Heat and Mass Transfer

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Lecture No. 01

Namaste. My name is S P Sukhatme and along with my colleague professor U N Goitonade, I will be giving you a series of lectures on the subject of heat and mass transfer. We are from the department of mechanical engineering at the IIT Bombay. Now the subject matter which we will be covering under these lectures is the syllabus as is prescribed for the subject ‘heat and mass transfer’ in most universities in India and we will be doing this through about thirty odd lectures. We are from the department of mechanical engineering as I said. So, the matter that we will cover will be primarily from the point of view of mechanical engineering students. However, heat and mass transfer is an important subject also in the chemical engineering curriculum, in the aeronautical engineering curriculum and also taught, parts of it are also taught in other disciplines. So, although we will be covering the subject from the point of view of what is the syllabus in mechanical, what we have to say would, I think, be of interest also to students from other disciplines. We will proceed something like this. I will give you an outline of the lectures which we are going to give. First of all, we will have an introduction to the subject covering a few lectures to cover the laws - the basic laws - that govern the subject.

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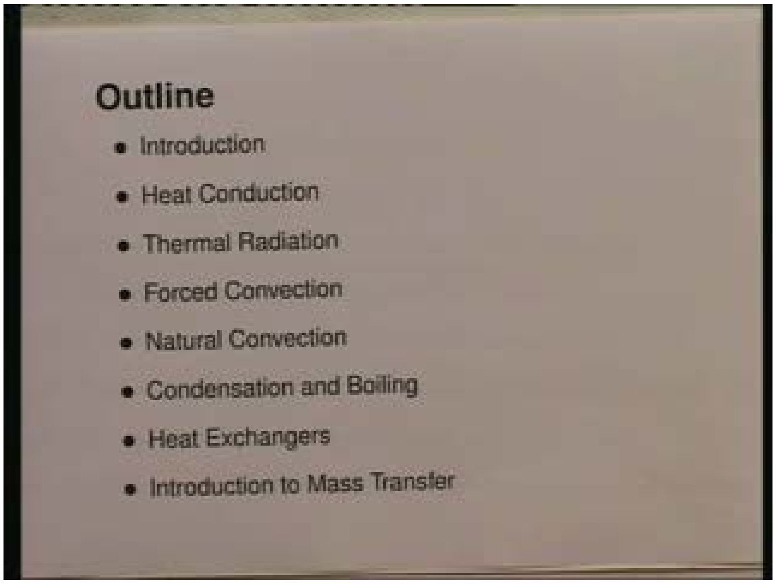

Outline

- Introduction
- Heat Conduction
- Thermal Radiation
- Forced Convection
- Natural Convection
- Condensation and Boiling
- Heat Exchangers
- Introduction to Mass Transfer

Then, we will move on to the topic of heat conduction in solids, then thermal radiation, then the mode of heat transfer by convection and in this we will talk first of forced convection, then natural convection, then we will go on to change of phase. Change of phase means: either during the heat transfer process a liquid gets converted into vapor because it receives heat - latent heat - which converts it from liquid to vapor or heat is taken out of it and therefore it condenses and from the vapor state it becomes liquid. Now, during this heat transfer process what is the rate at which heat transfer occurs forms the subject matter of the topic condensation and boiling. Then we move on to the topic of heat exchangers. Heat exchangers are devices which are widely used for a variety of purposes in many applications to transfer heat from one fluid to another - one fluid at a higher temperature, one fluid at a lower temperature. And we will talk about the thermal design and the working of such heat exchangers and then finally we will go to the topic of mass transfer and introduce the elements of mass transfer.

Now, you may ask me the question why is mass transfer taught alongside heat transfer when really we are covering heat transfer through most of these lectures. And the answer is something like this. The process of mass transfer has many similarities with the process of heat transfer. Heat transfer occurs when there is a temperature difference. Mass transfer occurs when there is a concentration difference. The equations describing these are very similar or analogous and therefore when we derive a relation - an equation - for a particular heat transfer situation it is very often true to say that that relation - with some modification - is also valid for a corresponding analogous mass transfer situation. So, the purpose of introducing you to mass transfer is to point out the similarity so that you can use heat transfer relations for studying certain types of mass transfer problems. As far as the books for this subject are concerned, there are a variety of books; there are many books written and are available to cover the syllabus. The two books which I am putting down in front of you - the first is which I have written - ‘A Textbook on Heat Transfer’ - the fourth edition of the book.

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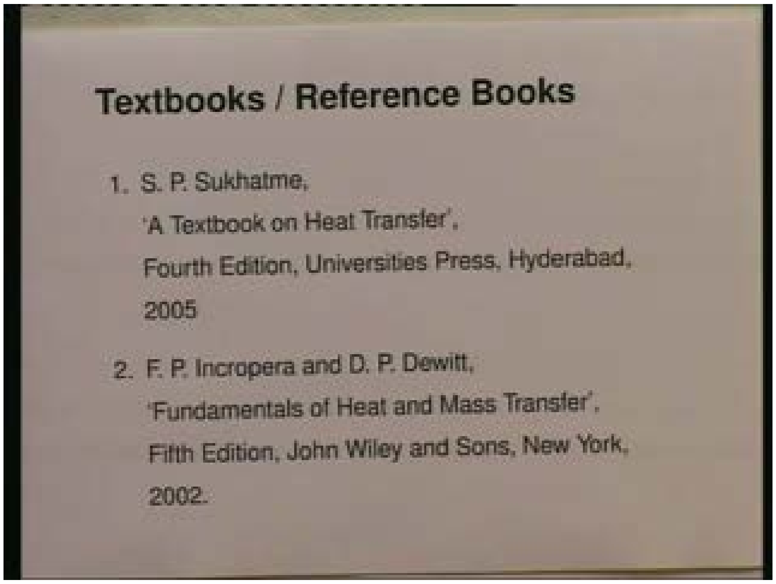

Textbooks / Reference Books

1. S. P. Sukhatme,
   ‘A Textbook on Heat Transfer’,
   Fourth Edition, Universities Press, Hyderabad,
   2005
2. F. P. Incropera and D. P. Dewitt,
   ‘Fundamentals of Heat and Mass Transfer’,
   Fifth Edition, John Wiley and Sons, New York,
   2002.

It is by Universities Press. This is a book which we will be following to a large extent but not all of it because it goes much beyond the syllabus that is normally prescribed in the undergraduate curriculum. The book which we will also be referring to is the book by Incropera and Dewitt on fundamentals of heat and mass transfer. It is widely used in India, widely used in the US, has been used for the last twenty years - an excellent book with a lot of practice oriented problems. So, these are two books which would be useful to you to refer to but there are many more. And the important thing is while you are going through these lectures, we will be also doing certain numerical problems for you. Now you will have to do some problems on your own also and that is why you will automatically need to refer to certain text books or reference books to do further problems on your own. Now let us begin with the introduction.

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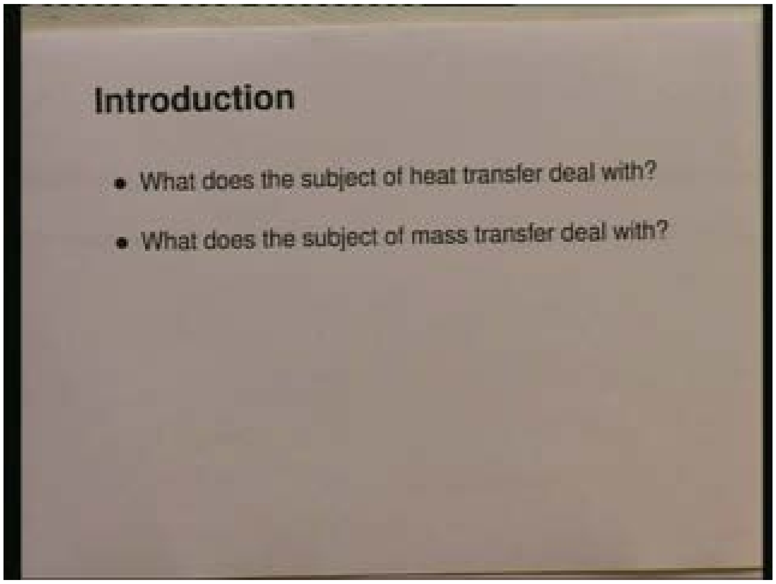

Introduction

- What does the subject of heat transfer deal with?
- What does the subject of mass transfer deal with?

The first thing we ask ourselves is - what does the subject of heat transfer deal with? What is it all about? Why is it important? And then we ask the same question for ourselves about mass transfer. What does the subject of mass transfer deal with? What is it all about? Why is it important? So, let us take up heat transfer first.

Now, first of all, when does heat transfer occur? Now, whenever there are temperature differences in a body, we know from experience that these temperature differences are reduced in magnitude in the course of time by heat flowing from the regions of high temperature to the regions of low temperature. The body under consideration may be in the solid state, it may be a liquid or it may be in the gaseous state. It doesn't matter which state it is. The point is when there are temperature differences, we know from experience, heat flows from the region of high temperature to the region of low temperature. The subject dealing with the rate at which this heat flow occurs, I emphasize again 'rate', the subject dealing with the rate at which the heat flow process occurs is called heat transfer. Now, it is important straight away to distinguish the subject of heat transfer from the subject of thermodynamics which all of you must have studied a little earlier. You must have studied the first law, the second law, certain power cycles and so on.

In thermodynamics, normally when we have a system in a certain state and that system undergoes certain heat and work interactions; because of those heat and work interactions, the system goes from one equilibrium state to another equilibrium state and during that shift from one equilibrium state to another equilibrium state, because of the heat and work interactions the system goes - attains a certain state which it is described by temperature, pressure, etcetera, etcetera. Now in heat transfer, in thermodynamics, we are not ever generally asking the question how much time goes in that process. We never concern ourselves with the rate at which that heat interaction takes place. On the other hand, in heat transfer we say because there is a temperature difference heat flow occurs; what is the rate at which that heat flow is occurring? And at a certain point if I want only a certain temperature to be attained, how much time would it take - that is the kind of questions we will ask. So, it is a subject which is dealing with the rate at which heat flow occurs. That is the distinction between what we study in thermodynamics and what we study in heat transfer.

Now, why is it important? Why is it important to study heat transfer? It is important because once we have these laws which govern the process of heat transfer, we will be in a position to design equipment - size equipment - in which the heat transfer process occurs. Now, let me given an example so that, you know, you will understand what I mean. All of you have sat in a car; all of you have seen a car radiator sitting in the front of the car. If you open the bonnet, right in front there is a very small rectangular box-like structure which is the car radiator. What does the car radiator do? The car radiator receives hot water which has come from the engine cylinder walls; that hot water typically is at about say 95 degrees centigrade and that hot water is cooled by air which flows over that radiator - cooled by 5 or 10 degrees - and then again circulated round the cylinder walls. So, the hot water picks up heat in the cylinder walls and gives up heat in the radiator and this way it maintains the cylinder walls at a particular temperature - safe temperature. In the radiator, it gives up heat to the air which flows over it; that air is pulled by a fan which is behind the radiator. So, the purpose of the radiator is to take away heat from the hot water and give it to air which is the environmental air, the surrounding air. That device - the car radiator - is a heat exchanger.

To be able to design that heat exchanger, you need to understand the process of heat transfer - the convective process of heat transfer occurring on the air side, occurring on the water side, the conduction process that is occurring in the fins and the tubes which make up the radiator and then only can you design that car radiator. So, the whole object of studying heat transfer is to be able to design size devices in which heat transfer takes place and the car radiator is a good example because as you well know, millions of car radiators are made every year for the millions of car which drive us all over the world. So, that’s just one example to illustrate why this subject is of importance. So, during this course we will be deriving such equations in convection, in radiation, in conduction so that we can design heat transfer equipment; by design, I mean find the appropriate size for a given end state that you are desiring in your fluid. We would be able to size heat exchange equipment and be able to do elementary design - that is the whole object of teaching this subject.

Now, let me move on to mass transfer. Just like I said in heat transfer, if there is a temperature difference, we know that heat flows from the region of high temperature to the region of low temperature. Similarly, if there is a concentration difference, we know that mass moves from the region of high concentration to a region of low concentration. Let me again take an example. Take this room. This room contains air - oxygen and nitrogen in a proportion of say four is to one typically. Nitrogen, oxygen in the ratio four is to one approximately, all right. Let us say in the corner there in that room at the top there, I hold a cylinder of a compressed gas of nitrogen and let some nitrogen out. Obviously, in that corner - top corner - there the concentration of nitrogen in the air is going to increase compared and going to be higher compared to the concentration elsewhere in this room. What will be the net result if I let out the certain amount of nitrogen? Immediately, that nitrogen will move and diffuse in this room so that eventually the concentration will again be uniform in this room. There is a high concentration of nitrogen there; there is a lower concentration here. Nitrogen will move in this direction, will diffuse in this direction so that that concentration difference is reduced. So, mass transfer occurs. In this case, the mass being transferred is nitrogen. The species being moving is nitrogen.

Mass transfer occurs when there is a concentration difference. Heat transfer occurs when there is a temperature difference. All right, now mass transfer is important also in a variety of processes. For example, to give you an example, let us say we have to dry a particular surface - a film on a particular surface. This is done all the time in many pieces of equipment. We have a film of liquid. We need to dry it. In order to dry that film, you pass air over that film and the air picks up. The film of water or liquid - whatever it is - evaporates into the air and mass transfer takes and it dries. What is the rate at which that mass transfer will occur? What should be the size of that surface so that I will be able to get the required film thickness totally removed by the time the air moves over a certain region over that surface? These are the kind of question we have to answer in order to size mass transfer equipment for a particular purpose. So, when we study mass transfer, we will be able to design equipment in which mass transfer occurs. Now, to further our understanding let us look at some problems of interest in heat transfer.

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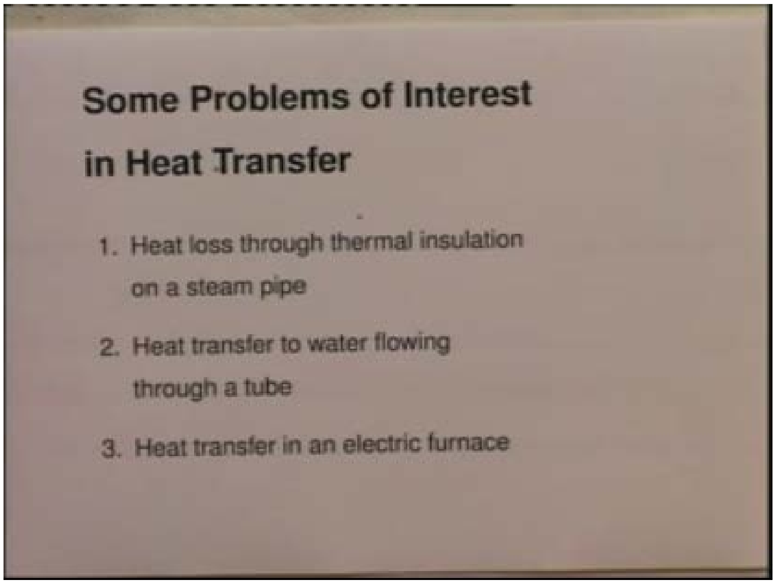

Some Problems of Interest in Heat Transfer

1. Heat loss through thermal insulation on a steam pipe
2. Heat transfer to water flowing through a tube
3. Heat transfer in an electric furnace

It is important that you try to appreciate the width of the subject, the breadth of the subject before we take up - really get into the equations which govern the laws, etcetera. I am going to look at three problems. First of all, I am going to look at the problem of heat loss through thermal insulation on a steam pipe. That is the first problem. Then, I am going to look at the problem of heat transfer to water flowing through a tube and then I am going to look at heat transfer in an electric furnace. These are three problems of interest in heat transfer and we look at them one by one. The first one now: heat loss through thermal insulation on a steam pipe.

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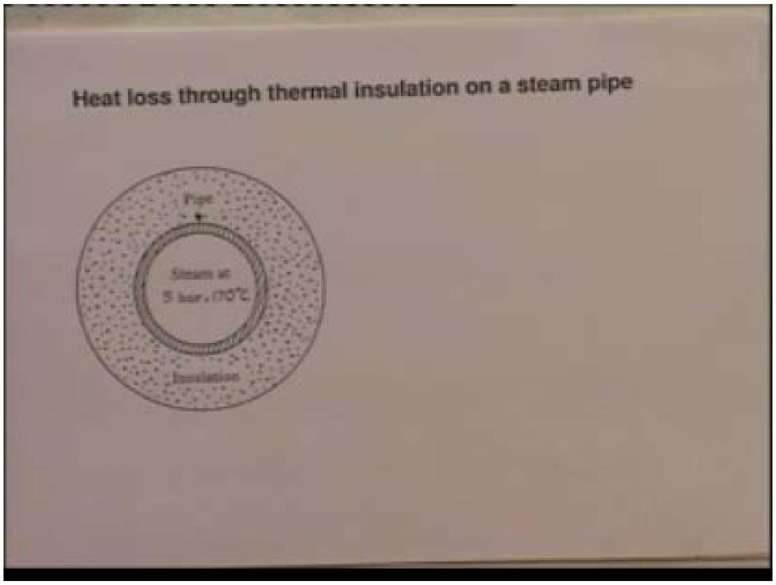

Heat loss through thermal insulation on a steam pipe

Steam is widely used in manufacturing process industries. All of you know that. Suppose, let us say I have a big plant with a lot of workshops - sheds all over - and steam is needed in each of those sheds. Typically, one may have a central facility where a steam generator is located. Steam is generated and there will be pipes - pipelines - which carry that steam to the various sheds. Even within the shed, there will be long pipelines along the walls which carry the steam all along the length or the breadth of that shed so that it can be delivered at a particular point where it is required.

Now, we have gone to a lot of trouble to generate that steam in a steam generator, you know, with a burnt oil or something like that, given heat to water and raise that steam at the pressure required. So, here in this example as you can see, we have talking of steam at 5 bar and 170 centigrade - super heated steam at this condition - and we are passing it through a pipe.

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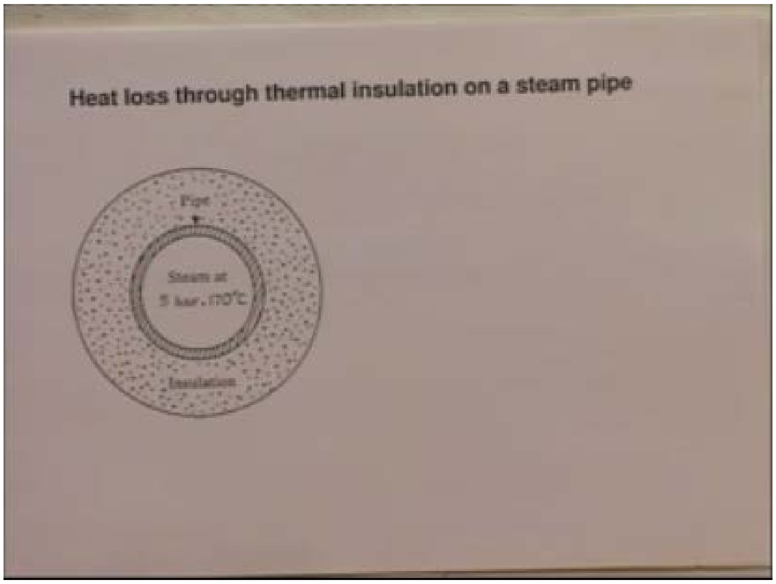

Heat loss through thermal insulation on a steam pipe

Having gone to all the trouble to generate that steam, obviously we don’t want that steam to condense or loose heat so we put insulation around it. Insulation may be in the form of some fibrous insulation like mineral wool, glass wool, etcetera which is put around and a certain thickness of insulation is put on the pipe. The question before the heat transfer engineer is what should be the thickness of insulation to put? Now let me just draw a sketch so that, you know, we will understand things better. Let us say, let me draw a graph, let us say in this graph on the x-axis, I have the thickness of insulation. On the x-axis I have the thickness of insulation which is put around the pipe. Let us say thickness of insulation in centimeters and on the y-axis I have the heat loss rate in watts per meter that is heat loss rate per unit length of the pipe.

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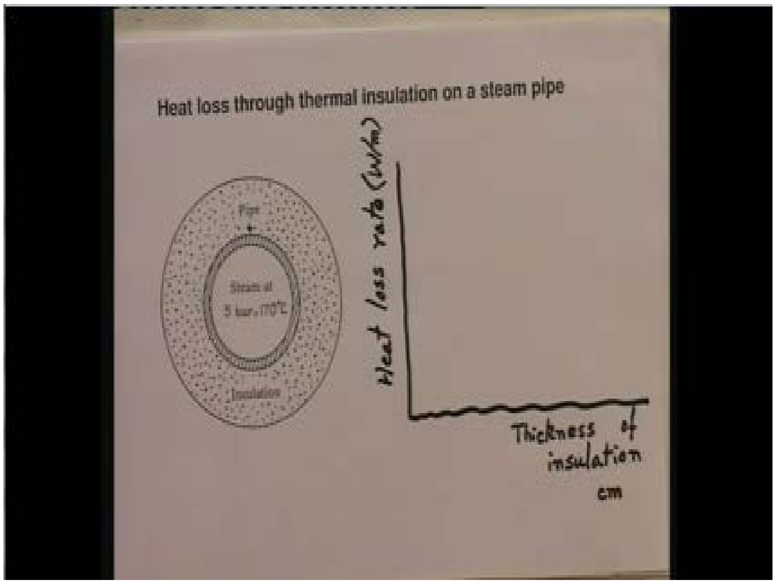

Heat loss through thermal insulation on a steam pipe

Let us say, when I have no thickness of insulation, there is no insulation on this pipe. The amount of heat being lost is as indicated by the cross here. That is the amount of heat being lost. Obviously if I put insulation on this pipe the heat loss rate is going to decrease. Typically, I will get a graph something like this - as the more and more insulation is put, the heat loss rate watts per meter will go on decreasing. Now, the problem before the heat transfer engineer who is to design this and decide what thickness to put is the following. He is told - restrict the heat loss rate to a particular value - let us say given by this as I mark in here. So, find the thickness of insulation to restrict the heat loss rate to the value specified here. In which case, having done this calculation and got this graph for a particular insulation that he is using, he will go horizontally, then go vertically and say this is the thickness of insulation needed.

Or the problem may be in reverse. He will be told - we are going to put 3 centimeters of insulation or 5 centimeters thickness of insulation. What will be the heat loss rate as a consequence? In which case, given a certain thickness, he will go up like this. Having got this graph to this graph, then draw horizontal line like this and say this is the heat loss rate and therefore, from here to here that is from this point which is the heat loss rate without insulation to the heat loss rate because of the insulation, this is the amount of reduction in the heat loss rate. So, because of his knowledge of heat transfer and heat conduction occurring in the insulation, the heat transfer engineer will be able to either decide on the thickness of insulation to put or find the heat loss rate for a given thickness of insulation. This is a typical problem for calculation which we encounter. Now, let us go to the next problem that I mentioned - that is heat transfer to water flowing through a tube.

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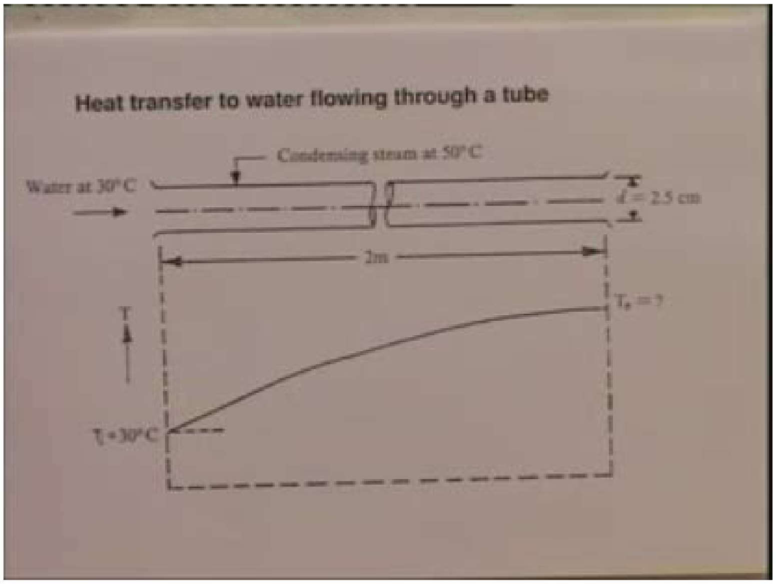

Heat transfer to water flowing through a tube

Now, here is a tube. The diameter I have given is 2.5 centimeters for this tube. Water is entering it at 30 degrees centigrade. On the outside of this tube, we have steam - low pressure steam - at 50 degree centigrade condensing on the outside of this tube. So, obviously heat is going to flow from the outside to the inside and this water which is flowing through the tube is going to get heated up and going to go on increasing in temperature as it moves around the length of the tube.

Now, where does this situation occur? This is the situation which will typically occur in a steam condenser. You have power plants. In a power plant, from the turbine exit you have low pressure steam. You need to condense that steam with the help of cooling water and then raise the pressure of that condensed water, then put it back into this steam generator. That is the Rankin power cycle. So, this tube which I am showing you would actually not be by itself, but would be one tube in a large bundle of tubes on which steam would be condensing. I am showing one as an example. So let us say coming back to the single tube - what is the problem before the heat transfer engineer? The problem is the following - steam condensing on the outside at 50, cooling water entering the inside of the tube at 30. The problem before the engineer is if the length of the tube is 2 meters - 2 I have taken as an example - what would be the exit temperature T_o of the water leaving this tube or vice versa?

Suppose I specify that I want an exit temperature of say 35 degrees centigrade. Then what should be the length L of the tube in order to have an exit temperature of 35 or 40, whatever it is. Obviously, the highest temperature that this steam, this water, can attain- because steam is condensing at 50 - is fifty and that would be attained with an infinitely long tube. So, the heat transfer engineer who is designing for the situation will typically have to tell what would be the length of the tube for a given exit temperature or what is the reverse problem. That means, given a length, what would be the exit temperature?

Now, let us go on to the third problem which I mentioned. The third problem is heat transfer in an electric furnace.

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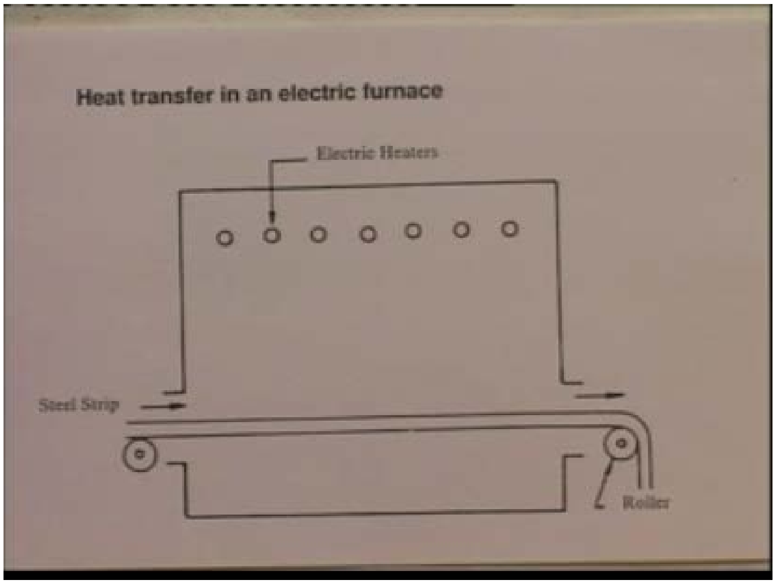

Heat transfer in an electric furnace

Here we have steel strip which has been rolled in a steel mill undergoing a heat treatment process. Now, typically a steel strip would be a few millimeters in thickness. It would be may be a millimeter in thickness and may be a few centimeters wide. It has been rolled by some rolling process and it has been formed into a bundle after the rolling process.

Now during the rolling process, because of the deformation that has taken place, the steel loses certain properties - certain desirable prosperities like ductility, malleability, etcetera, etcetera. We want it to regain these properties and typically for that, one does some kind of annealing heat treatment process. The heat treatment process here consists in heating that steel strip up to a temperature which is specified for steel heating it just above that specified temperature and then allowing the steel strip to cool down slowly. So, the job of this furnace is to heat the steel strip up to a temperature required for that heat treatment process to occur, some temperature usually around 600-700 centigrade of that order.

So, the problem before the heat transfer engineer would be the following now. He is told here is an electric furnace. The temperature in this furnace is say 1200 degrees centigrade or 1000 degrees centigrade. It is required that the temperature of the steel strip at the exit be 720 centigrade or some temperature like that. The steel strip is entering at room temperature - 30 degree centigrade - and is flowing, moving with a certain velocity which is specified. What should be the length of this furnace in order that you get this desired exit temperature or the reverse problem. Given a certain length, what should be the velocity with which that steel strip should move so that the required exit temperature is attained. That exit temperature must be just above the annealing temperature for that particular steel so that when it goes out it is just above the temperature. Then, it cools downs slowly and during that cooling process which is at a slow rate, after that cooling process it acquires the desirable properties - mechanical properties - that we are looking for. So, this is a typical heat transfer problem an engineer would face

Now, I could go on, of course, giving you examples but I think you get the idea. But let me just show you one more example of a problem which is of current interest. We are in a situation now-a-days in which electronic circuits or electronics plays a key part in our lives and miniaturization in electronics is the key word today, VLSI for instance or VVLSI, whatever it is. Now, we go on making transistors, thousands and hundreds of transistors over very small areas compared to the old days when hundred transistors might occupy a whole table top, for instance like this. Now, transistors generate heat, remember that, and it is a requirement that if the transistor is to operate well, its temperature inside must not exceed some safe value. In fact, there are two temperatures - one temperature is a temperature which if exceeded will completely stop the transistor from functioning. That should obviously never be attained. But also, it is known that if the temperature works at high temperature, its life - its period - for which it will work consistently reduces.

We would like say design specification, may be you want the transistor to work for a few thousand hours. In which case, it will be specified that the surface temperature should never exceed a particular value - typically 50 centigrade, 55 centigrade, typical values that we have. Now let me just draw for you a situation.

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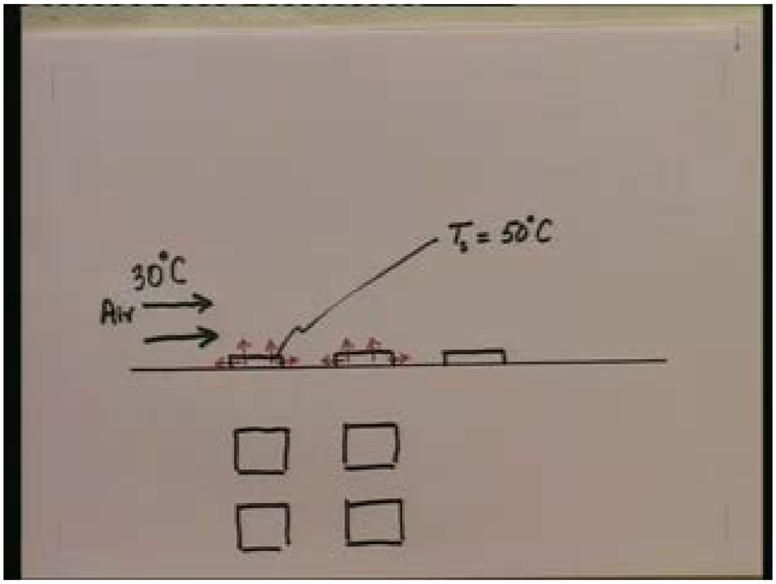

Let us say, this is what you call a board. This is a board on which we have a number of electronic chips. Let me just draw a few as an example. This is a board and let us say on this board I have a number of electronic chips like this -1 2, I am just drawing 3. If I had a plan view actually, there would be, there may be an array like this. 1 would be like this in the plan view, 2 like this and so on. So, it could be a rectangular array of chips. Typically, each of these may be, let us say a centimeter by centimeter by may be a millimeter high and within it they have all the electronics that we are talking about. Now a requirement would be, the heat that is being generated from these chips would be flowing out like this. This is how the heat is flowing - shown by the red arrows.

The requirement before the heat transfer engineer would be that the surface temperature- the surface temperature here T_s or T_{wall} - whatever we want to call it should be or should not exceed a value like say 50 degrees centigrade or 60 degrees centigrade. That is a typical specification. So the heat must flow out, which is flowing out of this will obviously raise the temperature of the surface but that temperature must never go above a temperature which is specified, typically 50-60 or something like that. So what we do? One is to hold down the temperature is, we may have say, for instance, air blown over these electronic chips. We may blow air over these chips. The air may be say entering at

30 degree centigrade. We ensure therefore, this surface temperature never exceeds this specified value.

Now the problem before the heat transfer engineer is at what velocity should this air be blown so that this surface temperature is not exceeded? That is a typical convective heat transfer problem for which you need equations, data, the flow around the electronic chips and so on to be analyzed. So here is another example - the cooling of electronic chips as an example which would be of interest to us as we go along. Now that we have a feeling of the types of problems that we are going to handle, let us discuss the modes of heat transfer.

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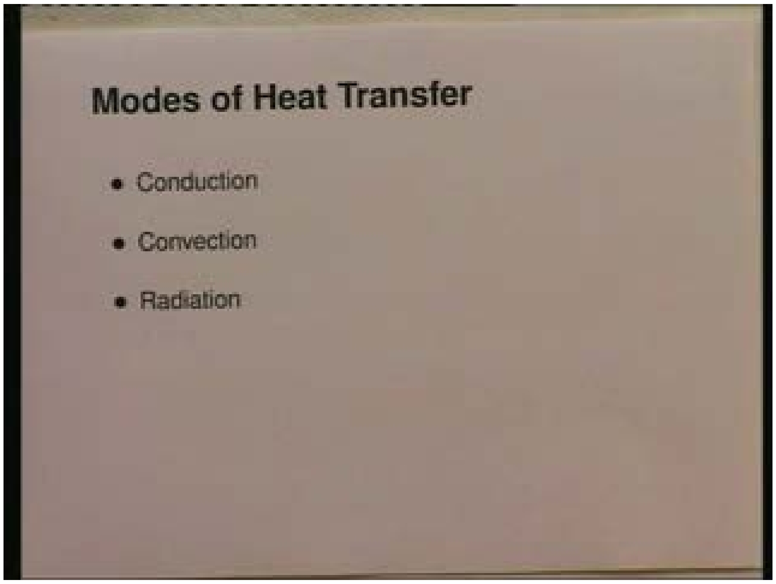

Modes of Heat Transfer

- Conduction
- Convection
- Radiation

There are three modes and all of you must have heard of these. You have done twelfth, you have done heat, studied heat. The three modes are conduction, convection and radiation. Let us take them up one by one. Conduction first. First of all the definition, then let me explain what we mean by, what the definition.

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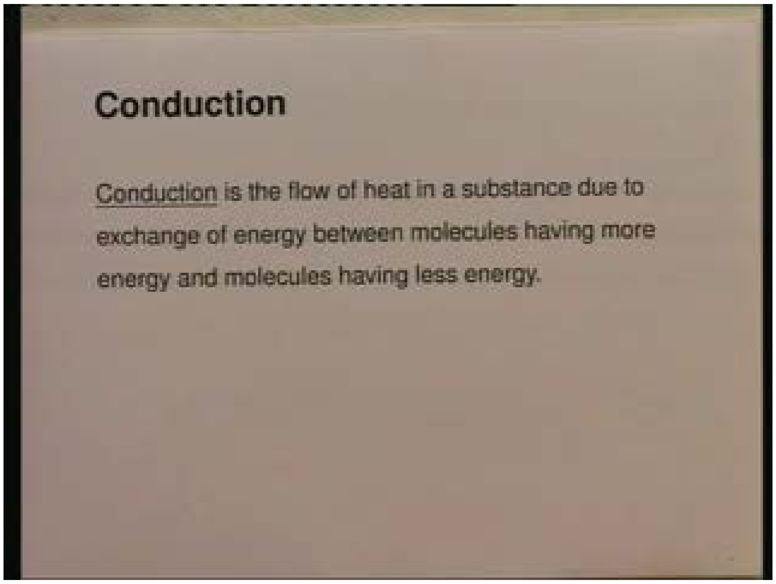

Conduction

Conduction is the flow of heat in a substance due to exchange of energy between molecules having more energy and molecules having less energy.

Conduction is the flow of heat in a substance due to exchange of energy between molecules having more energy and molecules having less energy. It is the flow of heat in a substance - the substance may be a solid, it may be a liquid or it may be a gas, doesn’t matter what is the state - due to the exchange of energy between molecules which have more energy and molecules which have less energy. Molecules having more energy are at a higher temperature, molecules having less energy are at a lower temperature. All right? That is conduction, the flow of heat because of this situation. Now, let me just draw a sketch or to two to illustrate ideas, what we mean by conduction. First of all let us consider a solid, a solid structure.

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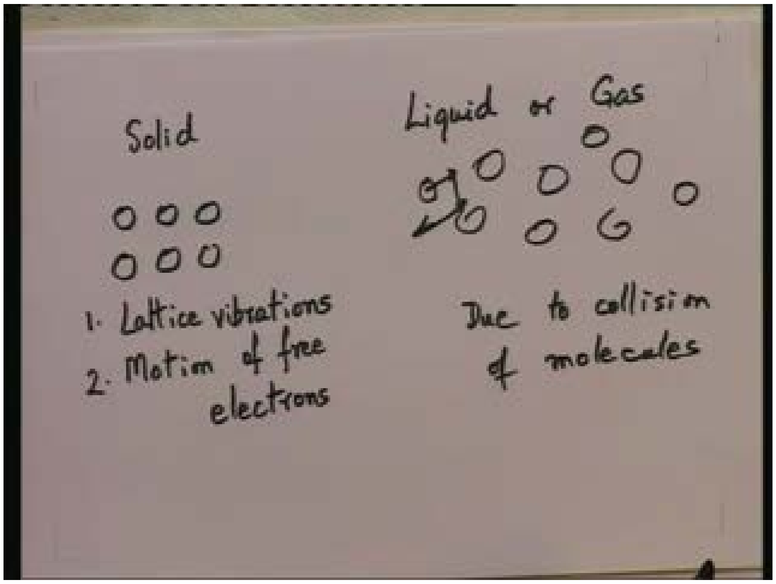

A solid typically has molecules or atoms. Let us say the molecules like this. I am just drawing a set of molecules, they may not be in a square array, whatever be the pattern.
A set of molecules making up this solid and typically these solids which form a lattice will be vibrating in that solid. More vibration means a higher temperature. So, when we say that – let us say the molecules here, these molecules are at higher temperature, these molecules are at a lower temperature which are at some distance away. Then the vibrations here will be higher than the vibrations here. There will be more energy associated with these molecules than with these and because of these vibrations they will tend to interact with the next set and the next set and the next set and transfer that energy from one molecule to the next to the next. So, the transfer of energy by conduction is because of the lattice vibrations and these vibrations are more because of the higher temperature region than in the lower temperature region.

So, one - in a solid - one mode of mechanism by which the transfer of energy takes place is lattice vibrations, lattice vibrations. Now, solids if they are in the metallic form also have free electrons. That is the structure of metallic solids. Free electrons are the basis on which electricity flows in solid. When electricity flows, it is these electrons that are flowing. In the same way, those electrons also carry energy which is heat transfer by conduction. So, the free electrons in a solid, when there is a temperature difference, also form the basis for transfer of heat by conduction. So, a second mode by which conduction takes place in a solid - if it is a metal mind you, non-metals there are no free electrons - is the motion of free electrons. These are the two modes, the second for metallic solids, the first for solids in general - non metallic solids.

Now unlike a solid, in a liquid or a gas that is a fluid, in a liquid or a gas, molecules have freedom of movement. In a solid, they are restricted to a particular point where they will be vibrating or something like that. In a liquid that is not so or in a gas. Molecules have some freedom. Let us say there is a set of molecules making up a liquid or a gas.
Well, those molecules have some freedom of moving around in some fashion or the other. You follow, and they move over short distances in the solid or liquid in a random fashion. Now in an overall sense, the liquid or gas may be stationary in a macroscopic sense - MA - macroscopic sense. The solid or liquid may be stationary but in a stationary liquid or gas, there is always this random motion taking place over short distances. In a gas, those distances are a little longer, in a liquid, those distances are a little smaller. Now the transfer of energy which occurs due to collision between molecules when they move in this random fashion over short distances within a liquid or a gas is also what we call as conduction in a liquid or a gas. So, in a liquid or a gas the transfer of energy occurs due to collision of molecules. Molecules at a higher temperature giving their energy to molecules at a lower temperature but this is, remember, the random motion that is taking place. In an overall sense the liquid or the gas is stationary. So this is how the conduction mode occurs in various substances – solids, liquids and gases.

Now, in convection which is the next mode - we just now mentioned that in a liquid or gas there is this random motion of the molecules taking place - now in addition to this random motion, fluids can be made to move on a macroscopic scale in a fluid or a gas. They can be made to move by forcing them to move. Say I have air in a pipe, I blow that air through the pipe so I can make the air move because by forcing it to move or I can make the air move because of creating temperature differences. Temperature difference causes a density difference which causes a movement of the air. You understand?

So, fluids can be made to move in a microscopic sense, in a fluid which may be in the liquid or in the gaseous state. The transfer of energy - let me read this out.

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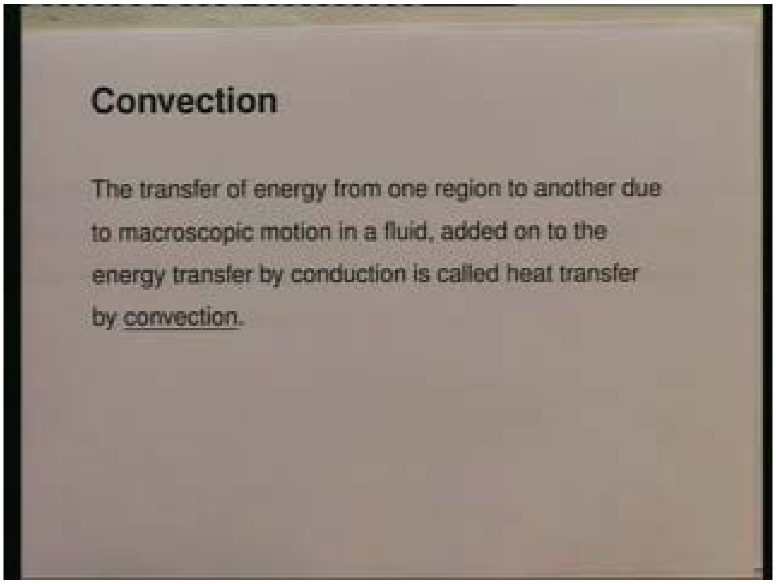

Convection

The transfer of energy from one region to another due to macroscopic motion in a fluid, added on to the energy transfer by conduction is called heat transfer by convection.

The transfer of energy from one region to another due to macroscopic motion in a fluid, added on to the energy transfer by conduction - which I have described earlier - is called heat transfer by convection. That is the meaning of convection. We already have conduction taking place if we have temperature differences. In addition if I have a certain movement in that liquid or gas - the movement may be caused by a temperature difference or it may be forced, some macroscopic motion - then energy being moved from one point to another because of the movement of molecules. So, the transfer of energy due to this microscopic motion added on to the energy transfer by conduction which is occurring because of random motion, the two together are what we call - the sum of the two together - is what we call as heat transfer by convection. And as I mentioned a moment ago and let me repeat that, if I force the flow to move in a particular manner then it is called forced convection - that is the fluid motion is caused by an external agency.

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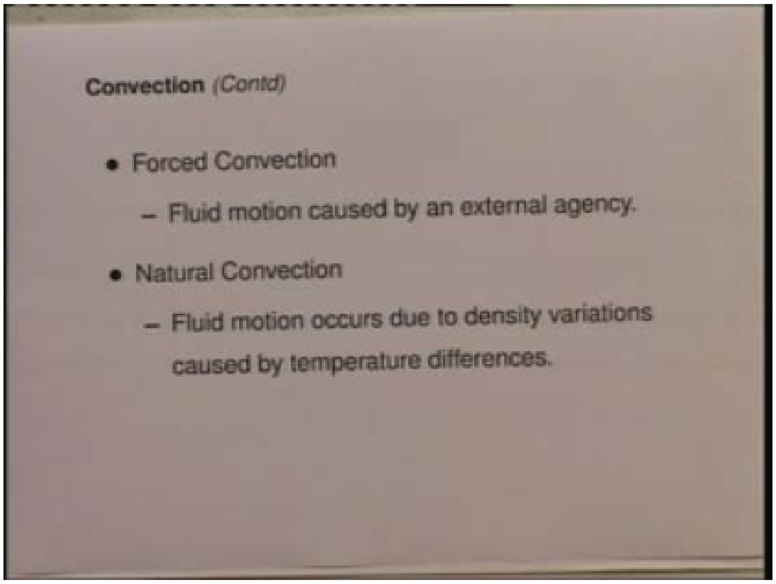

Convection *(Contd)*

- Forced Convection
  - Fluid motion caused by an external agency.
- Natural Convection
  - Fluid motion occurs due to density variations caused by temperature differences.

And on the other hand if the fluid motion occurs due to density variations caused by temperature differences, then that is called as natural convection. So, convection is of two types: forced convection, when I cause the fluid motion to be caused the fluid motion is caused by an external agency and natural convection, when the fluid motion occurs due to density variations which are caused by temperature differences. Now the third mode is radiation which is quite different and let me read out the definition.

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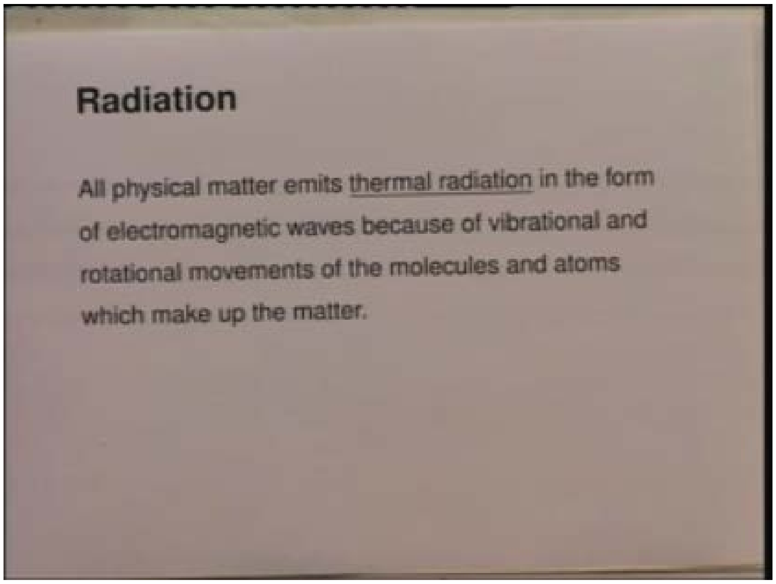

Radiation

All physical matter emits thermal radiation in the form of electromagnetic waves because of vibrational and rotational movements of the molecules and atoms which make up the matter.

All physical matter emits thermal radiation in the form of electromagnetic waves because of vibrational and rotational movements of the molecules and atoms which make up the matter. This is known from physics. The matter may be again in any state - it could be a solid, it could be liquid, it could be a gas, it could be a plasma - it doesn't matter what it is. If it is at a certain temperature level, whatever be the temperature level - it is known it emits radiation in the form of electromagnetic waves and this is emitted because of the vibrational and the rotational movements of the molecules and atoms which make up that matter in solid, liquid or gaseous state. This is known. What are the characteristics of the radiation?

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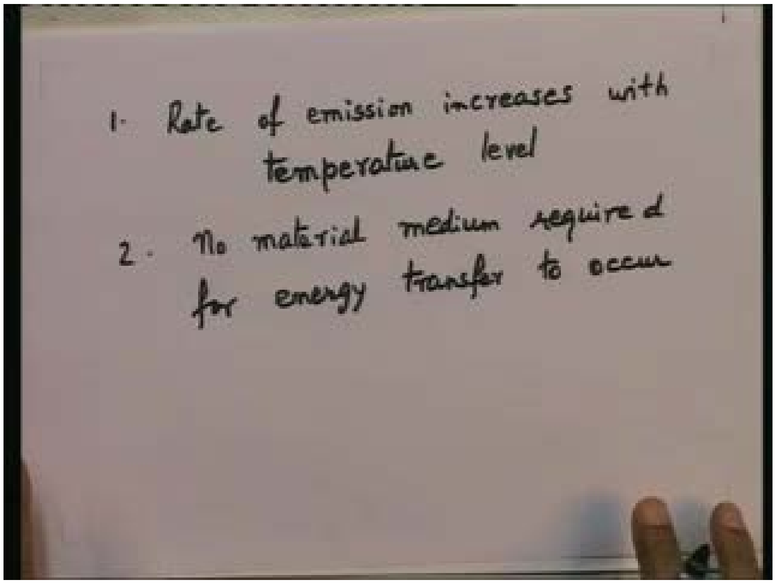

1. Rate of emission increases with temperature level
2. No material medium required for energy transfer to occur

The characteristics are, the characteristics of this radiation are: No.1 - the rate of emission, the characteristics of this radiation are, let me read that, write that out. Number 1: the radiation increases with temperature level. Let me write that out. Number one characteristic, rate of emission rate of emission increases with temperature level - the higher the temperature, the more the radiation emission by thermal radiation. Rate of emission increases with temperature level. That is one characteristic to note. A second characteristic to note is - we do not require any material medium for the energy transfer to occur. It is in the form of electromagnetic waves. Electromagnetic waves can go through a vacuum. They don’t need any material medium like air or a gas or a liquid for transfer of energy. So, we do not require - no material medium required for energy transfer to occur. These are two characteristics to note.

Radiation - thermal radiation - in the form of electromagnetic waves does not require any material medium for its transfer. So, now we have discussed the three modes of heat transfer – conduction, convection and radiation. And now if you go back to the problems that we described a movement earlier, you will recognize immediately that the first problem - thermal insulation around a pipe - is primarily a problem of heat conduction primarily, the second problem that we talked about - flow of water in a tube - primarily a problem of heat transfer by convection and that too forced convection and the third problem of annealing steel strip primarily a problem of radiative heat transfer – radiation. So, these were three problems and you will notice these problems were of each of these three modes, the first of conduction - primarily of conduction, second - forced convention and the third - thermal radiation.

But I don’t want you to get the impression that this is so always. In general, problems in heat transfer are not amenable to this kind of separation. Very often - more often than not - the problem that occurs or a situation that one faces is one in which all the modes of heat transfer occur together and one must be able to tackle the problem by understanding these modes and analyzing them together. So I don’t want you to give the impression that the situations always occur in which one can separate and say this is the mode or that is the mode. There are very often situations in which the modes will occur - all will occur simultaneously and one needs to take account of.

Now, I am going to give an example of a situation in which all these modes are occurring. We are going to take up one example like that. All of you must have heard the word ‘energy crises’. Now energy is on the - is a dominant part, read the news paper. Every day, there is talk of the price of oil that price of oil is increasing. We have to import oil in India - lots of it. We have to pay for it. So any increase in the price is something which we feel very much in India. So, energy is dominant in our thinking and is going to be dominant in our thinking because much of our energy requirement - much of our commercial energy requirement - in India and in many countries is met by fossil fuels. Fossil fuels means coal, oil and natural gas and all these are depleting because they are not renewable, they are decreasing. So, we need to, therefore, look for other ways of getting energy. Solar energy is one such option. The solar energy option, particularly the direct form is one such option. Now let us look one way of using solar energy which, to illustrate different modes of heat transfer. I am going to show you and you will see it here.

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I am showing you here on the screen an array of what are called as solar flat plate collectors. You are seeing four collectors here, here each of them typically is about 2 meters by 1 meter and they are used for heating water. An array like this would heat water typically to a temperature like 60 70 80 degrees centigrade with ease and we need hot water for so many applications at home and hotels, hospitals, canteens, etcetera, etcetera. So, this is one application of solar energy which is a very viable application which pays for itself fairly soon. It is being widely used in India. Now, let us look at one such solar collector. There are four in the picture.

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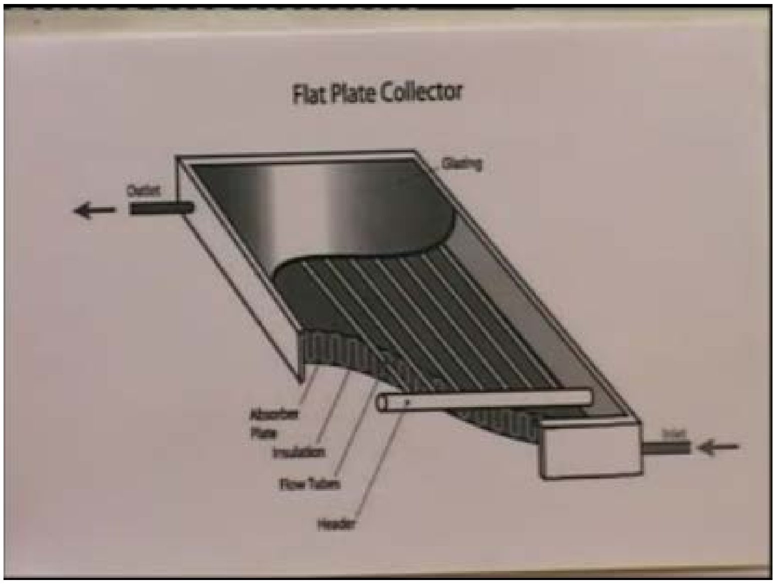

Flat Plate Collector

I am going to now look at one - this is one collector - so that we see the inside of it, what it looks like. A solar collector - this is 2 meters in length, 1 meter in width as I mentioned. Typically on top there is a glass cover which you had seen in the picture and below that there is an absorber plate. This is the absorber plate. It is a thin copper sheet, a millimeter or so in thickness. On that absorber plate or on the backside of it, a number of flow tubes are soldered and the water which is to be heated flows in these tubes. So it enters here at the point which is called the inlet - flows in this header which I have shown here, which I am pointing out here - then gets distributed in these flow tubes and then goes out through the outlet header. That is the position. So the water, the solar energy falls on the flat plate collector and the water as it flows through, gets heated and typically as I said you can get hot water at temperatures like 60 70 80 degrees centigrade in this collector. Now, let us look at a cross section of this collector. What would it look like? A cross section of this collector would look like this.

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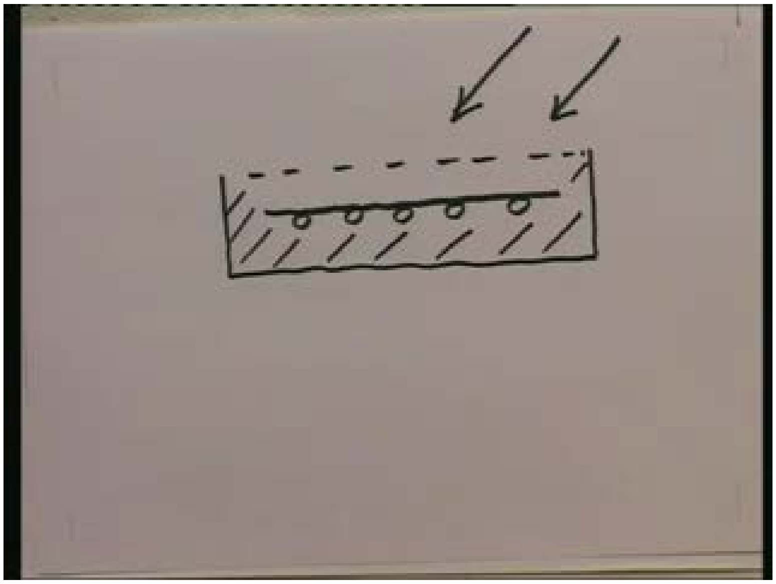

This is the casing of the collector. This is the absorber tube, the absorber plate, these are absorber tubes below it and this is the glazing, the glass cover on top. This is how the cross section would look. Solar energy falls on this, is falling on this solar flat plate collector and heating up the water which is flowing through these tubes. Now, today we will stop here but next time I will look at the different modes of heat transfer that are occurring in this device. So, we will take off from this point in the next lecture.

We have described a solar flat plate collector. You know what are the components that make it up - an absorber plate, tubes, a glass cover on top and on the back side here. There is insulation to prevent heat loss to the sides and the bottom. These are the components that make up the plate collector. Next time, in the next lecture, we will look at the different modes of heat transfer that occur within this device and write down a simple energy balance equation for it. So today, we are going to stop here but let me recapitulate for you what we have done today so that we get a feel again for what we have achieved. Today for instance, we have done the following.

First of all, I have outlined the subject that we are going to cover in thirty lectures - given an outline of it, what are the different topics that we are going to cover. Secondly, I have talked about what the subject is all about - the subject of heat transfer and the subject of mass transfer. Then I described for you a number of problems of interest in heat transfer. Then, I took up the different modes of heat transfer – conduction, convection and radiation and towards the end I started talking about the example of a solar flat plate collector to illustrate how different modes of heat transfer exist within a particular device. We haven’t completed that; we will be taking it up, continuing that next time. So today, we will stop at this stage.