a liquid. It occurs by mixing hot and cold portions of the fluid. Convection is restricted to the flow of heat in fluids. Radiation refers to the transfer of heat energy from one body to another through space by electromagnetic waves. So this is important.

Conduction

- Conduction refers to the mode of heat transfer in which heat flow though the material medium occurs without actual migration of particles of the medium from a region of higher temperature to a region of lower temperature.
- Heat conduction occurs by the migration of molecules and more effectively by the collision of the molecules vibrating around relatively fixed positions.

STEADY STATE UNIDIRECTIONAL HEAT CONDUCTION IN SOLIDS:

- Steady state heat flow means the temperature at any location along the heat flow path does not vary with time
- The rate at heat transfer does not vary with time
- Temperature varies with location but not with time

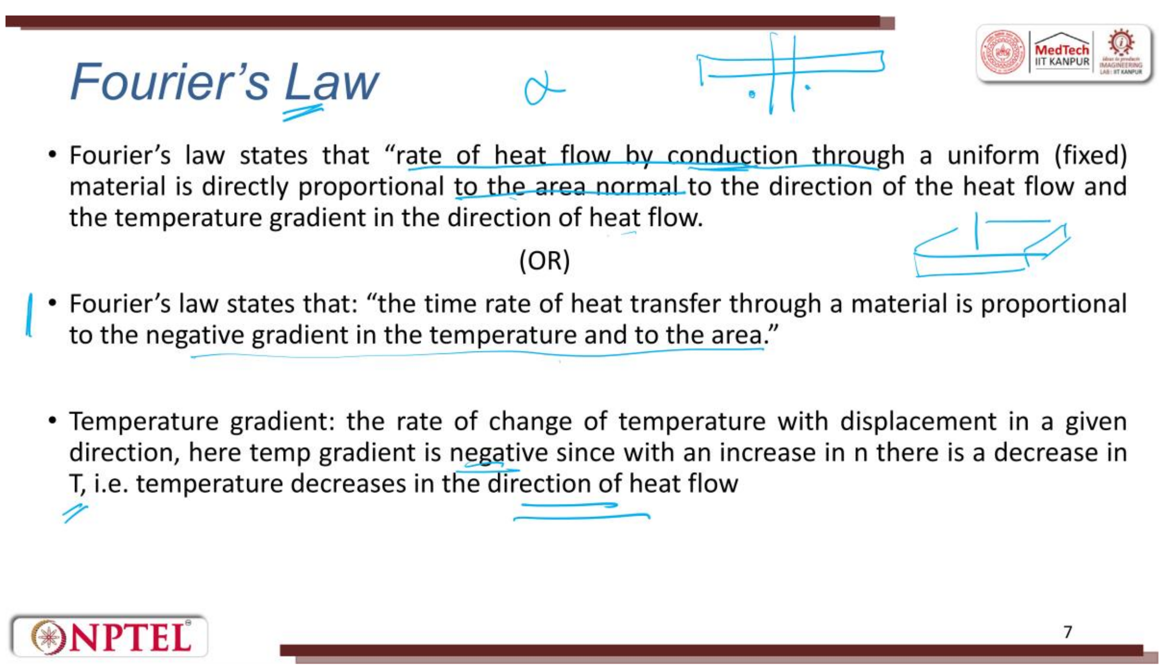


https://thermtest.com/heat-transfer-basics

Conduction refers to the mode of heat transfer in which heat flows through a material medium without the actual migration of particles from a region of higher to lower temperature. Conduction occurs by the migration of molecules and more effectively by the collision of molecules vibrating around relatively fixed positions. So we are talking about dipole-dipole movement which happens.

So, when there is a migration of molecules and more effectively by the collision. So, assuming that there are two molecules. So, they try to collide with each other and try to transfer heat by the collision of molecules vibrating around their relatively fixed positions. So, that is how heat transfer happens. There is steady-state unidirectional heat conduction in a solid.

Steady-state heat flow means the temperature at any location along the heat flow path does not vary with time. The rate of heat transfer does not vary with time. The temperature varies with location but not with respect to time. So that is one of the most important things. Steady-state unidirectional heat conduction in solids. Temperature varies with location but not with time.



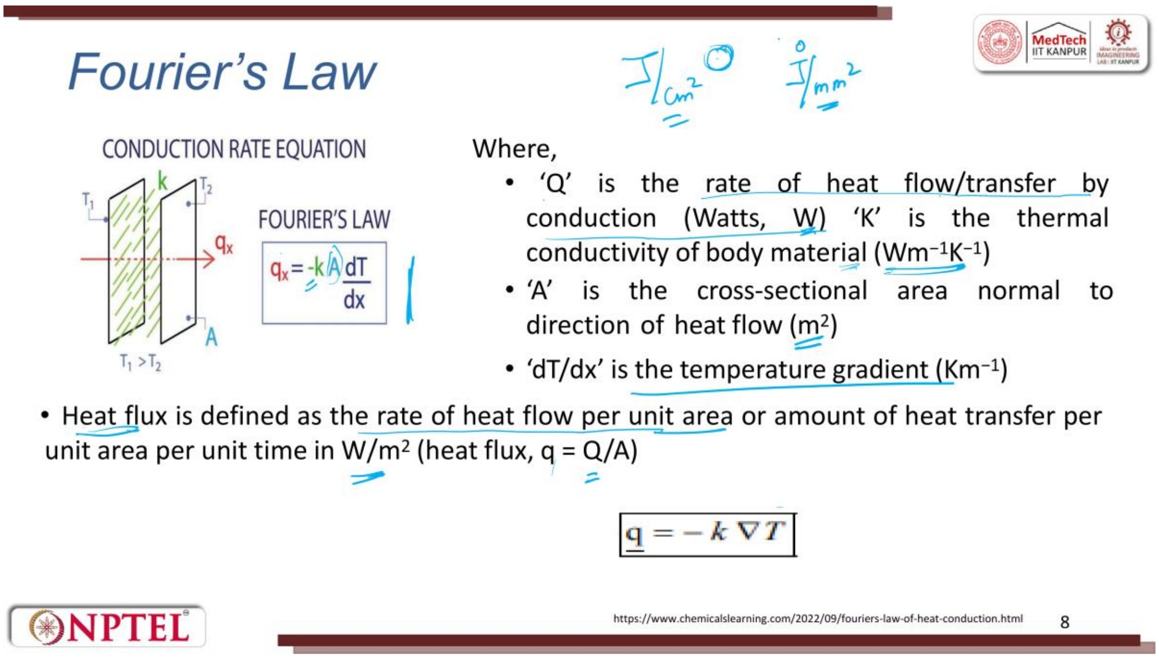
So Fourier's law is an important law when we talk about heat transfer. Fourier's law states that the rate of heat flow by conduction, by conduction mode, is very important. The rate of heat flow by conduction through a uniform material is directly proportional to the area normal to the direction of heat flow. And the temperature gradient in the direction of the heat flow.

Two important points. The rate of heat flow by conduction. Directly proportional to the area normal. Suppose, it flows like this area normal, this is an area normal, is directly proportional to the area normal to the direction of the heat flow and temperature gradient in the direction of the heat flow. So, proportion to the area normal to the direction of heat flow and the temperature gradient in the direction of heat flow.

Fourier's law states that the time rate of heat transfer through a material is proportional to the negative gradient in temperature and to the area. So, this is another way of presenting the same law. The temperature gradient is what you have here. You try to measure temperature here, temperature here along the length. The rate of change of temperature with displacement in a given direction.

Here, the temperature gradient is negative since with an increase in n, there is a decrease in T. The temperature decreases in the direction of heat flow. So, this is the pictorial representation of Fourier's law of heat conduction. So, the conduction area equation can be represented as qx equals minus k times. k is the thermal conductivity, or you can take it as a constant for a given material. And then, A is what we have been saying time and again: qx, the rate at which the heat flows, equals minus k (a constant), A is normal to the area dT by dx. So, Q is the rate of heat flow or transfer by conduction.

Q is the rate of heat flow or transfer by conduction; K is the thermal conductivity of the body material. So, it is represented as watts per meter Kelvin. A is the cross-sectional area normal to the direction of heat flow, that is, meter squared.



The rate of heat flow or transfer by conduction is in watts. The thermal conductivity of the body is expressed in this. Area is in this. So, dT/dx is the temperature gradient, which is km^{-1}. So, the heat flux is defined as the rate. The rate of heat flow per unit area is the heat flux. What is heat flux? The heat which is applied over a unit area.

The heat flux, if it is high, then what will happen? Heat will be applied here. For example, let us apply J/cm^2. J/mm^2. The area is reduced.

So, now what do you say? The flux is increased. So, the heat flux is defined as the rate of heat flow per unit area, or the amount of heat transfer per unit area per unit time, given in watt per meter square. So, heat flux is nothing but q = Q/A, where Q is the rate of heat flow. A is the area.

So, you can see this is the area. So, the heat is flowing from T1 to T2. So, the heat flux equation can be expressed as minus k multiplied by the gradient. So, Fourier's law is very important. So, please keep that in mind.

There can be some questions about Fourier's law of conduction. So, there are only two formulas. q = - kA x dx/dT. This is a gradient. q = - k dT.

Thermal Conductivity

- Thermal Conductivity is the measure of the ability of a substance to conduct heat.
- It is the quantity of heat passing through a quantity of material of unit thickness with unit heat flow area in unit time when a unit temperature difference is maintained across the opposite faces of material.
- Thermal conductivity depends on the nature of material and its temperature.
- Larger the values of K, higher will be the amount of heat conducted by that substance.
- It is a characteristics/transport properties of a material through which heat is flowing and varies with temperature.
- Thermal conductivities of solids are higher than that of liquids and liquids are having higher thermal conductivities than gases. { Metals : good conductors of heat}

Thermal conductivity is a measure. So conduction, whatever happens, is the law we are stating. But now, when you are trying to go to a market and buy a material, you are supposed to specify it in terms of some value. For example, give me a pen of 20-centimeter diameter or 20-centimeter length. Give me an ice cube of 1 meter by 1 meter by 1 meter. So, the dimensions are there.

So, when we say 1 meter, it is size, so it is in meters. Similarly, the temperature also has to be measured and must be constant for a given material at a given temperature. So, the parameter for measuring the thermal response of a given material is conductivity. Why is it important? Conductivity can expand the material.

Your MCBs, whatever work in your home, works on the concept of thermal conductivity or the wire which is used as a fuse wire, which is used also works on thermal conductivity. When there is more current drawn, there is heat generated. Moment there is heat generated, it thins or it softens and then it yields. And by doing so, it brings a disconnect between the live wires. And the second thing is thermal conductive is very important because what is the length of the stirrer I use in the kitchen.

So, that also plays an important role because if the heat gets conducted very fast, very slow, if it is very fast, I should keep a longer handle. So, that also depends on thermal conductivity. So, thermal conductivity is one of the properties with which you can evaluate a material for heat related applications. Thermal conductivity is a measure of a substance's ability to conduct heat. It is the quantity of heat passes through a quantity of material of unit thickness with unit heat flow in unit time.

So, this is very important: heat passing through a quantity of material of unit thickness with unit heat flow area in unit time. When the unit temperature difference is maintained across the opposite faces of the material. This is very, very important. Friends, keep the every point is important heat passing through a quantity of material, a given area, quantity of material of unit thickness, right? So, we are talking about area. Area is only x y plane. Now, they talk about also thickness. So, now they are talking about volume; quantity of material of unit thickness with unit heat flow rate in unit time.

So, you are trying to measure within 1 minute what the unit time is, with unit thickness, with unit heat flow, right? When the unit temperature difference is maintained across the opposite phases of a material. So, this is one phase, this is the other phase, this is the top phase, the bottom phase, right? Thermal conductivity depends on the nature of the material and its temperature. The larger the value of k (thermal conductivity), the higher will be the amount of heat conducted by the substance.

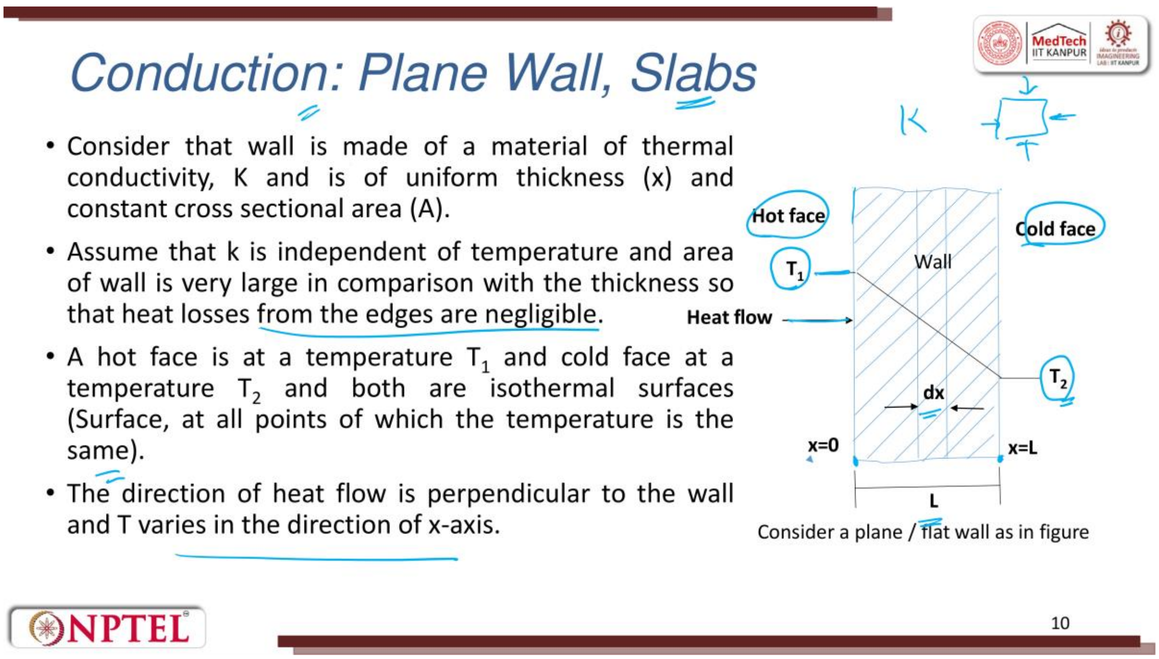
So that is why, if you see in many of the spoons, you will have steel and then you will have a non-conducting material. This will be non-conducting. This will be conducting. So, we are least bothered. So, we always touch the non-conducting part.

It is a characteristic or a transport property of a material through which the heat is flowing, and it varies with temperature. The thermal conductivity of a solid is higher than the thermal conductivity of a liquid, and liquids have higher thermal conductivity than gases. Why? Because the atoms are not compacted. So, if the atoms are not compacted, the heat cannot travel very fast. So, the conductivity of a solid is always higher than that of a liquid or gas.

So, that is why we say metals are good conductors of heat. So, here also you can see aluminium conducts faster, and stainless steel slightly slower, right? So, each material has its own thermal conducting property. So now, conduction through a plane wall or a slab. So, this is the hot face.

This is the cold face, right? There is a wall in between. The wall has a thickness of dx. So, here the length is 0, and here the length is L. So, the width of the wall is L, right? This is a hot phase, and this is a cold phase.

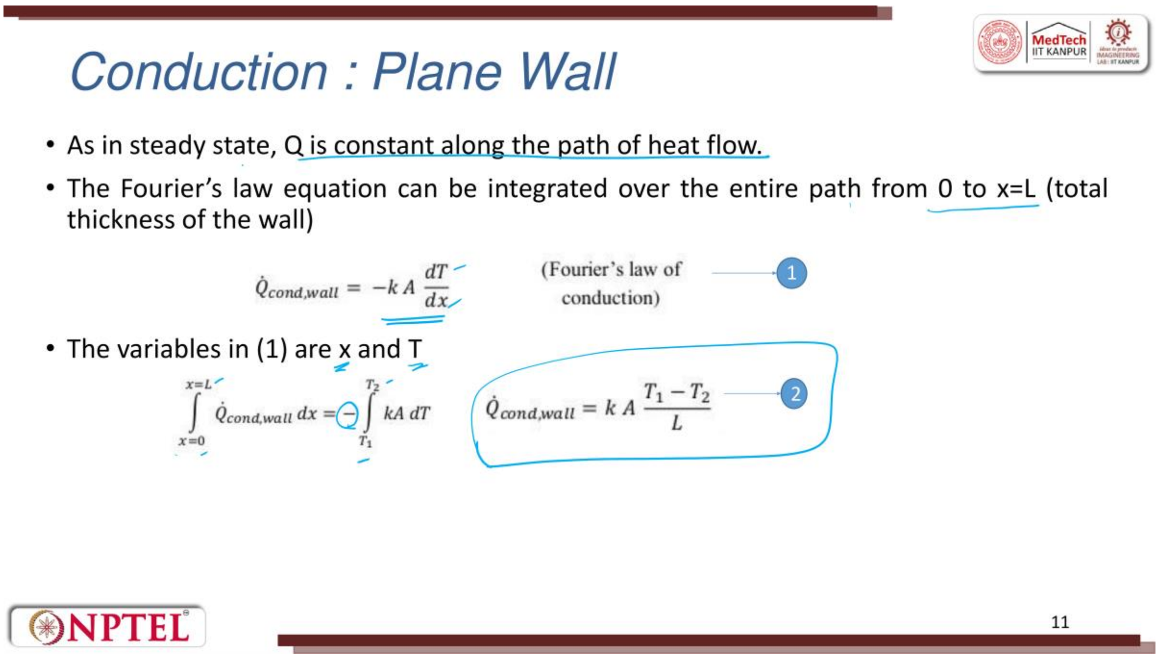
So, now you would like to know: when I apply a temperature T1 on the hot phase, what will be the temperature T2, and how much time will it take?



So, that is what we can try to find out by the conduction plane wall slab: consider a wall made of a material with thermal conductivity K, uniform thickness x, and a constant area. So, this is a wall. So, the wall has an area. So, this is the area: length multiplied by breadth.

So, it has a uniform thickness x right, it has a uniform thickness x and it has a cross section area A. Assume that k is independent of temperature, conductivity is independent of temperature, and the wall area is very large in comparison with the thickness. So, we are trying to take a large area board, the thickness is low. Assume that you have a paper large area and the thickness is very low. So that is what we say. The area of the wall is very large in comparison with the thickness so that heat loss from the edges are negligible.

So the hot phase is T1 and the cold phase is T2. And both are isothermal surfaces at all points of which the temperature is the same. So here also throughout the temperature will be T1, here also throughout it will be T2. The direction of the heat flow is perpendicular, the heat flow is perpendicular to the area, to the wall and the T varies in the direction along the x direction. So x = 0 to x = L.

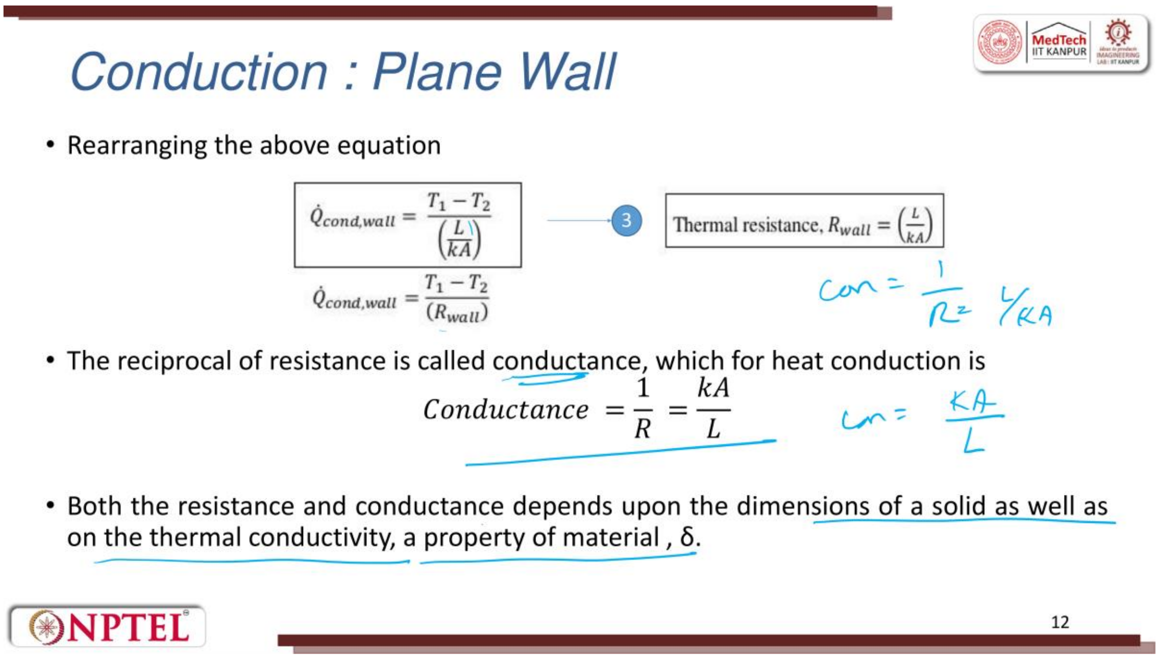


So, as it is a steady state, Q is constant along the path of heat flow. What is Q? Q is the rate of heat flow. So, as in the steady state, Q is constant along the path of heat flow. The Fourier's law equation can be

$$\dot{Q}_{cond,wall} = -kA\frac{dT}{dx} \qquad \text{(Fourier's law of conduction)}$$

Now, the variable is in 1 are from x and T

$$\int_{x=0}^{x=L} \dot{Q}_{cond,wall}\, dx = -\int_{T_1}^{T_2} kA\, dT \qquad \dot{Q}_{cond,wall} = kA\frac{T_1 - T_2}{L}$$



So, by rearranging this equation,

$$\boxed{\dot{Q}_{cond,wall} = \frac{T_1 - T_2}{\left(\frac{L}{kA}\right)}} \longrightarrow ③ \quad \boxed{\text{Thermal resistance, } R_{wall} = \left(\frac{L}{kA}\right)}$$

$$\dot{Q}_{cond,wall} = \frac{T_1 - T_2}{(R_{wall})}$$

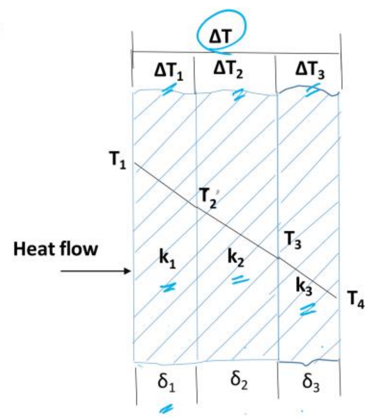
So, you can do that, and then what happens? You get this equation. So, it is nothing but the thermal resistance of the wall is L by kA. So, it is T1 minus T2 by R wall, right? The reciprocal of the resistance is called conductance. So, this is conductance, K = 1/R = kA/ L. Both the resistance and the conductance depends on the dimensions of the solid as well as on the thermal conductivity, a property of a material called δ. So, what did we try to find out?

We used Fourier's law, which we studied. We were trying to take a wall or a slab. We were trying to measure a temperature T1, T2, and the wall thickness. So now, what we will do is we have found out what is the conductance which is happening, and then 1 by R is the conductance.

Both the resistance and the conductance depend upon the dimensions of a solid as well as the thermal conductivity of the material. Now, this is a single homogeneous material. This example was a single homogeneous material.

Conduction : Composite Wall

- Consider a flat wall constructed of a series of layers of three different materials.
- Let k_1, k_2 and k_3 be the thermal conductivities of the material of which layers are made.
- Let thickness of the layers be δ_1, δ_2 and δ_3 respectively.
- Let ΔT_1 be the temperature drop across the first layer, ΔT_2 that across the second layer and ΔT_3 that across the third layer.
- Let ΔT be the temperature drop across the entire composite wall.



Now, what I want is to have multiple materials. For example, like a sandwich: you have bread on top, something in between, and bread on the bottom, right?

So, assuming there is a sandwich, each of these materials has its own property. So, that is what a composite slab is. Consider a flat wall constructed of a series of layers of three different materials, k1, k2, and k3 (A, B, and C). k1, k2, and k3 are the thermal conductivity properties of the materials of which the layers are made. Then the thicknesses are δ1, δ 2, and δ 3, respectively. So, let δT1 be the temperature drop across the first layer, δT2 be the temperature drop across the second layer, and δT3 be the temperature drop across the third layer.

Conduction : Composite Wall

- Let T_1,T_2,T_3 and T_4be the temperature at the faces of walls.
- $T_1$is the temperature of the hot face and T_4 is the temperature of the cold face, assume that the layers are in excellent thermal contact.
- Let the area of the composite wall be A.
- Overall temperature drop is related to the individual temperature rops over the layers by the equation

$$\Delta T = \Delta T_1 + \Delta T_2 + \Delta T_3$$

- In the steady-state condition, the heat flow q is the same for all the layers and is constant. The equation for heat transfer through these layers is

Conduction : Composite Wall

$$q = k_1 A \frac{T_1 - T_2}{\delta_1} \quad \text{for the first layer} \qquad \text{(i)}$$

$$q = k_2 A \frac{T_2 - T_3}{\delta_2} \quad \text{for the second layer} \qquad \text{(ii)}$$

$$q = k_3 A \frac{T_3 - T_4}{\delta_3} \quad \text{for the third layer.} \qquad \text{(iii)}$$

$$\left(\frac{T_1 - T_2}{\delta_1}\right) K_1 A = q$$

$$T_1 - T_2 = q\left(\frac{\delta_1}{K_1 A}\right)$$

- The temperature differences across the layers, from above equations, are

$$T_1 - T_2 = q\left(\frac{\delta_1}{k_1 A}\right)$$

$$T_2 - T_3 = q\left(\frac{\delta_2}{k_2 A}\right)$$

$$T_3 - T_4 = q\left(\frac{\delta_3}{k_3 A}\right)$$

$$\frac{1}{R} = \frac{KA}{L}$$

Adding the above equations, we get

$$T_1 - T_4 = q\left(\frac{\delta_1}{k_1 A} + \frac{\delta_2}{k_2 A} + \frac{\delta_3}{k_3 A}\right)$$

R_1 , R_2, R_3 be the thermal resistance offered by layer 1,2 and 3

or

$$q = \frac{T_1 - T_4}{\frac{\delta_1}{k_1 A} + \frac{\delta_2}{k_2 A} + \frac{\delta_3}{k_3 A}}$$

or

$$\boxed{q = \frac{T_1 - T_4}{R_1 + R_2 + R_3}}$$

So, let ΔT be the temperature drop across the entire wall. So, what we are trying to say is, we are trying to say this is T1 drop, T2 drop, T3 drop. It can be uniform; it need not be uniform. So, the overall temperature drop will be ΔT. So, T1, T2, T3, T4 are the temperatures at the faces of the wall. T1 is the temperature of the hot phase.

T4 is the temperature on the opposite side of the hot phase. That's the cold phase. Assuming that the layers are in excellent thermal contact. So, between these two, there can be air as a contact. Between these two, there can be welding, right?

So, it is nothing like perfect. But here, we assume that it is perfect contact or in excellent thermal contact. Let the area of the composite be A. So, the overall temperature drop $\Delta T = \Delta T1 + \Delta T2 + \Delta T3$. In the steady-state condition, the heat flow is q. The area for all the layers is constant. The equation of heat transfer through these layers is given by

$$q = k_1 A \frac{T_1 - T_2}{\delta_1} \quad \text{for the first layer} \tag{i}$$

$$q = k_2 A \frac{T_2 - T_3}{\delta_2} \quad \text{for the second layer} \tag{ii}$$

$$q = k_3 A \frac{T_3 - T_4}{\delta_3} \quad \text{for the third layer.} \tag{iii}$$

The temperature differences across the layers, from above equations, are

$$T_1 - T_2 = q\left(\frac{\delta_1}{k_1 A}\right)$$

$$T_2 - T_3 = q\left(\frac{\delta_2}{k_2 A}\right)$$

$$T_3 - T_4 = q\left(\frac{\delta_3}{k_3 A}\right)$$

Adding the above equations, we get

$$T_1 - T_4 = q\left(\frac{\delta_1}{k_1 A} + \frac{\delta_2}{k_2 A} + \frac{\delta_3}{k_3 A}\right)$$

or

$$q = \frac{T_1 - T_4}{\dfrac{\delta_1}{k_1 A} + \dfrac{\delta_2}{k_2 A} + \dfrac{\delta_3}{k_3 A}}$$

or

$$q = \frac{T_1 - T_4}{R_1 + R_2 + R_3}$$

So, where R1, R2, R3 are the thermal resistances offered by 1, 2, and 3. I am converting into the resistance. We go back and see here also: what did I do? I converted into resistance. So, here also, what I will do is I will convert into resistance.

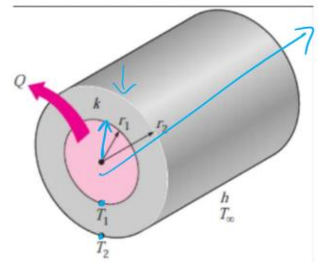
T1 – T2 = q $\left(\frac{\delta 1}{K1A}\right)$

So, what is k1A? So, we know that 1/R = kA/L. How did we get this? We got this from here. So, we just represented it. Now, all of these are changed into resistance. So, q is the heat which flows, and then you get the temperature difference by this formula.

Conduction : Plane Cylinder

- Consider a thick walled hollow cylinder of inside radius r_1 , outside radius r_2 , and length L.
- Let the temperature of inside and outside surface be T_1 and T_2 . Assume $T_1 > T_2$, heat flows from inside of the cylinder to outside.
- Fourier's law in general form for radial heat flux in a cylinder is:

$$\boxed{Q = -kA\frac{dT}{dr}}$$



Where,

Q/ q_r - Heat flux in the radial direction (W/m²)

k - Thermal conductivity (W/m·K)

A - Cross sectional area of the cyclinder (m²)

$\frac{dT}{dr}$: Temperature gradient (K/m)

Conduction : Plane Cylinder

- Separating the above equation gives

$$dT = -\frac{Q}{2\pi kL}\frac{dr}{r}.$$

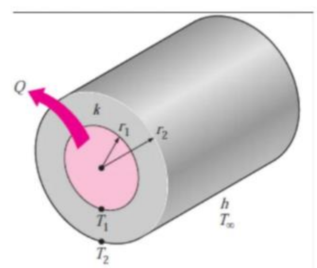
- Integrating from $T = T_1$ @ $r = r_1$ to $T = T_2$ @ $r = r_2$

$$T_2 - T_1 = -\frac{Q}{2\pi kL}(\ln r_2 - \ln r_1)$$

$$T_2 - T_1 = -\frac{Q}{2\pi kL}\ln\frac{r_2}{r_1}$$

$$T_1 - T_2 = \frac{Q}{2\pi kL}\ln\frac{r_2}{r_1}$$

$$2\pi kL\,(T_1 - T_2) = Q\ln\frac{r_2}{r_1}$$



Moving on to conduction through a plane cylinder. Examples: you can think of a pipe, wherein you have an inner wall and outer wall thickness. The difference between a cylinder and a pipe is, in a pipe, the thickness of the sheet, whichever is there, will be thin. So, they will have an outer diameter and an inner diameter.

The difference between the outer diameter and inner diameter will be small, and if it is longer, it is a pipe. If it is shorter and thicker, then it is called a cylinder. So, it has a lot of applications: boilers, for example, are considered cylinders—thick cylinders, thin cylinders—they account for all those things. So now, we will try to see how we can extrapolate what we saw for a flat surface, for a composite surface, to a cylinder. So, consider a thick-walled hollow cylinder with an inner radius R1 and an outer radius R2.

The length of the cylinder is L. Let the temperature inside and outside the surface be T1 and T2. T1 is at the innermost and T2 is at the outermost. So naturally T1 is higher than T2. The heat flows from the inside of a cylinder to outside. According to Fourier's law, which we saw, we have

$$Q = -kA\frac{dT}{dr}$$

Where,

q_r - Heat flux in the radial direction (W/m²)

k - Thermal conductivity (W/m·K)

A - Cross sectional area of the cyclinder (m²)

$\frac{dT}{dr}$: Temperature gradient (K/m)

Separating the above equation gives

$$dT = -\frac{Q}{2\pi kL}\ \frac{dr}{r}$$

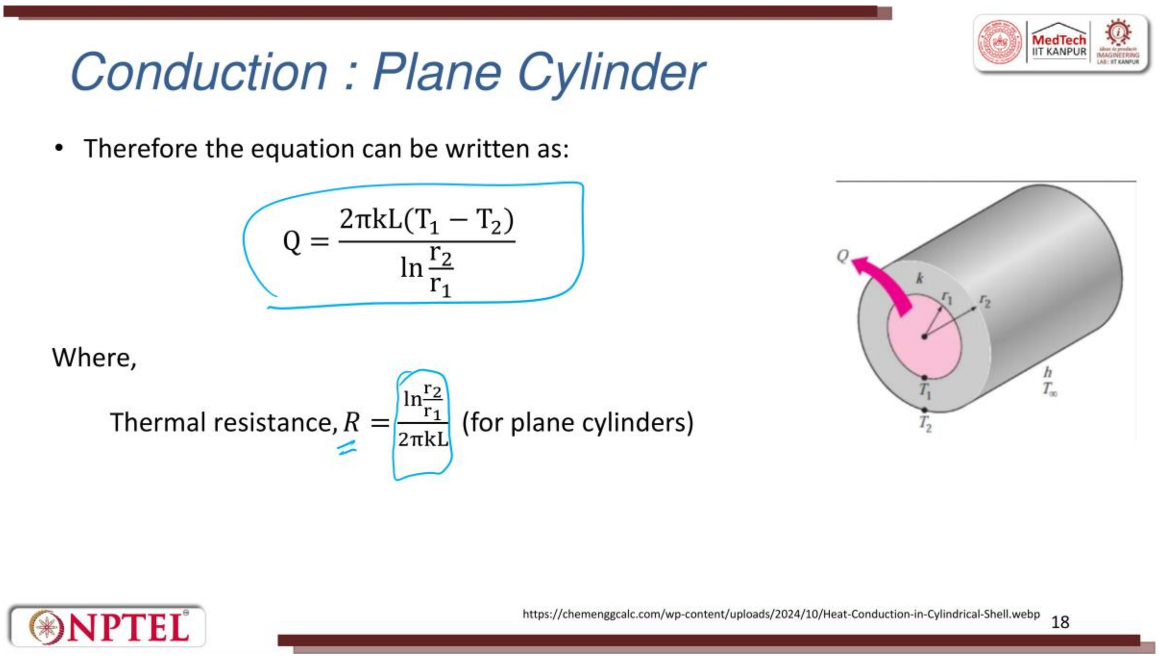
Integrating from $T = T_1$ @ $r = r_1$ to $T = T_2$ @ $r = r_2$

$$T_2 - T_1 = -\frac{Q}{2\pi kL}\ (\ln r_2 - \ln r_1)$$

$$T_2 - T_1 = -\frac{Q}{2\pi kL}\ln\frac{r_2}{r_1}$$

$$T_1 - T_2 = \frac{Q}{2\pi kL}\ln\frac{r_2}{r_1}$$

$$2\pi kL\ (T_1 - T_2) = Q\ln\frac{r_2}{r_1}$$



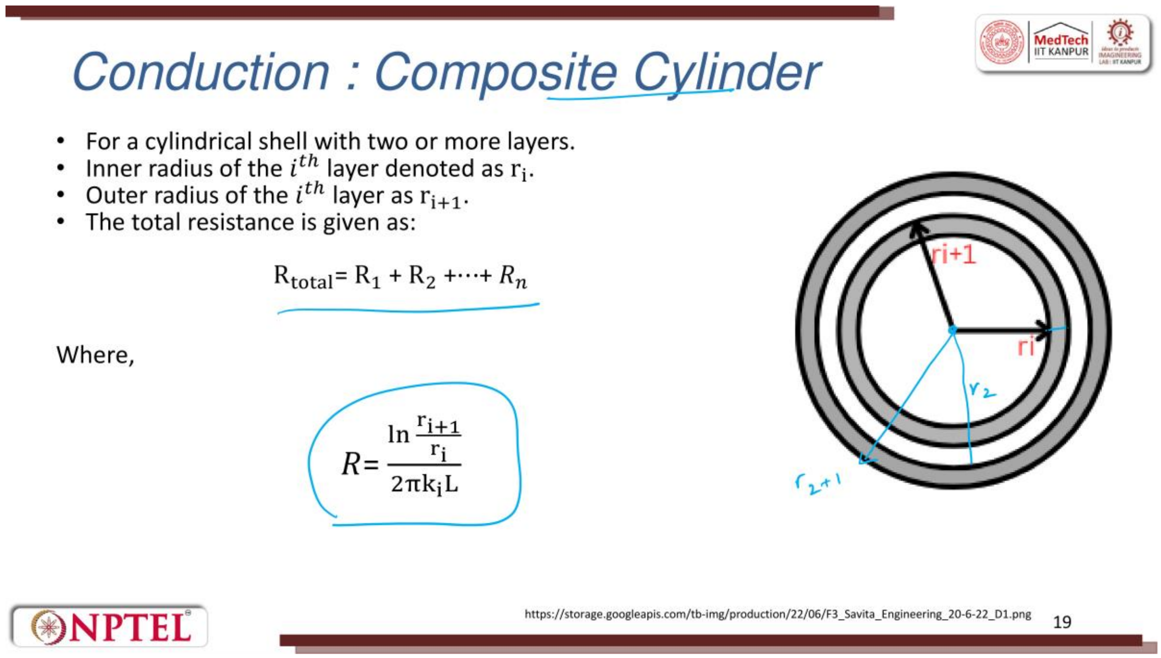
Therefore, the final equation can be written as this:

$$Q = \frac{2\pi kL(T_1 - T_2)}{\ln\frac{r_2}{r_1}}$$

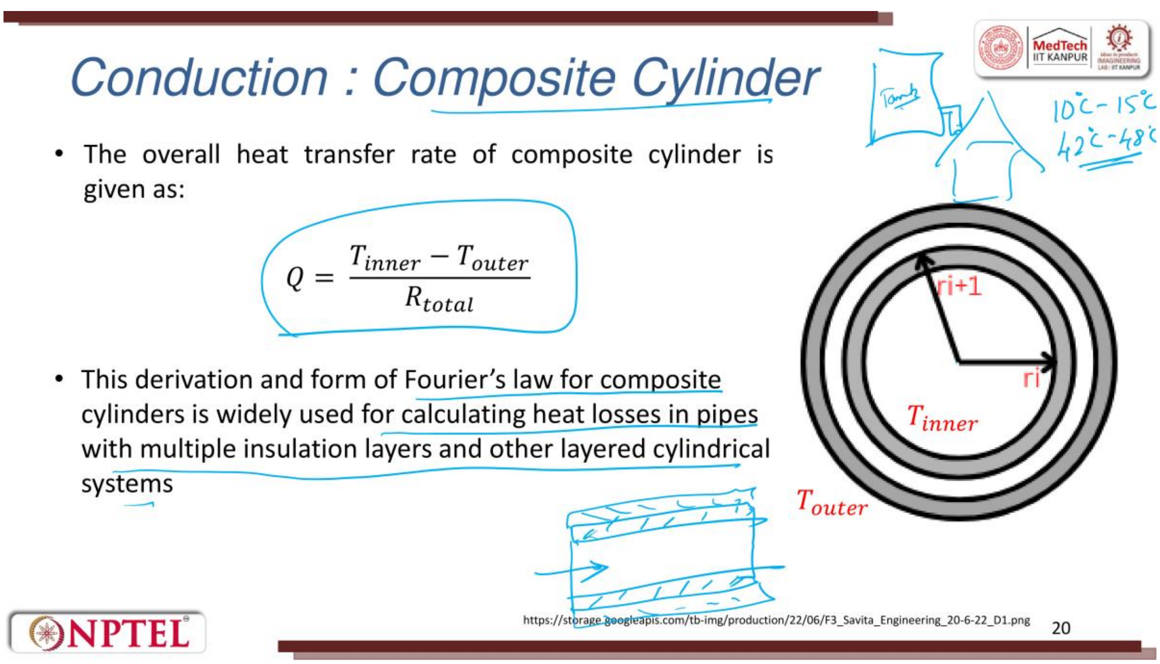
Where,

Thermal resistance, $R = \frac{\ln\frac{r_2}{r_1}}{2\pi kL}$ (for plane cylinders)

So the same thing we did for composites and for a plane wall, we are now using the same concept and trying to apply it to a plane cylinder. We can also try to extrapolate for a composite cylinder.



A composite cylinder will have an inner radius r, and then inner radius plus its thickness—whatever we have is ri + 1. Then we can try to go to r2, then it is R2 + 1. So here, $R_{total} = R_1 + R_2 + \cdots + R_n$. The rest is the same as what we see in the plane cylinder.



So the overall heat transfer for a composite cylinder will be

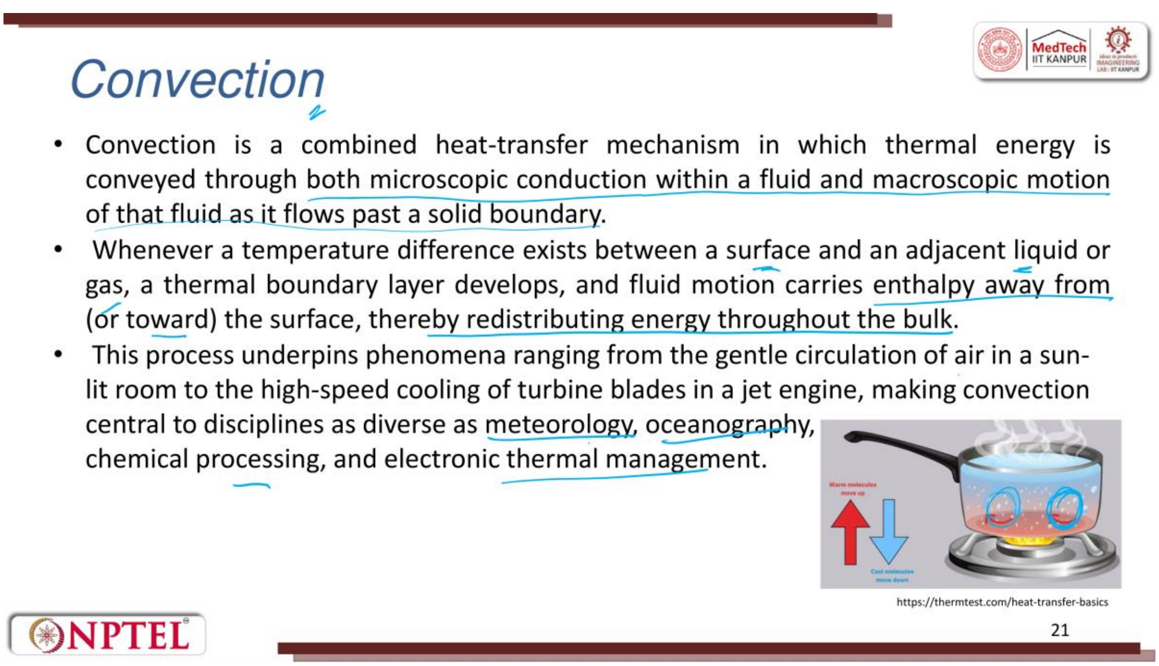
$$Q = \frac{T_{inner} - T_{outer}}{R_{total}}$$

This derivation and form of Fourier's law for a composite cylinder is widely used for calculating heat loss in a pipe with multiple insulation layers and other layered surfaces. For example, you can think of having a water tank on the top of your house. And here, you get a connection made through a pipe to your house.

So now, on a cold winter day in North India, the temperature ranges between 10 degrees Celsius to 15 degrees Celsius at night. And in summers, it ranges between 42 degrees Celsius to 48 degrees Celsius. Now, what is the way forward? You try to take a pipe and then you try to put insulation on the pipe. You try to put insulation on the pipe.

So now what happens is, it is nothing but a composite cylinder. So Fourier's law of composite cylinders is widely used for calculating heat losses in pipes. Heat loss means when you are trying to push in water, heat is lost. The other way around is because it is exposed to the atmosphere. The tank is exposed to the atmosphere.

So the temperature is very low. So now what we do is, we try to increase the temperature here and send it through. So calculating heat loss in pipes with multiple layers of insulation. So if you see here, you can have one more layer of insulation. And then you can try to find out what is the conduction that happens through the layered surface.

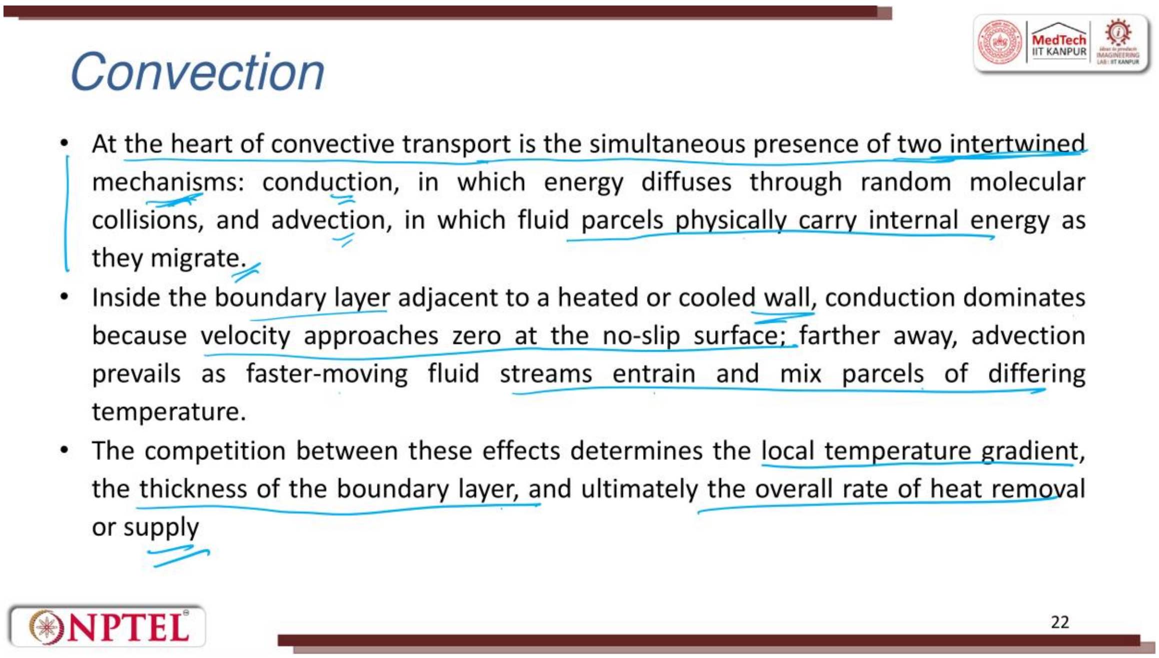


Now, let us move to the next topic of convection. Convection is a combined heat transfer mechanism in which thermal energy is conveyed through both molecular conduction within a fluid and macroscopic motion of the fluid as it flows past a solid boundary. Whenever a temperature difference exists between a surface and an adjacent liquid—for example, the liquid can be air or gas—a thermal boundary layer develops.

The fluid motion carries enthalpy away or toward the surface, thereby redistributing energy throughout the bulk. This process underpins phenomena ranging from the gentle circulation of air in a sunlit room to the high-speed cooling of a turbine blade in a jet engine. So, this convection phenomenon happens from the gentle circulation of air in a sunlit room.

That means, if you have a glass panel and you are sitting inside the room, it applies to the high-speed cooling of a turbine blade in a jet engine. Making convection central to disciplines as diverse as meteorology, oceanography, chemical processing, and electronic thermal management is very important. So, convection—you can see there is a convection phenomenon happening. The hot water goes up, the cold water comes down, and a vortex is created. So, I will go back.

Whenever a temperature difference exists between a surface—take a surface, this is a surface—and an adjacent liquid, you are immersing it in water or keeping it in air. Adjacent liquid—your thermal boundary develops. So, between this and the next, there is a physical boundary. In the same way, there is a thermal boundary that gets established. A fluid motion carries away the enthalpy. Heat carries away the enthalpy or brings the enthalpy toward the surface. Therefore, the redistribution of energy takes place throughout the bulk.



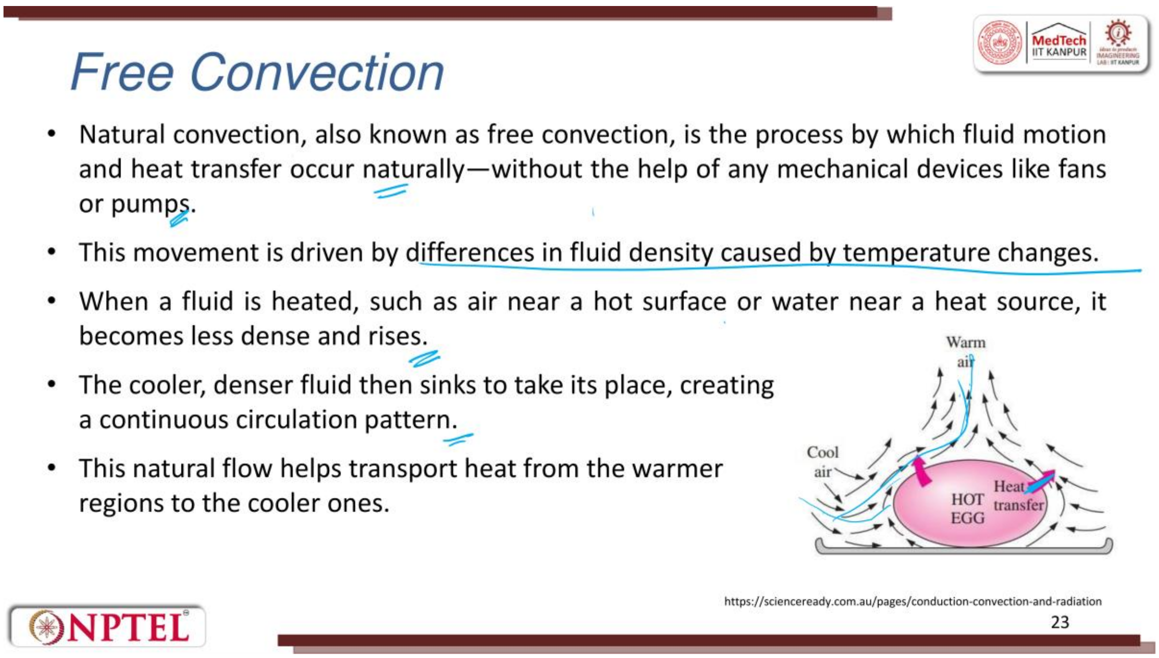
At the heart of convective transport is the simultaneous presence of two intertwined mechanisms. One is conduction, in which energy diffuses through random molecular collision, and advection, in which the fluid parcels physically carry internal energy as they migrate. So, at the heart of convective transport is the simultaneous presence of two intertwined mechanisms: conduction and convection.

So, conduction will happen while moving. Advection, in which the fluid parcels physically carry internal energy as they migrate. Inside the boundary layers adjacent to a heated or a cold wall. Inside the boundary layer adjacent to the heat. So, assume that this is the boundary layer.

Inside the boundary layer adjacent to the heated or a cold wall, conduction dominates because velocity approaches zero at a non-slip surface. Further away, advection prevails as faster moving fluid streams entering and mix parcels of different temperature. So, this is what it is parcels of mixed temperature advection. So, that is what this is called as conduction advection it has become convection. The competition between these effects determine the local temperature gradient, the thickness of the boundary layer and ultimately the overall rate of heat removed or supplied.

Determines the local temperature gradient and the thickness of the boundary layer. Suppose if the thickness is very large, then there is going to be a different phenomenon.

When the thickness is very small, there is going to be a different phenomenon. Depends upon the local temperature gradient and the thickness of the boundary layer. So, as we were talking about, we were always saying that it is very much used in meteorology and oceanography.



So, here we will see free convection. So, free convection, also known as natural convection, is also called free convection. It is the process by which fluid motion and heat transfer occur naturally. I boil an egg and keep it in the free atmosphere. So, without the free atmosphere, without any help, there is a transfer of heat.

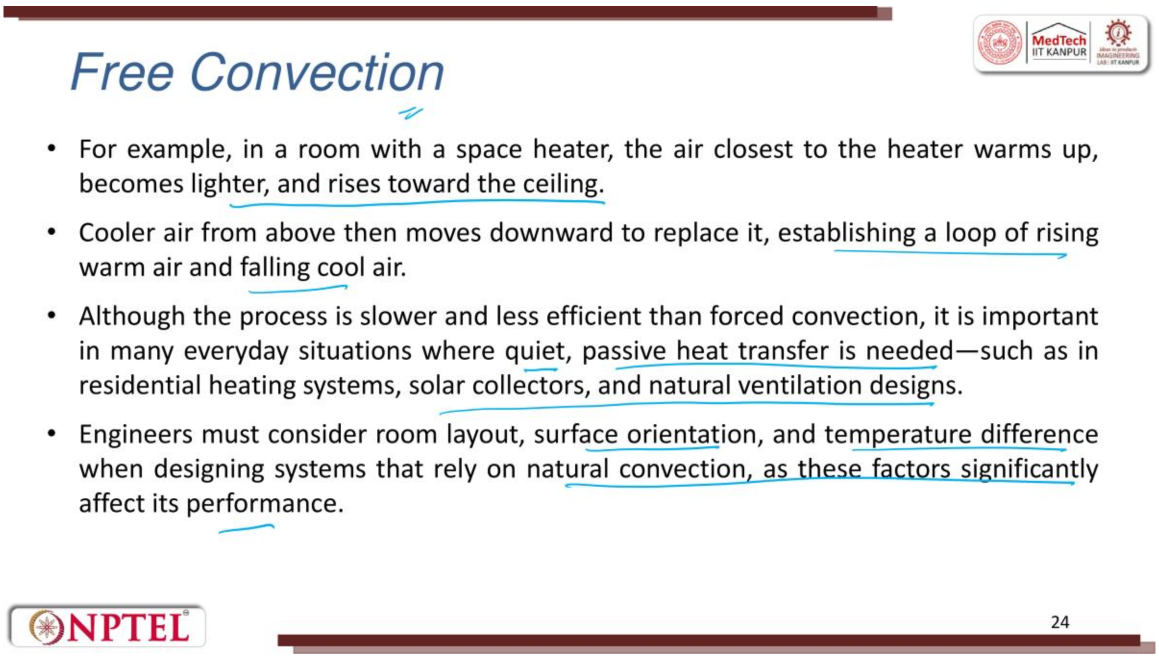
Without the help of any mechanical device, fan, or pump, the heat gets transferred. The cold air comes. So, this is a hot egg. The cold air comes, hits the hot surface, tries to become lighter, and moves further away. Cold air is heavy.

So it comes and hits the egg. So the egg tries to increase the temperature. Then this cold air becomes warm. Warm air is lighter. So it goes to the top.

So here, heat transfer is happening. So natural convection, also known as free convection, is a process by which fluid motion and heat transfer occur naturally. There, we don't apply any energy. The movement is driven by the difference in fluid density caused by temperature. Cold is down; hot is up.

And then, when the cold moves up, the hot—if you put it inside a cold, confined body—this hot goes up. Then, when the hot goes up, the cold tries to fill in the space. So then, heat is filled everywhere. Now it tries to circulate. When the fluid is heated, such as air near a hot surface or water near a heat source, it becomes less dense and then rises.

The cooler, dense fluid then sinks to take its place, creating a continuous circulation pattern. This natural flow helps transport heat from the warmer region to the colder region.



Free convection, for example, occurs in a room with a space heater. The air closest to the heater warms up, becomes lighter, and rises to the ceiling. The cold air from above moves down to replace it and establishes a loop of warm and cold air.

Convection happens. So although the process is slow and less efficient than forced convection, it is important in many everyday situations where quiet, passive heat transfer is very much needed. Because if you forcibly apply energy there, then the same heat transfer will happen, for which you have added work to it.

Such as in residential heating, solar collectors, and natural ventilation systems, we design it like that. Engineers must consider room layouts, surface orientation, and temperature differences when designing systems that rely on natural convection, as these factors significantly affect their performance.

Free Convection

Mechanism of free convection:

- In natural convection, the fluid motion occurs by natural means such as buoyancy.
- Buoyancy forces are developed due to density variations in the fluid caused by the temperature difference between the fluid and the adjacent surface.
- Since the fluid velocity associated with natural convection is relatively low, the heat transfer coefficient encountered in natural convection is also low.

So what is the mechanism of free convection? In natural convection, the fluid motion occurs by natural means, such as buoyancy. Buoyancy forces are developed due to the density variation in the fluid—hot and cold. Variation in the fluid is caused by the temperature difference between the fluid and the adjacent surface. Since the fluid velocity associated with natural convection is relatively low, the heat transfer coefficient encountered in natural convection is also low. So, the heat transfer coefficient, the transfer of heat is also low.

Forced Convection

- Forced convection is a mode of heat transfer in which the fluid motion is induced by an external source such as a fan, pump, or blower.
- Unlike natural convection, where fluid movement is driven solely by temperature differences, forced convection uses mechanical devices to move the fluid, allowing for much faster and more controlled heat transfer.
- This method is especially useful in applications where quick heat removal is required, such as in automotive engines, air conditioning systems, and electronic cooling fans.
- For example, in a car radiator, coolant fluid is actively pumped through narrow tubes, absorbing heat from the engine and transferring it to the surrounding air as a fan forces airflow over the radiator fins.

NPTEL

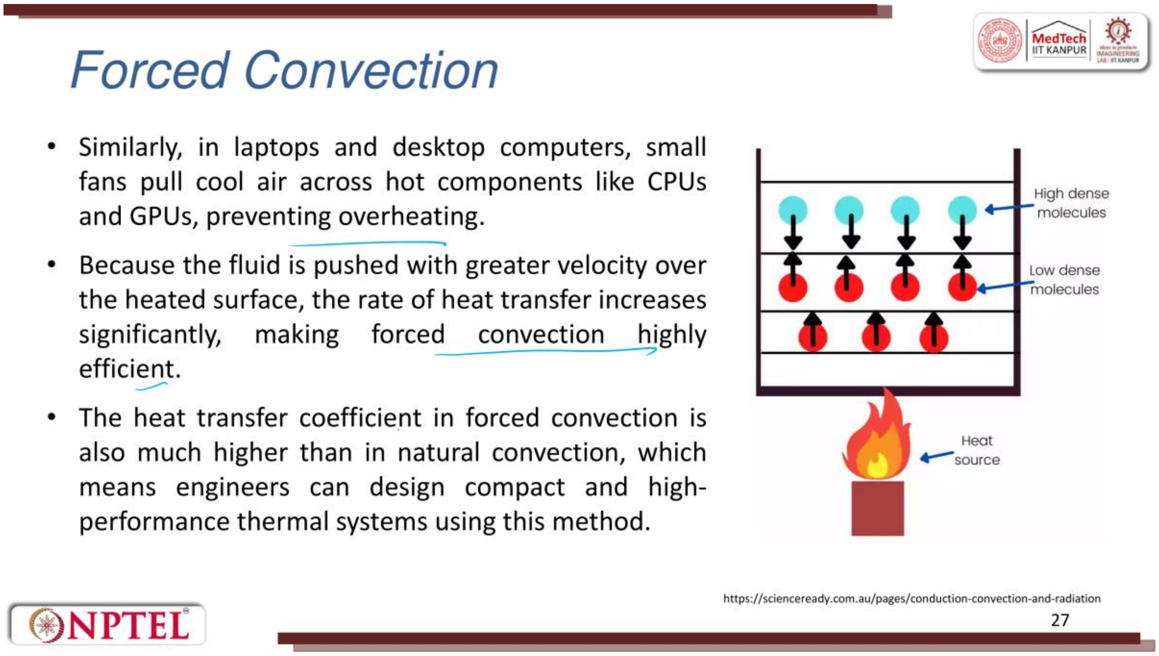
So now, let us move to forced convection. So, hot body, cold air, warm air. Now, this is happening naturally. Now, I force air. Forced convection is a mode of heat transfer in which the fluid motion is induced by an external source, such as a fan, pump, or a blower.

Unlike natural convection, where fluid flow is driven solely by temperature difference, forced convection uses a mechanical device to move the fluid, allowing it to have a much faster and more controlled way of heat transfer. Right. This method is especially used in applications. That is why, if you see, there are fans in your laptop; there is a fan which forces air onto the processor, and the heat is extracted.

So, there is a fan. The same way, you have a fan in the compressor. You have a split AC. You will have a blowing station inside your house and the compressor outside your house. The compressor will have a big fan. This big fan will try to force air and hit it on the compressor such that the heat, whatever is generated because of compression, which we saw in the jet engine cycle and all compression.

So, there will be a lot of heat because pressure and temperature increase when you try to. So, that heat has to be extracted. So, that is where we use fans, right? For example, in a car radiator, cooling fluid is actively pumped through narrow tubes, absorbing heat from the engine and transferring it to the surroundings as a fan forces air over the radiator fins.

So, in order to extract heat, that is why in a radiator or in an AC unit, you see a lot of fins. These fins are used for increasing the surface area for heat transfer.

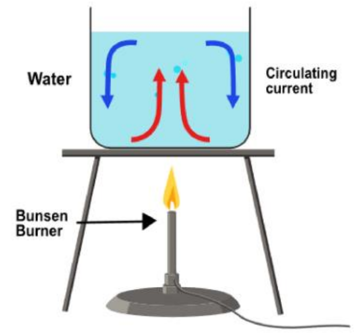


Similarly, in laptops and desktop computers, small fans pull cold air across hot components like the CPU and GPU, preventing overheating. So that's why in the early days, they used to say, keep your desktop computer in an air-conditioned unit. Even today, if you have a very big server. In order to maintain the server's temperature between 12 and 18 degrees, we always keep it inside an air-conditioned room with a controlled atmosphere.

Because the fluid is pushed with greater velocity over the heated surface, the rate of heat transfer increases, making forced convection highly effective. The heat transfer coefficient in forced convection is much higher than in natural convection, which means engineers can design compact and high-performance thermal systems using forced convection. So, if you see, when you try to heat the high-density molecules, they come down, and the low-density molecules go up, so there is a transfer.

Forced Convection

- Forced convection allows for better control over flow rate, direction, and temperature gradients, making it ideal for both small-scale and large-scale industrial processes.
- It is used in jet engines, refrigeration systems, nuclear reactors, and even food processing equipment, where maintaining precise temperatures is critical.
- The efficiency of forced convection depends on factors such as fluid velocity, surface area, fluid properties, and turbulence of the flow.



https://scienceready.com.au/pages/conduction-convection-and-radiation

Forced convection allows for better control over flow rate, direction, and temperature gradient, making it ideal for small-scale and large-scale industrial processing. So we burn, there is water that gets heated and circulates, and then after a period of time, it tries to maintain a uniform temperature.

It is used in jet engines, refrigeration systems, nuclear reactors, and even food processing equipment where precise temperatures must be maintained, using forced convection. The efficiency of forced convection depends on factors like fluid velocity, surface area, fluid properties, and the turbulence of the flow.

So, these are all important properties that dictate forced convection: fluid velocity, surface area, and fluid properties. This is why we have AC fins, or radiator fins, and fluid properties. So, heat moves from hot to cold, and the turbulence of the flow affects it.

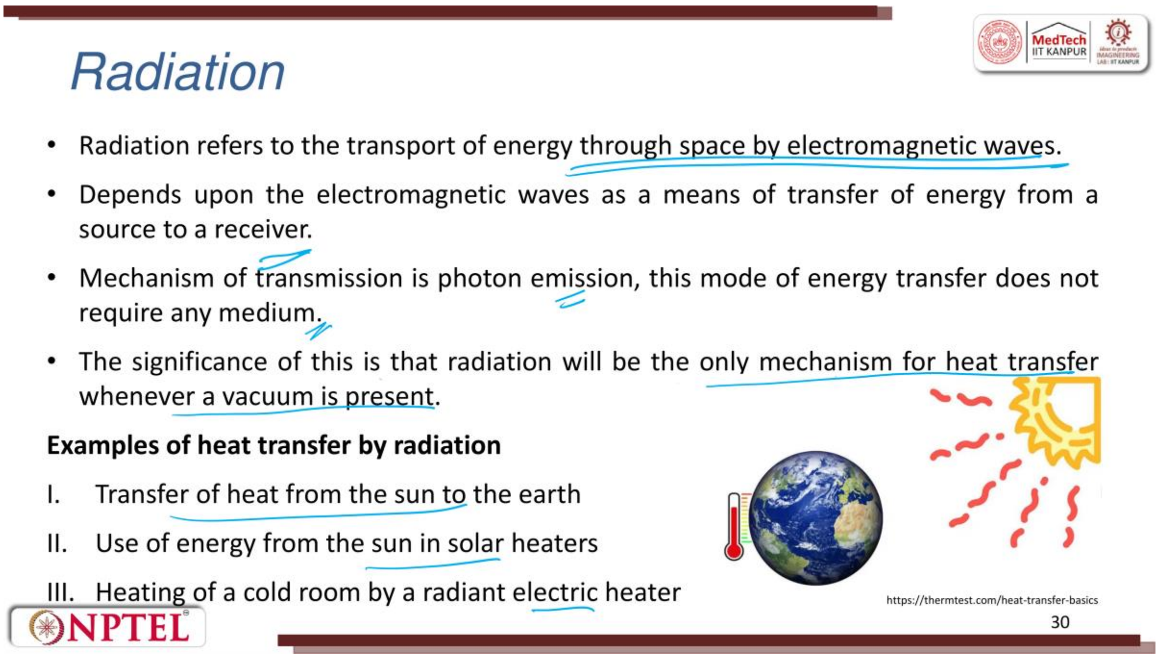
So, if it is lamellar flow, it is just flowing on top. If it is a lamellar flow, it will be a smooth flow. When there is disturbance, it is a turbulent flow. This turbulent flow can extract more heat.

Convection

- The rate of heat transfer in convection is described by **Newton's Law of Cooling**:
$$\boxed{q = hA(Ts - T_\infty)}$$
- In this formula, q is the amount of heat transferred per second, h is the heat transfer coefficient, A is the surface area, $T_s$is the surface temperature, and $T_\infty$is the fluid temperature.
- The heat transfer coefficient h is much higher for forced convection than for natural convection.
- Engineers use this formula to design systems that effectively manage heat, such as in engines, electronics, and building ventilation.

So, the convection, the rate of heat transfer in convection, is described by Newton's law of cooling. where $q = hA(Ts - T\infty)$, where q is the amount of heat transfer per second, h is the heat transfer coefficient, A is the total area, S is the surface temperature, and T infinity is the fluid temperature.

So, by using this, you can see we saw Fourier's law of conduction, and we saw convection is Newton's law of cooling in convection. The heat transfer coefficient h is much higher for forced convection as compared to that of a natural convection. Engineers use this formula to design the system and make energy-efficient systems.



The last one is going to be radiation. Radiation refers to the transport of energy through space by electromagnetic waves only. The first two are conduction through atoms. Next, it can be through atoms or it can be through advection. So it is very important you should know this. At the heart of conduction transport is the simultaneous presence of two intertwined mechanisms.

One is conduction. You know conduction. Hot rod, conduction, molecule-wise motion, random motion, vibration, collision, conduction. And then you have the other one, which is advection. In which fluid parcels physically carry internal energy as they migrate.

So here, in radiation, it passes through space by electromagnetic waves. You can have a vacuum or you can have space also. Depending upon the electromagnetic waves as a means of transferring energy from a source to a receiver. The mechanism of heat transfer is photon emission, and the mode of energy transfer does not require any medium. It can be through a vacuum, or it need not be in a vacuum, right?

So, it does not need a medium. The significance of this is that radiation will be the only mechanism for heat transfer whenever a vacuum is present. This is the only way, right? So, examples of heat transfer by radiation include the transfer of heat from the sun to the earth, the use of solar energy in solar heating, and the heating of a room by electric radiators. So, when we talk about radiation, there are properties like absorptivity, reflectivity, and emissivity.

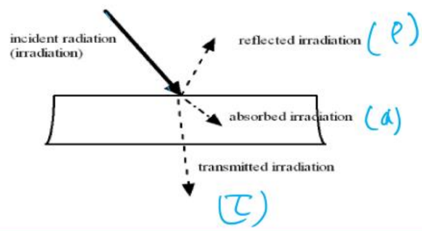
So, for example, if you have a clean polished surface, when heat hits it, it reflects, right? Any substance receives and emits energy in the form of electromagnetic waves. When the energy emitted by a heated body falls on a second body, it will be partially absorbed, partially reflected, and partially transmitted. So, what we are trying to say is, when heat hits, one way it travels is by being partially transmitted. So, this is transmitted; then the other way is it is getting absorbed, and the third one is it is getting reflected.

So, this is an electromagnetic wave. So, you can have transmission, you can have reflection, and then the next one is absorption by the medium itself. It is only the absorbed energy that appears as heat in the body. So, whenever sun rays fall on a human, you absorb heat; if you put a glass mirror, it reflects. It can also absorb and transmit. For example, a microwave allows the microwave to pass through a glass bowl, transmitting it to the food and water inside, right?

Oneness it transmits it absorbs, transmitters is enters and it exits also. There are ceramic material where it is transparent. It is the only absorption energy that appears as a heat in the body. The incident radiation is equal to absorption. Then it is transfer outside and then heat reflected. This proportion of the incident energy that are absorption, reflection and transmitted depends on the characteristics of a receiver.

Radiation

- Fraction of the incident radiation on a body that is absorbed is absorptivity (α).
- Fraction of the incident radiation on a body that is reflected is reflectivity (ρ).
- Fraction of the incident radiation on a body that is transmitted through the body is known as transmissivity (τ).
- The energy balance about a receiver on which the total incident energy falling is unity (sum of all fractions is unity).



$R = \rho + \alpha + \tau$

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Radiation: fraction of the incident radiation on the body that is absorbed is absorptive. So, which gets absorbed is absorptive A or alpha then which gets reflected which is called as rho which gets transmitted it is called as tau. So, the energy balance about a receiver on which the total incident energy falls is unity. So, what they are trying to say is when the radiation falls, so R = ρ + α + τ, whatever it is, which is unity.

Radiation

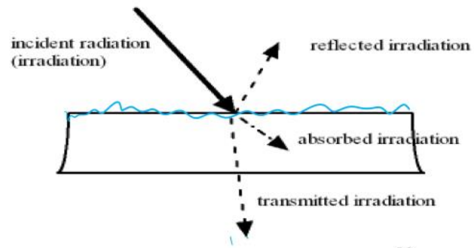
- For an opaque material, $a + r = 1$ since $\tau = 0$; For perfectly transparent

$$\tau = 1, a = r = 0$$

- For non-reflecting surfaces

$$r = 0, \ r = 1,$$

perfectly reflector $a = 1$, perfectly absorbing surface or a black surface



So, for an opaque material $a + r = 1$ since $\tau = 0$ what is opaque which does not allow anything to transmit. So, for a perfectly transparent material so $\tau = 1$, $a = r = 0$ reflection will not be there absorption will not be there. For a non-reflecting surface, non-reflecting surface means suppose if the surface is rough or if there is an oil film on top of it. So, then what happens? The r = 0 and r = 1.

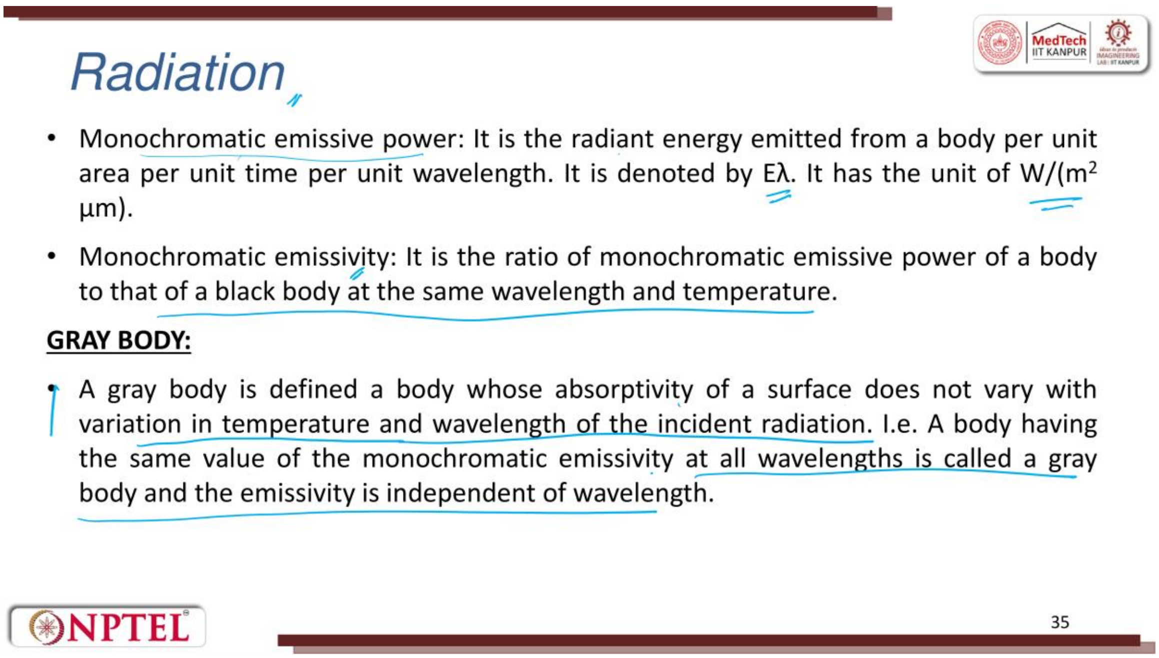
Radiation

BLACK BODY:

- A body for which $a = 1, r = \tau = 0$, i.e. which absorbs all the incident radiant energy is called a black body.
- It neither reflects nor transmits but absorbs all the radiations incident on it, so it is treated as an ideal radiation receiver.
- The black body radiates maximum amount of energy at a given temperature.
- Lamp black is the nearest to a black body which absorbs 96 % of the visible light.
- Both the absorptivity and emissivity of perfectly black body are unit.

A perfect reflector has an a = 1, while perfect absorption is that of a black body. So, a black body will have $a = 1, r = \tau = 0$. It neither reflects nor transmits but absorbs all the radiation incident on it. So, it is treated as an ideal radiation receiver. The black body radiates the maximum amount of energy at a given temperature.

Lamp black is the nearest to a black body, absorbing 96% of the visible light. Both absorptivity and emissivity of a perfectly black body are unity.



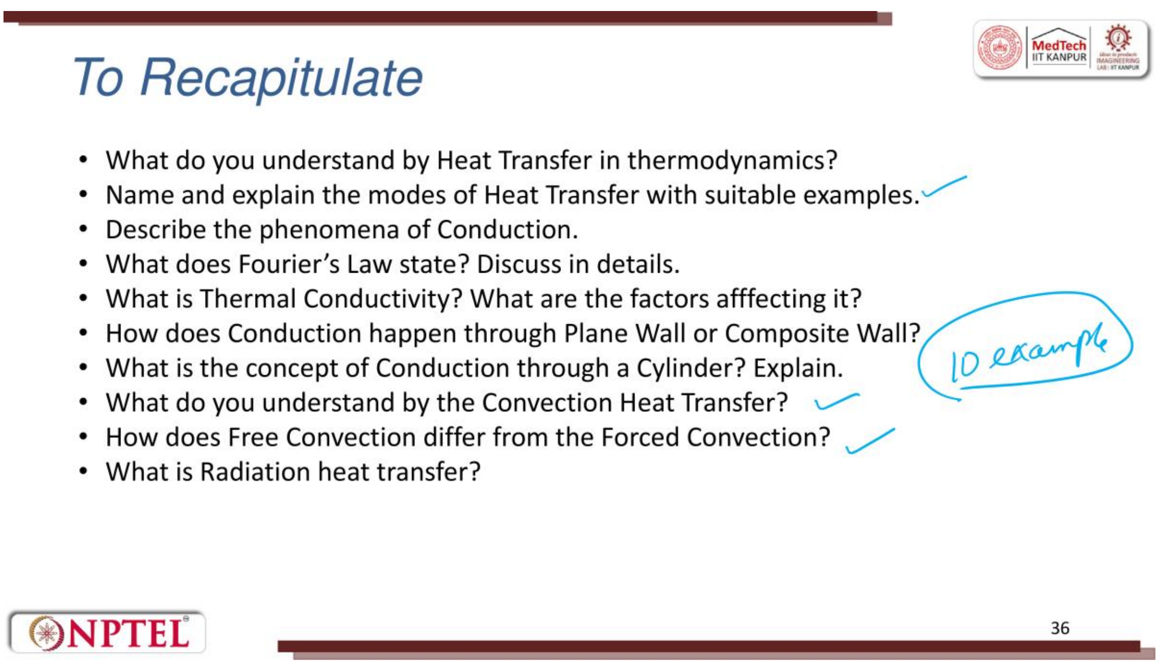
So, in radiation, you also have monochromatic emissivity and monochromatic emissive power. Monochromatic radiation means single wavelength. Monochromatic emissive power: it is the radiation energy emitted by a body per unit area, per unit time, per unit wavelength.

It is denoted as E_lambda, given by a formula in watts per meter square into micrometer. So, this is single-wavelength radiation. What comes through a heated body need not be a single monochromatic radiation. But here, we are discussing a phenomenon called monochromatic emissive power. Monochromatic emissivity is the ratio of the monochromatic emissive power of a body to that of a black body at the same wavelength and temperature.

So, when we try to look at the physical properties, we try to talk about specific heat or heat conduction, and also emissivity and reflectivity. There are bodies which are called gray bodies. We know black bodies. The other one is gray. A gray body is defined as a body whose absorptivity of the surface does not vary with changes in temperature or the wavelength of the incident radiation.

A gray body is defined as a body whose absorptivity of a surface does not vary—whatever absorption happens on the surface does not change with variations in temperature, whether 20, 30, 40, or 50, or the wavelength of the incident radiation. So, here we were talking about a monochromatic single wave. So, here, regardless of the variation in temperature and regardless of the incident ray. So, we have a gray body.

That is, a body having the same value of monochromatic emissivity at all wavelengths is called a gray body, and the emissivity is independent of wavelength, which is very important. See, when you pass electricity through an incandescent bulb, the coil is heated and radiates light, right? So, that need not be in a single chroma; it can be at any wavelength. So, friends, I am sure this lecture has been a great learning experience with many practical examples I provided.



So, to recap what we covered in this lecture: What do you understand by heat transfer in thermodynamics? Name and explain the modes of heat transfer. We studied the phenomena of conduction, then Fourier's law, different types of conduction, then we saw how conduction happens in a plane wall and a composite wall in a cylinder. What do you understand by convection? Convection involves conduction plus advection. So, it is conduction here. Then there are two types of convection, forced and free.

Then finally, we saw radiation. Friends, this lecture has a lot of examples, and you can also see various examples. I would like to give you a small exercise. Please try to look at this one, this one, and this topic, and try to give 10 examples of each of them which you don't know but are learning for the first time. 10 different examples for each of these phenomena. And in which you try to understand new concepts through them.

References

1. Patrick Chasseing. 2023, Fundamentals of Fluid Mechanics: For Scientists and Engineers, Springer.
2. Younus A. Çengel, Michael A. Boles, Mehmet Kanoğlu, 2023, Thermodynamics: An Engineering Approach, McGraw Hill Education.
3. Frank M White, 2017, Fluid mechanics, McGraw Hill Education
4. R. Fletcher, 2000, Practical methods of optimization, Wiley
5. J.P. Holman, 2010, *Experimental Methods for Engineers*, McGraw Hill Education.
6. Adrian Bejan, 2016, *Advanced Engineering Thermodynamics*, Wiley.
7. Michael J. Moran, Howard N. Shapiro, 2014, *Fundamentals of Engineering Thermodynamics*, Wiley.

These are the reference materials we have used for making these slides.

Thank you very much.