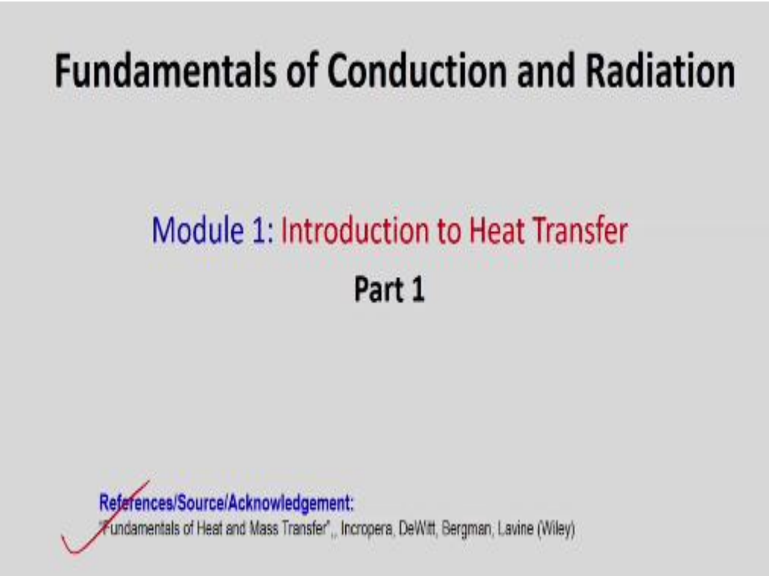
Fundamentals of Conduction and Radiation
Prof. Amaresh Dalal and Dipankar N. Basu
Department of Mechanical Engineering
Indian Institute of Technology – Guwahati

Lecture - 1
Module 1: Introduction to Heat Transfer
Part 1

Hello everyone. Welcome to this new MOOCs course on the topic of fundaments of conduction and radiation. As mentioned during our introduction video and from the course swipe page, this course will be shared by 2 faculty members. I am Dipankar Basu associated with the department of mechanical engineering, IIT Guwahati, and my colleague professor Amaresh Dalal will also be with me for this particular course. We shall be sharing the lectures among us, which I shall be shortly explaining through the course structure.

(Refer Slide Time: 00:26)



Now, I am sure that you have gone through the course structure, the details of the modules that are given on the course swipe page and also the names of the books. But still I would like to mention here that, we are primarily going to follow this particular text book. Several of the illustrations that we are going to use in the slides have also been taken from the soft copy of the same book.

Now, you must be knowing that heat transfer is one of the most fundamental and at the same time most applied subjects that you can identify in your entire course of mechanical engineering. This course, I should clarify, is primarily aimed for the students of mechanical engineering. But students who are belonging to similar discipline something like, power engineering, energy engineering or production and manufacturing engineering or any such allied branches; they can also participate in this course and will definitely learn something about the modes of conduction and radiation.

Now, as I have just shortly mentioned that heat transfer is one of the most fundament subjects but there are reservations about this. Many scientists who are more of conventional type, they believe that thermodynamics and fluid mechanics are the most fundamental subjects and heat transfer is more an application of that. Definitely it is very much true. Because both thermodynamics and fluid mechanics are the fundamental subjects and heat transfer starts only with the background of thermodynamics.

But still, there are so many applications of heat transfer, almost in every sphere of our life that, you can identify heat transfer as one of the fundamental subjects. In every mode, starting from the mode of energy interaction that human body can have with the surrounding to our day-to-day activities like cooking, to very large scale industrial applications like nuclear power generations; everywhere you can identify some applications of heat transfer. To analyze such kind of systems, we need the understanding of different modes of heat transfer; and that creates the background for this course, where we are expecting the audience to have a basic understanding of thermodynamics. Thermodynamics, as you know, is always taught either in the first year or sometimes in the second year may be in the third semester of your engineering disciplines. Not only the students of mechanical engineering, but rather students of several other disciplines also learn thermodynamics.

Now, once you have a big background about the thermodynamics, then you can easily participate in this course; because we shall be starting from the very basics of the heat transfer.

(Refer Slide Time: 03:42)

Course outline

Week	Module	Topics
1	Introduction to Heat Transfer	Review of thermodynamics, Physical modes of heat transfer, Units & dimensions, Practical applications of heat transfer concept.
2	Introduction to Conduction	Fourier's law of heat conduction, Thermal conductivity, Generalized heat diffusion equation in Cartesian, Cylindrical & Spherical coordinate systems, Initial & boundary conditions.
3	1-D Steady-state Heat Conduction	Heat transfer scenario in plane wall, cylinder & sphere, Electrical analogy, Contact resistance, Overall heat transfer coefficient.
4	Special 1-D Heat Conduction Situations	Conduction with thermal energy generation in plane wall & cylinder, Variable thermal conductivity.
5	Heat Transfer from Extended Surfaces	A general conduction analysis, Fins of uniform and non-uniform cross-sectional area, Performance parameters.
6	2-D Steady-state Heat Conduction	Analytical & graphical approaches.
7	Transient Heat Conduction	Lumped capacitance approach, Cartesian & radial systems with convection, Semi-infinite solid.
8	Numerical Methods in Conduction	Use of finite-difference method for 1-D & 2-D steady-state problems, Use of finite-difference method for 1-D transient problems.
9	Fundamentals of Radiation Heat Transfer	Basic concepts & terminologies, Radiation fluxes & intensities, Black radiation.
10	Radiative Properties of Real Surfaces	Absorption, reflection & transmission, Kirchoff's law, Gray surface.
11	Radiation Exchange between Surfaces	View factor, Blackbody radiation exchange, Radiation networks, Radiation shield.
12	Radiation with Participating Media	Gas radiation, Radiative Transfer Equation

These are the course outline which has already been displayed there. It is a 12 week course, 30 lectures or 30 hours. Accordingly, we have divided the entire syllabi into 12 modules. Out of them, module number 1 to 8 belongs to conduction and the last 4 modules belong to radiation. So up to this, we have conduction heat transfer. This is how we are going to go for in the first week. That is, in this week, we are going to have just 2 lectures. 2 may be a bit brief lectures, where we are just going for the introduction, reviewing the basics of thermodynamics, then mentioning about the physical modes of heat transfer, possible units and dimensions and some practical applications of heat transfer concepts in terms of practical applications and also some numerical examples. Then in the next week, I shall be moving into the conduction heat transfer starting with the Fourier's law of heat conduction, mentioning about the thermal conductivity as a property. Then we shall be developing the generalized heat diffusion equation in all 3 possible coordinate systems, like Cartesian, Cylindrical and Spherical coordinate systems. And also, we shall be talking about the boundary conditions required to solve such systems of equations. Then in week number 3, we shall be using the one dimensional versions of this equation under steady state. So, in this 1-D steady state heat conduction, we shall be solving different heat transfer scenarios like heat transfer through plane wall, cylinders, or spheres. We shall be seeing the electrical analogy of heat transfer, the topic or concept of contact resistance, and also the overall heat transfer coefficient will be introduced. Then some special scenarios of 1-D heat conduction situation will be discussed in week number 4, something where the thermal energy generation is involved in both plane wall and cylinder or where we are talking about variable thermal conductivity system, or a few more; let us see what we can go through.

Then in week number 5, we shall be moving to another application of 1-D steady state heat conduction, in terms of the extended surface or fins, where a general conduction analysis will be given. Then, different kinds of fins will be introduced. Fins of both uniform and non-uniform cross section areas will be analyzed. Then in week number 6, we shall be moving to the 2-dimensional steady state heat conduction in terms of both analytical and graphical approaches.

In week number 7, we shall be talking about the transient heat conduction, primarily in one dimension, where "lumped capacitance approach" will be followed. Then, Cartesian and radial systems with convection and the very important concept of the semi-infinite solid will be introduced. And in week number 8, we shall be reviewing some numerical methods which are associated with the conduction heat transfer simulations; primarily the finite-difference method for both 1-D and 2-D steady state problems will be discussed, in terms of numerical methods or numerical problems. Then, use of finite-difference method for 1-D transient problems will also be discussed. That will cap up our discussion on conduction. Then in week number 9, we shall be moving into radiation, where first the fundamental concepts of radiation will be introduced in terms of different terminologies. Different kinds of radiation fluxes and intensities, the concept of black body or black radiation and also the gray surfaces will be introduced.

Then in week 10, we shall be talking about the radioactive properties of real surfaces, like absorptivity, reflectivity and transmissivity. The Kirchhoff's law will also be coming into picture. Gray surface, as I have just mentioned, we can cover in week number 9 or we can also cover this in week number 10, because that is a property of real surfaces. Then in week number 11, we shall be talking about the radiative exchanges between surfaces.

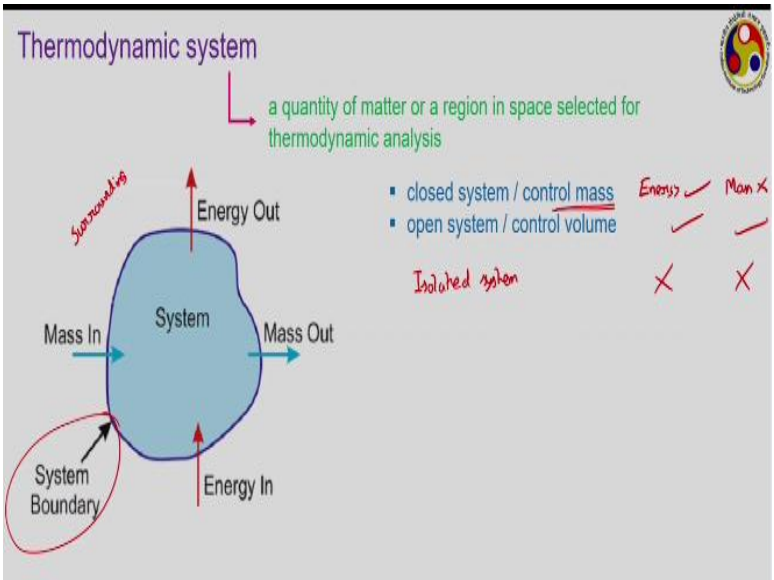
As we already have discussed about the properties that individual view surface can have, then it is much easier to discuss about the exchange that multiple surfaces can have. The concept of view factor, blackbody radiation exchange, and the concept of radiation network will be introduced and finally, radiation with participating media in terms of gas radiation and radiative transport equation will be discussed to round off the entire course.

Here, as there are 12 weeks, both of your instructors will be participating in 6 of the weeks. Like, I shall be your instructor for week number 1 to 4, then professor Dalal will be talking about week number 5 to 8; then I shall be back with the fundamentals of radiation in week number 9 and 10 and professor Dalal will be discussing about week number 11 and 12 to round off the course.

(Refer Slide Time: 08:07)

These are the text and reference books that we are going to follow in this course. As I have mentioned, the first one is the most important book followed worldwide. I have mentioned here the seventh edition, but probably there is a higher edition already available in the market. You can to go some older edition also, just see whatever you can have. This is one book which probably you should have in your personal collection as well. Inexpensive Indian versions are also available, so probably, you can have a copy of this book for your own collection. The other 3 are also very good books on fundamentals of heat transfer, so you can follow any one of them, if you are not getting the first one. So, as I have mentioned, heat transfer is a subject which starts with the idea of thermodynamics and that's why to start our discussion of heat transfer, I shall be starting with the review of some of the basic thermodynamic concepts.

(Refer Slide Time: 09:09)



Now, the first term you must have been introduced in thermodynamics is the thermodynamic system. Now, what do you mean by thermodynamic system? System refers to a quantity of matter or a region in space, selected for thermodynamic analysis. That is, this is basically the object where we want to perform the analysis. Now your object can be a quantity of matter or mass or it can be just space; just like an example that is given here, where the one identified by the blue colour is the system because that is our focus.

The dark purple line which is surrounding the system is known as the boundary, and everything outside the system is referred as the surrounding. Now, this boundary of the system can be a real one or can be an imaginary one. Your boundary can be a fixed one, thereby fixing the volume of the system, or it can be movable one so that the volume of the system can keep on changing.

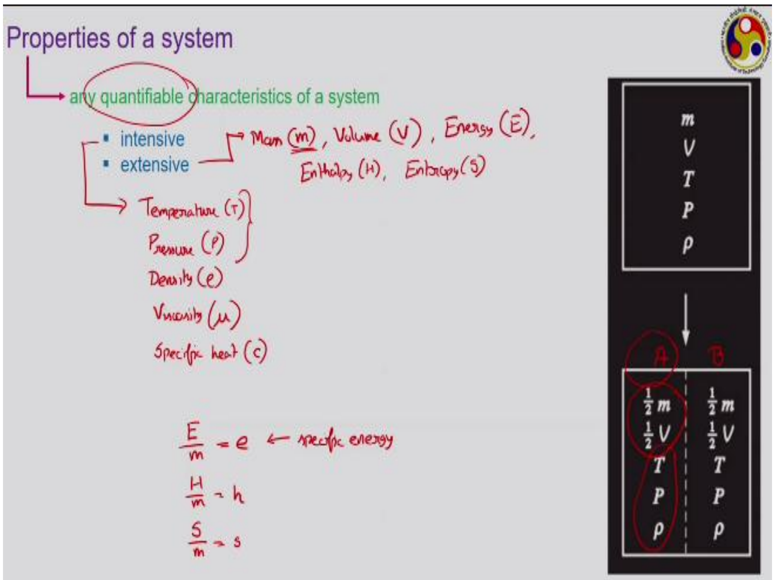
It can be a rigid or flexible one as well, and accordingly our choice of system can be quite flexible. And, for the same scenario, we can have different choices of the system; and depending upon your choices of system, the interaction between the system and surrounding can vary. And what are those interactions? The interactions are primarily in the mode of either mass or energy transfer or may be both. So mass can enter the system from surrounding or can leave the system to move to the surrounding. Similarly energy can also move in or out of the system.

Accordingly, the total energy content and the mass content of the system can change. Now, depending upon the nature of the interactions between system and surrounding, we can classify systems into 2 categories, closed systems or control mass system; and open system or control volume system. For closed system, there is only energy interaction and no mass interaction. That is, we can definitely have energy interaction, but no mass interaction, whereas for open system, mass is allowed to move in or out of the system.

Therefore, for the open system we can have both energy interaction and mass interaction as well. Now, there can be another kind of system defined in certain text books of thermodynamics that is identified as a third kind of system. But truly speaking that can be identified just as a special case of closed system, which is referred as isolated system. An isolated system is a special case of closed system, which does not have any energy interaction as well. Mass interaction is not there for closed system, and if energy interaction is also not there, then we should be calling it an isolated system.

So an isolated system is completely separated from its surrounding. It does not have any interaction at all with the surrounding. Now, for a closed system as there is no mass interaction, the mass of a closed system remains constant. So accordingly we can call it a control mass also; whereas for an open system, the mass content can change. Generally this is not a universal rule, but commonly open systems are associated with a rigid boundary; so that their volume remains constant and that's why open systems are often referred as control volume systems as well.

(Refer Slide Time: 12:32)



Now to quantify or rather to identify the physical condition of a system, we need to define the properties. Properties are any quantifiable characteristics of a system. So anything that you can think about which can be quantified, can be identified as a property. Properties can be classified into 2 categories, intensive and extensive. Intensive, which are independent of the mass or size or extent of the system, whereas extensive properties are dependent on the mass or size or the extent of the system.

Now, for a given property, how can we identify that is intensive or extensive? This is a simple example. Suppose we have a system given, for which there are several properties mentioned. Like m for mass, V for the volume, T for the absolute temperature, P for pressure and ρ for density. These are the 5 properties that are specified for the system and you have to identify out of this 5 properties, which are intensive in nature and which are extensive in nature.

The easiest way of doing this is to divide the system into 2 equal compartments. Let us say this is your system A, this is your system B. And now we have to check the properties for both the systems. Let us just look at the subsystem A and compare which of the properties of the subsystem is the same as the original system.

Temperature, pressure, and density, these 3 remains the same. So they are intensive properties because they are independent of the mass or size of the system, whereas mass and volume; they are extensive properties, as their values are changing by subdividing the system into 2 compartments. So examples of extensive property can be mass m and volume V. We can have energy, as another very extensive property. As you have already done a course on thermodynamics, so you know terms like Enthalpy, Entropy, they are all extensive properties; whereas if you want to write intensive properties, temperature T, pressure P, density ρ.

You can identify several other properties also, like from fluid mechanics, you can identify viscosity, which generally specified by μ. In thermodynamics also you can identify specific heat generally given by small c, c_p or c_v. These are all intensive properties because they are not dependent upon the size or extent or mass of the system. Also another thing you must be knowing by now is that any extensive property per unit mass is an intensive property.

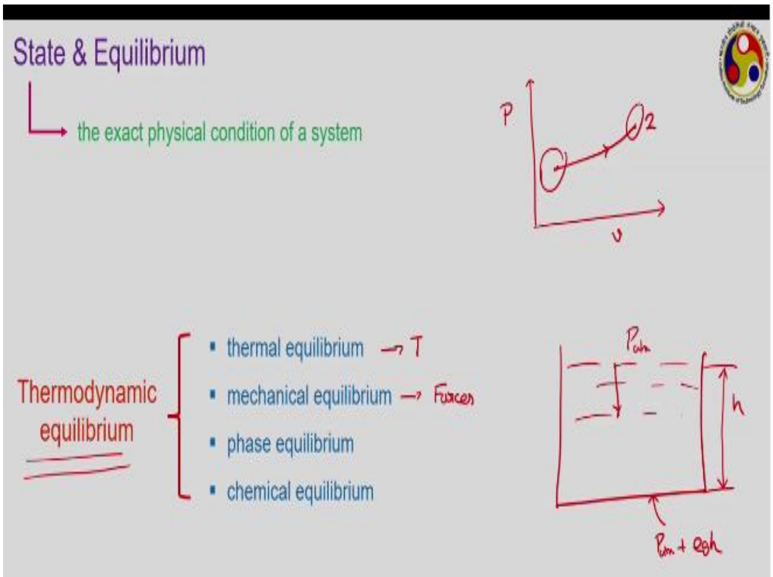
Say for example, energy (total energy content of the system); if that is divided by mass, then we get specified energy. Any extensive property per unit mass is identified as a specific version of the same property and this specific version of the properties are intensive in nature.

As it has already been divided by mass, its magnitude will be independent of the mass and therefore this is a specific property and an intensive property.

Similarly, enthalpy per unit mass, which gives us specific enthalpy or entropy per unit mass, which gives us specific entropy, they are all intensive properties. So, extensive property per unit mass gives us intensive properties. Also from the notations we can probably identify that extensive properties are commonly written using capital letters, whereas intensive properties are commonly written using small letters, with exceptions like mass.

Despite mass being an extensive property, we generally use ‘m’ to denote that. Similarly pressure and temperature, they are intensive properties, but still we generally use ‘T’ and ‘P’ respectively to denote them. For other properties generally, capital letter is used to designate extensive properties and small letter to designate intensive properties. Now, among all these kind of properties, there can be infinite number of properties that you can identify for a given system. And also I should mention at this particular point that, the term quantifiable is very important for something to be identified as a property. Like say, if we talk about colour, is colour a property? Probably not, from a thermodynamic point of view because color can’t be quantified. That is something that can be realized more from perception. The taste of something, that is also not a thermodynamic property because these are more like perceptions, they can’t be quantified truly. So, they are not properties.

(Refer Slide Time: 18:15)



Now, among all these properties, one property of particular importance from a transfer point of view is energy. But before moving on to the energy, we have to mention about the state and equilibrium. Now what is state? State is the exact physical condition of a system and to specify the state of a system, we need to know all the properties of that system. Once we mention that a system is at a particular state; that means, all the property values are known or at least they are fixed at a constant magnitude.

If the magnitude of any one of the property changes, then the system moves to a different state point. And in thermodynamics, we always deal with equilibrium state. Equilibrium state means there is no unbalanced potential. Now, there are several kinds of equilibrium we can talk about. The first one is thermal equilibrium. Thermal equilibrium means the temperature is same everywhere and therefore there is no heat transfer taking place. So, thermal equilibrium is concerned with the equality of temperature.

Similarly, we talk about mechanical equilibrium. Mechanical equilibrium generally is associated with the pressure or you can say it is associated with the equilibrium of forces. However, it does not mean that your pressure has to be same everywhere. Say, this is a tank filled with liquid water; and this portion is opened to atmosphere.

Now, you must be knowing from your knowledge of fluid mechanics that, as we are moving downwards, pressure keeps on increasing. And, if the height of this liquid column is h, then the pressure at this bottom surface will be the atmospheric pressure + ρgh. Now, as the pressure is changing in the vertically downward direction, then is the system in mechanical equilibrium? Probably it is, because here there are no unbalanced forces. The gravitational force is being balanced by this pressure distribution and that’s why this system is in mechanical equilibrium.

Third is the phase equilibrium. Phase equilibrium refers to equality of phases. Like, if we are talking about a system which is having multiple phases; and none of the phases are changing or their proportions remains constant. Then we can call the system to be in phase equilibrium. Suppose you take a mixture of liquid water and ice at 0 ºC and put that mixture into a thermo flask which is perfectly insulated. Then, we can expect that the fraction of mass occupied by the solid and fraction of mass occupied by the liquid remains constant over infinite period of time.

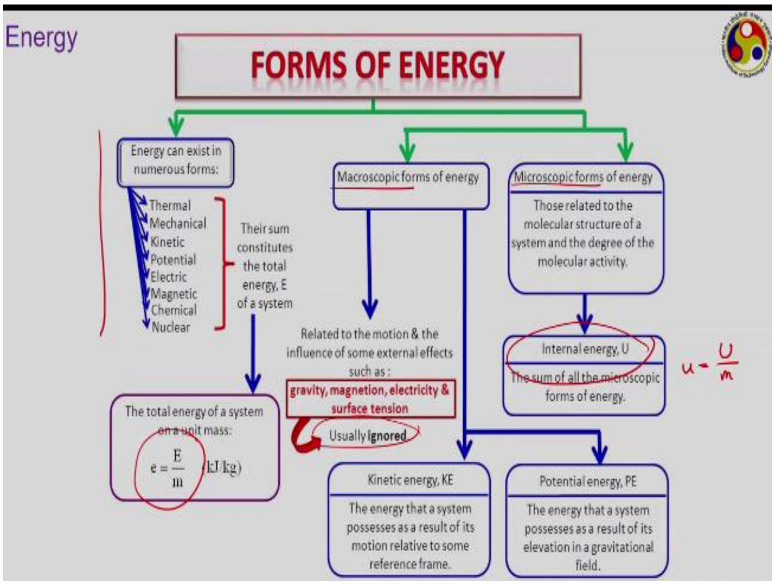
Then, we should call that system to be in phase equilibrium. And, finally in chemical equilibrium, which refers that the chemical composition of the system remains unchanged. That means there is no chemical reaction going on. So there is no chemical reaction potential. And when all these are satisfied, then we call the system to be in thermodynamic equilibrium. Now, whatever you have learned in thermodynamics, they are always concerned about the equilibrium state, like representation of a process on a property diagram.

Let us plot a property diagram such as a PV diagram. So this is our state point 1, this is our state point 2, and let us have a process that is going on from state 1 to state 2. Now, can you tell me under which situation we can represent the process by continuous line like this? We can represent this process with line from point 1 to point 2 when all the infinite number of points which constitutes this line are in equilibrium and we have a complete knowledge about each of them. That's why the term generally quasi-equilibrium or quasi-static are also commonly used.

So, state 1 is an equilibrium state; state 2 is also an equilibrium state, and all these intermediate states. They may not be perfect in perfect equilibrium, but they are in quasi-equilibrium condition, that is they are very close to an equilibrium state. So your entire study of thermodynamics was based upon this concept of thermodynamic equilibrium. And that is where the difference with heat transfer comes into picture.

If a system is in thermodynamic equilibrium, then it is also in thermal equilibrium. That is temperature everywhere in the system is constant. And if the temperature is constant everywhere in the system, then there will be no heat transfer. Because the primary consideration that we need to have in heat transfer is the difference in temperature. And therefore, if a system is in perfect thermodynamic equilibrium or at least in thermal equilibrium, there will be no heat transfer at all. In order to have heat transfer, we first need to have non-equilibrium and then only we can start discussing about heat transfer.

(Refer Slide Time: 22:46)



Now the property energy, which I was talking about, can be classified following several ways. One kind of classification can be just what we realize from our senses, like thermal energy, mechanical energy, kinetic, potential, electric, magnetic, nuclear, chemical, and other several types of energies. The total energy of a system is commonly given by the symbol E. And e is the specific energy which is an intensive property. There is another kind of classification of the energies such as macroscopic form and microscopic form of energies.

The macroscopic form refers to the form of energy which are associated with some external reference scale, like gravitational field, magnetic field, electric field, or surface tension. They are all macroscopic form of energy. Generally in thermodynamic analysis, they are ignored. Only on certain special cases they may appear. But these macroscopic forms are associated with the presence of some external influencing field. Like gravity being the most common one.

Another type of macroscopic form of energy is the kinetic and potential energies which are again associated with the choices of external length scale or external reference systems. Like kinetic energy is measured in terms of the velocity of the system with respect to some external reference frame. Similarly, the potential energy is measured in terms of the elevation difference of the system with respect to some reference scale and the choice of reference scale is always as per the convenience of the user.

Suppose you are traveling in a train. Inside the train if you start running from one side of the compartment to the other side, then how to measure the kinetic energy? One choice of reference frame can be the train itself. So, your velocity then needs to be measured with respect to the velocity of the train and accordingly, you can calculate kinetic energy. Another choice of reference frame can be the outside ground which is stationary.

Then, if you want to calculate the kinetic energy, we need to take into account the velocity of the train along with your velocity with respect to the train. Another choice of reference frame can be some hypothetical frame, which is placed outside the earth because the earth itself is rotating. So, if we want to calculate kinetic energy with respect to that particular reference frame, then the kinetic energy or the velocity of the earth also needs to be taken into account.

This is why the choice of reference frame can vary and accordingly the magnitude of kinetic energy can also vary. Same for potential energy; like if we want to calculate the potential energy say for this particular pen. Now you have to choose some reference frame. What can be your choice of reference frame? One choice can be the top of the table. Then we just have to measure the elevation difference from this pen to the top of the table. But if we choose our reference frame as the floor of this studio, then the height will be larger.

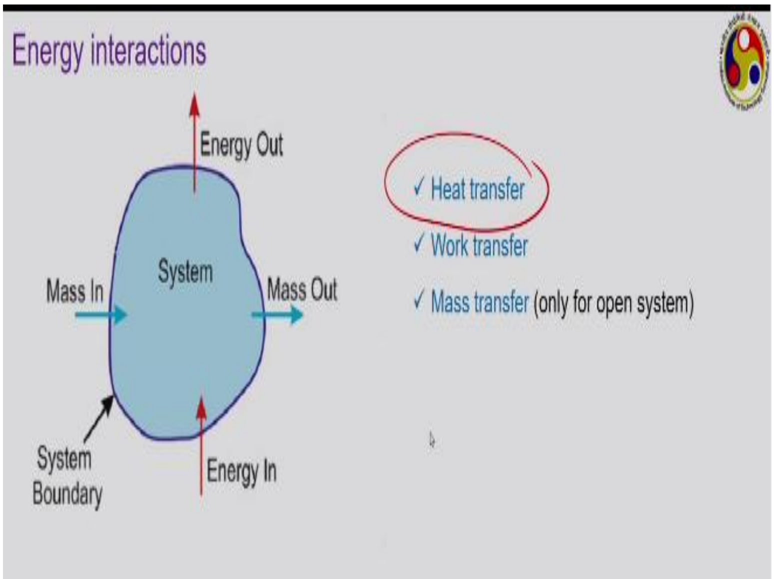
Corresponding magnitude of potential energy also will be larger. Now, we are sitting in the studio which is on the third floor of our building. So, if we choose the reference frame which is connected to the ground floor; then there are 3 more floors or corresponding height that needs to be taken into account. So accordingly, the magnitude of kinetic and potential energies can vary depending upon the choice of reference frame. But in thermodynamics, generally, we are always bothered about the change in the energy content of a system and accordingly we are always talking about the change in the kinetic energy and potential energy.

And as long as we are doing this calculation considering the same reference frame, then we don’t need to bother about the reference frame itself. But these all are macroscopic forms; because they all can be realized from our senses with respect to certain external reference frame or certain external influences. But, there is a microscopic form as well, which is associated with the molecular structure of the system and the degree of molecular activity. There can be several kinds of molecular activity; the molecules can have translational motion, rotational motion, vibrational motion etc.

Also, we can have this molecular energy in the form of sensible and latent energy. Latent energy is associated with the change of phase of a system and it is extremely difficult to get a perfect measure of all these individual components. And therefore we club all of them into this term called internal energy given the symbol U. The specific internal energy is denoted by u which is capital U divided by m. It is an intensive property whereas total internal energy or just internal energy is an extensive property.

It is a sum of all the microscopic forms of energies. Again, perfect measure of the magnitude of internal energy is not possible, so you always get the measurement with respect to certain reference.

(Refer Slide Time: 27:50)



And once we know about energy, then we need to talk about the energy interaction that system can have with the surrounding. A system can have energy interaction with the surrounding across the boundary following 3 different ways. Generally, in thermodynamics, we are not bothered about the energy content of the system itself; rather we are only concerned about the energy which is crossing the boundary of the system. That's why often these energy interactions are also referred as energy in transition or as a boundary phenomenon.

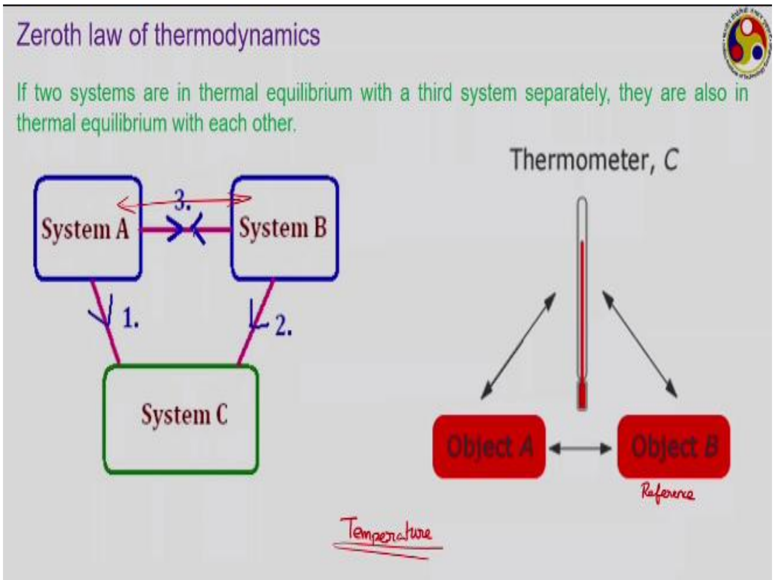
Whereas the energy content of the system itself is associated with the internal energy, of course, for a stationary system only. If the system itself is moving, then it can also have its own kinetic and potential energies. But in thermodynamics, we are generally bothered only about the energies which cross the boundary of the system or I should say they are realized at the boundary of the system. Then, there can be 3 kinds of energy interaction.

We can have heat transfer. Heat transfer refers to the energy interaction which is taking place because of a temperature difference between system and surrounding or thermal non-equilibrium between the system and surrounding. Second is the work transfer. Work transfer refers to the energy interaction between system and surrounding which is not taking place because of any temperature difference, rather taking place because of some other potential difference.

This potential difference can be a change in volume, can be gravitational energy or can be something else, but not temperature difference. So, among all forms of energy interaction that a system can have with its surrounding; only the one that is happening because of temperature difference is classified under this heat transfer and everything else are clubbed into this work transfer. There is a third one also called the mass transfer, which is applicable only for open systems; and of course for closed systems, there is no mass transfer. But whenever mass flows into a system, it will also carry some energy with it.

Accordingly, it will cause an increase in the total energy content of the system. Similarly when mass is leaving a system, i.e. crossing the boundary of the system and moving towards the surrounding, then it is taking some energy away from the system. So, mass transfer is always associated with energy interaction. And, out of these 3, our interest in this course is in heat transfer. So, heat transfer is the energy interaction which is taking place because of the temperature difference between system and surrounding. Now, before we define heat transfer, we need to discuss very briefly about the laws of thermodynamics.

(Refer Slide Time: 30:13)



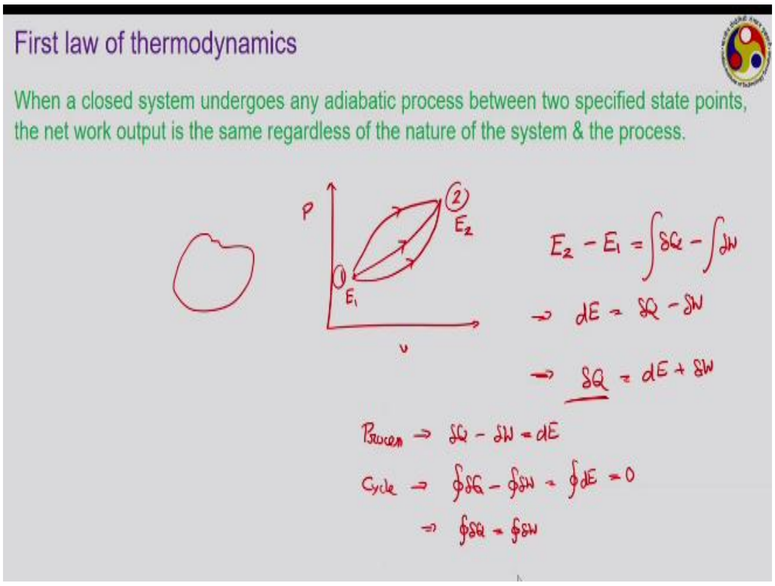
You know in conventional thermodynamics, we study 3 laws. First is the Zeroth law, which says that if 2 systems are in thermal equilibrium with a third system separately, they are also in thermal equilibrium with each other. Like shown here, system A and system C are in thermal equilibrium with each other; therefore system A and C are not having any heat transfer between them. Similarly, system B and system C are also in thermal equilibrium with each other and therefore they are also not having any heat transfer between them.

Then system A and system B are also in thermal equilibrium with each other. And if we take system A and system B in contact with each other, then they are not going to have any kind of heat transfer. That gives us two importance concepts. One is that it gives us the idea of measuring temperature using a thermometer. Here, I should mention that the term thermometer does not refer only to that mercury filled capillary tube that we use to measure body temperature, rather any temperature measuring device is a thermometer. That one is actually is a liquid in glass type of thermometer.

So in a thermometer, we get the reading by taking it in contact with our object A which is the target. Whatever reading we take, if we get the same reading when we take the thermometer into contact with some reference object with some known properties (B), then you should say that both object A and object B that is the reference, are in thermal equilibrium with each other. So that is the first idea. The second important concept that it gives is the concept of temperature. Temperature can’t be defined without the Zeroth law of thermodynamics.

So, we can only say that this one is hot, so it is at high temperature. This one is cold, so it is at a low temperature. But that is only perception. But from Zeroth law of thermodynamics, we can say that temperature is the property which is essential to ensure the thermal equilibrium. Or in other ways, we can say that if suppose system A and system B are in thermal equilibrium with each other, then the property that must be equal between them is temperature. Because the non-equality of temperature is essential to have heat transfer and therefore, only when the temperatures are different, then the systems can be having heat transfer across them. So the concept of temperature comes from Zeroth law of thermodynamics.

(Refer Slide Time: 32:43)



Next is the first law of thermodynamics which gives us an idea about the magnitude of energy interaction between the system and surrounding. When a closed system undergoes any adiabatic process between two specified state points, then the net work output is the same regardless of the nature of the system and the process. So, if we identify a closed system like this, and if it is undergoing any adiabatic process between two specified state points, like if we draw a diagram, let us say a PV diagram; so, this is the first state point, the initial state of the system and this is the final state of the system that is 2.

So the system has gone through some adiabatic process between these 2 state points, 1 to 2. Then the first law of thermodynamics is saying that, as long as this process is adiabatic and we are fixing up these two end points 1 and 2, then the net work output will be always the same regardless of the nature of the system and the process; that is because point 1 and 2 are two given state points. So they have fixed property values. Accordingly, the energy content of the system E_1 at state point 1 and energy content of the system E_2 at state point 2 are always same.

So, the change in the energy of the system E_2 - E_1 , over this process will always be the same. It doesn't depend upon the nature of the line; whether you are following the line that is shown here or a line something like this or a process something like this, this change in energy quantity will always be equal and from there we can derive that this is equal to the total energy interaction that has taken place. And for a closed system, we can have only two kinds of energy interaction.

One is the heat transfer that has taken place during this process and other is the work transfer that has taken place. Or, if we write in differential form, we can write that

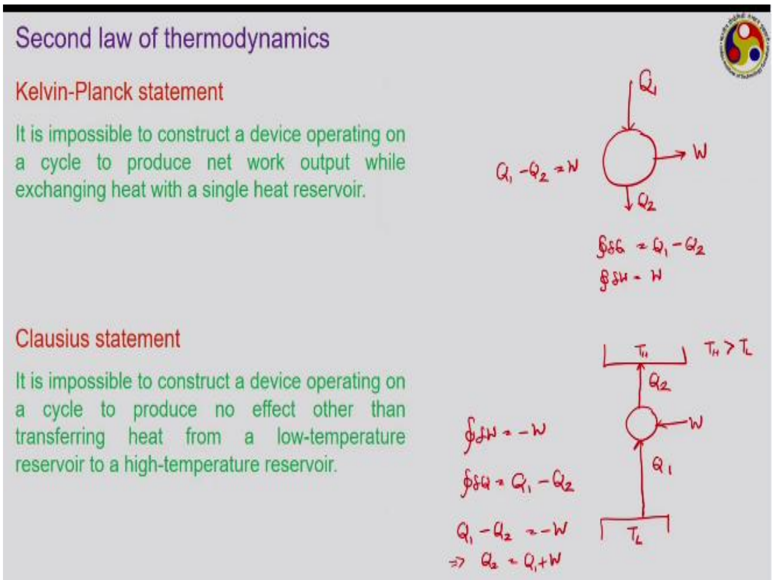
$$dE = \delta Q - \delta W$$

Here, of course, we are following the standard convention, that is the heat added to the system is positive and the work done by the system is positive. So, the first law of thermodynamics gives us a way of measuring the magnitude of heat transfer; that is from here we can write that

$$\delta Q = dE + \delta W$$

So, if we can measure the total work interaction that is δW, and total change in the energy content of the system, then their combination is going to give you the total heat transfer. So, the Zeroth law of thermodynamics gives us the idea of temperature or concept of temperature which is the property which determines whether heat transfer is possible or not and first law of thermodynamics gives us a way of measuring the quantity of heat transfer.

(Refer Slide Time: 35:30)



And then we come to the second law of thermodynamics. Based on the first law, we can define different kind of systems. Now, suppose if we define a system like this, which is operating over a cycle. Another important concept from the first law of thermodynamics, you must be knowing that the form that we have written that is for an individual process. So, for an individual process, we can always write

$$\delta Q - \delta W = dE$$

But if we are writing this over a cycle, then you write

$$\oint \delta Q - \oint \delta W = \oint dE$$

But cyclic integral of any property has to be equal to zero because properties are state functions. Accordingly, for a cycle we get

$$\oint \delta Q = \oint \delta W$$

So over a cycle, the total heat interaction has to be equal to total work interaction. Now, let us talk about a process where we are supplying say Q_1 amount of heat and this system is converting this entire to W amount of work. So, here

$$\oint \delta Q = Q_1$$

And

$$\oint \delta W = W$$

As long as we are having Q_1 = W, this is not at all violating the first law of thermodynamics. But any effort to create such a system always leads to failure, because this thing is not possible as per the second law of thermodynamics. There are 2 popular statements of the second law of thermodynamics and the first one is associated with the scenario like this which is the Kelvin-Planck statement. It says that it is impossible to construct a device operating on a cycle to produce net work output while exchanging heat with a single heat reservoir.

Means the amount of heat it is receiving; only a part of that can be converted to work and the rest, say Q_2 amount, has to be rejected to the surrounding. Then, in that case, total heat interaction is Q_1- Q_2, total work interaction remains W and now, we have

$$Q_1 - Q_2 = W$$

This is definitely possible. So, the second law of thermodynamics gives us an idea about the conversion of heat to work, at least the Kelvin-Planck statement.

Let us consider another scenario. We have 2 bodies, one is at low temperature T_L, and other is at high temperature T_H. Here, T_H is higher than T_L. The system is drawing Q_1 amount of heat from this low temperature body and transferring the entire quantity to the high temperature body. So, here at the moment, total work interaction is zero, total heat interaction we can write, as the system is receiving Q1, rejecting Q1, so that is equal to 0.

So the first law is definitely satisfied. But again such kind of process is not possible according to the Clausius statement of thermodynamics, which says that it is impossible to construct a device operating on a cycle to produce no effect other than transferring heat from a low temperature reservoir to a high temperature reservoir. That means to make this process done, we have to give some work input to the system and accordingly Q_2 amount of heat will be added to the high temperature body.

In that case, total work interaction is equal to -W and total heat interaction is equal to Q_1- Q_2. Now, applying first law, we have

$$Q_1 - Q_2 = -W$$

Or,

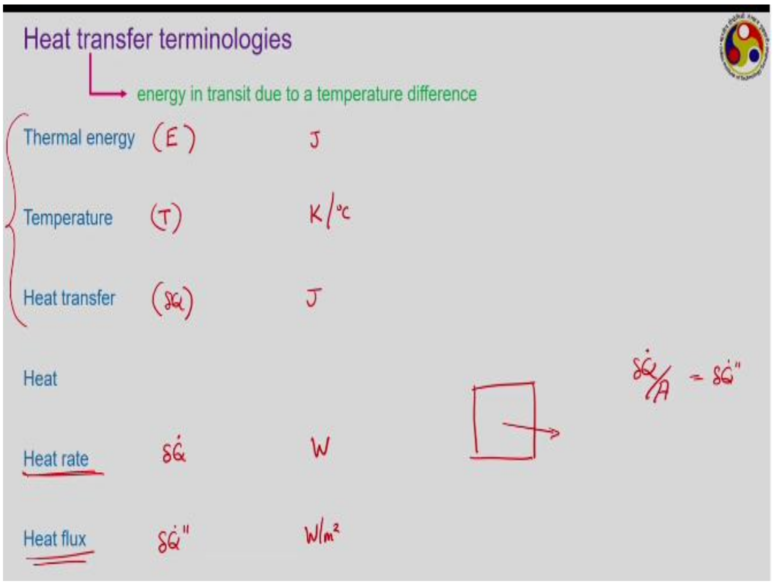
$$Q_2 = Q_1 + W$$

Now, it is possible. So, the second law of thermodynamics actually is giving us the direction of heat transfer. So, the Zeroth law gives us the concept of the property temperature which dominates the heat transfer. First law gives us a way of measuring the quantity of heat transfer.

And second law tells us about the possible direction or realistic direction of heat transfer. But none of them are giving us any idea about the nature of the heat transfer itself or modes of the heat transfer and that is precisely where the subject of heat transfer starts. Thermodynamics is never bothered about the nature of heat transfer or the exact nature of interaction between system and surrounding, it just takes the quantity heat as a gross or as a whole.

It is in the subject of heat transfer, where you study exactly what is the mode of heat transfer, what are the factors that can contribute to this, what are the ways we can control the amount of heat transfer and also the rate of heat transfer. Like in thermodynamics we can get the idea that Q amount of heat has been transferred from the system to the surrounding, but how much time over which it has taken place or how much time is required, what is the rate of this heat transfer, none of this questions can be answered by thermodynamics. And therefore we need to study heat transfer precisely to know the answer to these questions.

(Refer Slide Time: 41:02)



So, some terminologies with which I would like start the discussion on heat transfer. We know from the knowledge of thermodynamics that heat transfer is the energy in transit due to the temperature difference. Now, the first term we shall be talking about is thermal energy. Thermal energy is just in thermodynamic sense that Q or δQ that I have just used is a total amount of energy that has moved from system to surrounding or from surrounding to system because of some temperature difference between system and surrounding.

So δQ or Q is the symbol that will be used and it is energy only. So, corresponding SI unit can be Joule. The next is temperature, the symbol T will be used, SI unit is Kelvin but quite often we may be using units like degree Celsius. Similarly with Joule we may have to move to units like kilojoule or megajoule. So, temperature is again a thermodynamic property which gives us an idea about the total energy content of the system or at least the level of molecular activity. And also when we are talking about energy interaction between two systems, then the magnitude of temperature decides the direction of heat transfer.

Now comes the heat transfer which we are talking about. Heat transfer is again the energy in transit because of a temperature difference, which is nothing but the thermal energy. But the difference is that in heat transfer, we are specifically talking about this δQ whereas here the term thermal energy can refer to anything. It can refer to the total energy content of the system as well. Then, let us use the symbol E to denote the energy or the thermal energy which can primarily be associated with the total energy content of the system; whereas we are going to use the symbol Q or δQ to designate heat transfer.

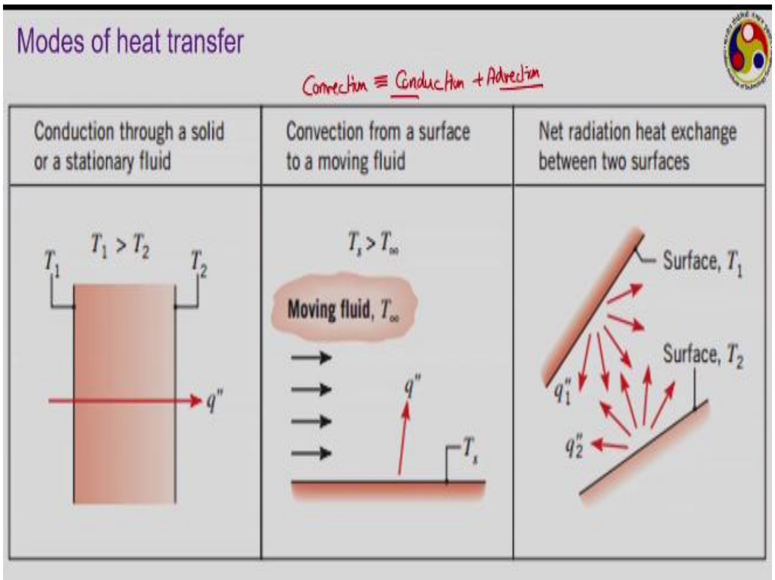
Then, now these 3 quantities, you have identified in thermodynamics as well, but not this one which is heat. Heat refers to the total quantity of energy that has been supplied over a period of time. Now, heat transfer or rate of heat transfer gives us an idea about the total energy interaction, but heat is the term that is primarily being used only in context with heat transfer. Heat rate is exclusively used in case of heat transfer, you can say it is $\delta \dot{Q}$, generally the dot symbol indicates the rate, and unit can be watt.

It is the rate of heat transfer or heat transfer per unit time. Similarly, another very common term is heat flux. Heat flux refers to rate of heat transfer per unit area. So, quite often it uses the symbol $\delta \dot{Q}''$; here the dot represents per unit time and each of these two small lines that I have drawn, designates per unit length, so two lines designate per unit length square or per unit area. So, watt per meter square is the basic SI unit for heat flux.

So, if we are talking about this is one area over which heat is transfer is taking place, then the total amount of energy that has left the system if that energy is δQ, then δQ divided by the area of this one is going to give you the heat transfer per unit area. And once you are dividing it by the time associated with this entire energy transaction, then we get this heat flux, which we shall be using $\delta\dot{Q}''$.

Sometimes, the dot we can ignore also because in heat transfer, we are primarily concerned about the terms like rate or flux which are always designated as per unit time. But this double prime is very important because we shall frequently be using per unit length or per unit area or maybe per unit volume. Accordingly we may have to use 1, 2 or 3 lines. And if there are no lines, that talks about the heat rate only. So, the terms like heat transfer or thermal energy we are not going to use anymore; we shall primarily be using heat or heat rate or heat flux.

(Refer Slide Time: 45:09)



Now, from your school level knowledge, you know that there are primarily 3 modes of heat transfer; Conduction, convection, and radiation. Or as the conventional scientist suggest, there are only 2 fundamental modes, conduction and radiation because convection is only a combination of conduction and advection of flow. In fact the term convection comes from there only. Convection is often referred as conduction plus advection. So, take con from there and vection from there that gives us convection.

Now, conduction is associated with the energy transfer because of the temperature imbalance from one part of the system to the other part. Any solid, liquid, or gaseous substance can participate in conduction heat transfer, though it is mentioned here as only solid or stationary fluid. But conduction is a fundamental phenomenon and any system can participate in this. It may be more pronounced in case of solids and very insignificant in case of gaseous where conduction is always there.

Whenever we have temperature gradient across a particular system or across the same substance solid, fluid, or gaseous; then there will always be conduction, whereas radiation is the heat exchange between two surfaces in the mode of electromagnetic waves and it can happen at the absence of any intermediate medium as well. But convection is primarily associated with the interface of a solid and a fluid. Whenever a fluid is flowing over a solid surface, it can take away some energy of the solid surface by virtue of its flow and accordingly we get the convective mode of heat transfer.

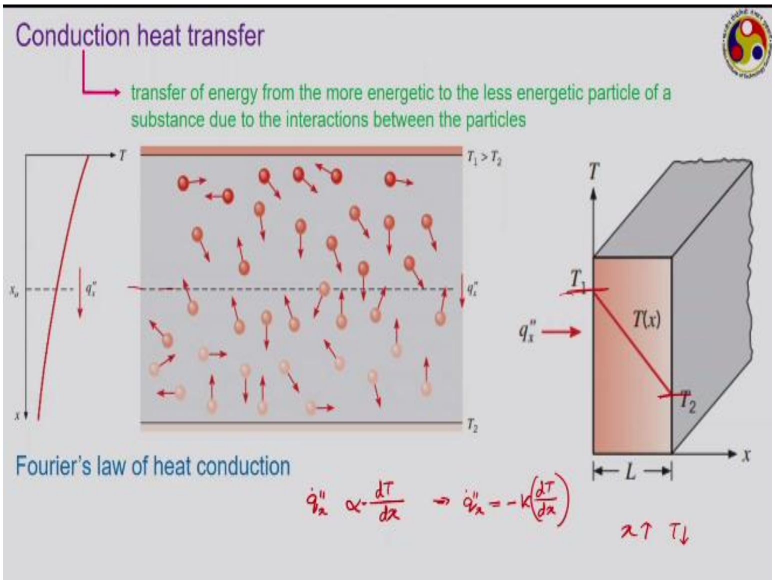
There are several ways you can realize this. Let us say I have this particular file with me and I am standing in front of a big class. There are 50 students sitting in chairs in front of me. Now, I want to transfer this particular file to the last student sitting at the end or sitting at the back. Then there are three ways I can do it. One is I can give the file to the first student sitting in the front row, he will pass it over to the second student, he will pass it over to the third student and this way it will pass through all the 50 students to reach the last student.

This is how conduction happens; energy is transmitted from one molecule to the next one to the next one to the next one till the smallest energy level or lowest energy level starting from the highest energy level. This is conduction. Second case is convection. Convection always starts with conduction. So, it is something like, I handover the file to the first student so that is a kind of conduction, now the first student physically moves to the last student who is sitting at the back and handover the file to him.

So, as he is handing over the file to the last student that is again an instance of conduction, but in between what has happened is advection. The student has physically moved and that is the carrier has physically moved from one position to another position and accordingly we have got the energy transport. So, convection has always both conduction and flow associated with this. Then what is the third mode? That is radiation.

Radiation is somehow I throw the file and it reaches the last student. Then, I am completely ignoring the presence of all the 49 students sitting in front of them; or I am completely ignoring the medium in between, and I am able to reach the reach the last student. Of course, I have to provide sufficient amount of energy so that it is able to reach the last student. Accordingly, we can have radiation mode of heat transfer.

(Refer Slide Time: 49:11)



A very brief review of each of them. Conduction heat transfer refers to the transfer of energy from a more energetic to the less energetic particle of a substance due to the interaction between the particles. Just like the example shown here. Suppose let us talk about system of gases where one side of the system is kept at a temperature T_1, other side at temperature T_2 and T_1 is higher than T_2.

Then the molecules of gases which are close to the surface at T_1 are expected to get a higher energy level compared to the molecules which are here close to the lower temperature wall. That is, a temperature gradient acting, here the temperature is high, here the temperature is low. Now, because of this temperature gradient and because of the higher energy content of the particles which are in this zone, there are two ways energy can get transmitted.

Because of their higher energy content they will be having higher kinetic energy. So they will be having much more movement compared to the low energy particles. And as they are moving over the domain, they will collide with other particles and whenever such a collision happens, if it is colliding with a less energy particle, it will transfer a part of its momentum to the lesser energy particle. Accordingly, the lesser energy particle will have uplift in its own energy content, which means an increase in its own temperature. So that is one mode which is because of the molecular activity or collision of the molecules.

There is a second one also. If we take any plane within this domain like the black dotted line shown here, because of the higher energy content of the particles or molecules which are on the top of this surface or above this dotted line compared to the molecules below this; the number of particles crossing this line from top to bottom will be higher compared to the number of particles crossing this from bottom to top. Accordingly, there is a there is a higher amount of energy transmitted from top to bottom and accordingly we can have energy transmission.

So this is what we have in case of conduction, at least associated with the gases; where we can see there are two primary mechanisms going on, one is the collision of molecules and second is the advection or physical movement of these molecules. When we go to liquids, there the liquid molecules are not allowed to move such feely, so the collision is dominant. But liquid molecules also can move to certain degree.

And, when we finally move to the solids, in case of solid generally molecules are arranged in a particular lattice structure, so they are not allowed to move at all. But they can keep on vibrating at their own position and because of their vibration, they keep on transferring it to the neighboring particles, just like the example of students sitting in a class and passing on the file that I mentioned, and accordingly it will be able to transfer energy from one end of the lattice structure to other end.

So, here the collision or vibrational energy based transfer is more dominant, there is hardly any molecular movement in case of solids; whereas in case of gases, the molecular movement is the most dominant one. Also, we can have 2 kinds of solids. If we are talking about nonconductors, then the one that I mentioned that is predominant, that is the vibrational energy being transmitted to neighboring molecules. But for conductors which can have significant amount of free electrons, we can also have energy transmission because of the movement of the electrons.

So for solid conductors, we can have energy transmission or conduction energy transmission by both molecular vibration as well as the transmission of free electrons. So, to understand the mechanism of energy transmission, let us say through a solid by conduction, say here the temperature is T_1, here the temperature is T_2 and the length of the domain is L, then there is a temperature gradient acting across this.

And, the fundamental law which gives us an idea about this particular amount of heat transmitted in this direction from the wall at temperature T_1 to the wall at temperature T_2 is the Fourier's law of heat conduction; which says that

$$\dot{q}_x'' \propto \frac{dT}{dx}$$

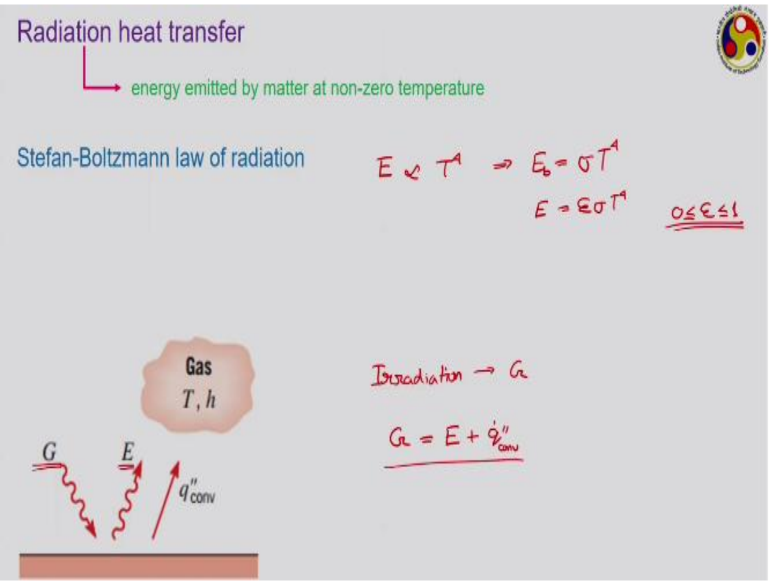
This is the most basic relation or basic form of the Fourier's law of heat conduction. In the next week, we shall be talking in detail about its more generalized form.

So, if we want to convert this one to an equality, the conduction heat flux in the x direction will be equal to

$$\dot{q}_x'' = k\frac{dT}{dx}$$

where k is some constant of proportionality which is called the thermal conductivity; and is a property of the material. And actually you should put a minus sign here because heat is flowing in the direction of reducing temperature. So, in the direction of increasing x, T is decreasing, so to have a positive value of dT/dx, we should have the minus sign for this. So Fourier's law of heat conduction is the fundamental equation with conduction of heat transfer starts.

(Refer Slide Time: 54:31)



Second fundamental mode is the radiation heat transfer; which talks about the energy emitted by any matter which is maintained at a temperature higher than zero. Here, the mode of emission or mode of energy transmission are electromagnetic waves, and it is completely independent of any medium, even if any medium is present from the source to the destination, it can completely eliminate the presence of the medium. And it is best when the medium is vacuum, or basically there is no medium at all.

The Stefan-Boltzmann law of radiation is the fundamental equation which gives us an idea about the radiating mode of heat transfer; which talks about say for a perfect substance, the total amount of energy transmitted can be written as

$$E_b \propto T^4$$

where T is the absolute temperature or,

$$E_b = \sigma T^4$$

where sigma is called the Stefan-Boltzmann constant. This is for the ideal substances or blackbodies, so that is why we generally put a subscript b.

For real substances, we generally have a term ε, which is called emissivity, coming to picture,

$$E = \varepsilon\sigma T^4$$

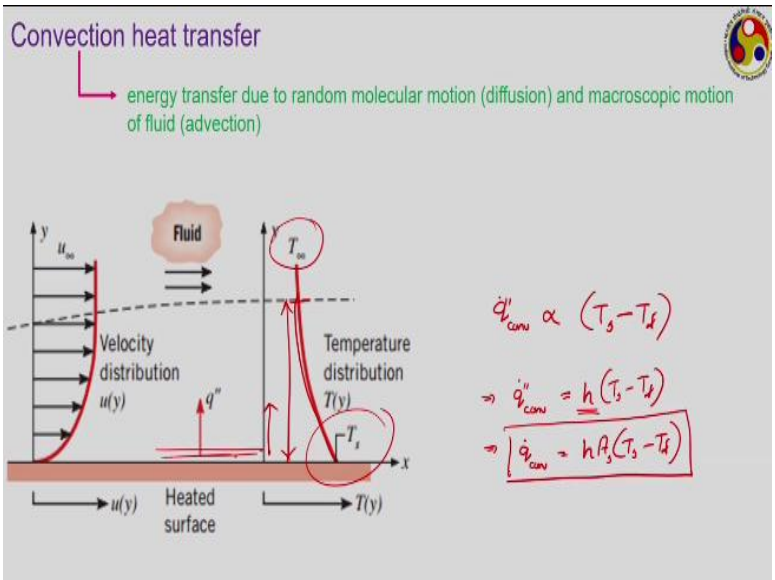
For the moment, you just take the relation. The details of this, I shall be coming later on. The Fourier's law of heat conduction mentioned in the previous slide is a phenomenological law, that it doesn't have any mathematical background. It has come just from observation. But Stefan-Boltzmann law of radiation can be proved from mathematical point of view which we shall be doing in the concerned module.

For the moment, you can just have the relation that the total amount of radiation energy emitted by a substance maintained at absolute temperature T is given as $\varepsilon\sigma T^4$, where epsilon is called the emissivity and its value can range between 0 to 1. We shall be having detailed discussion about the nature of this emissivity, different types of emissivities, and also the difference between blackbodies and real surfaces.

Now, if a surface can emit radiation like this one, it can also receive a radiation from it surrounding. So accordingly, G is the symbol generally associated with the term called irradiation. Irradiation refers to the amount of radiation energy received by a surface from its surrounding. So, as the surface is giving E amount of energy, it is also receiving G amount of energy.

And, If there is some convection happening because of some gaseous medium flowing over the surface, then we can easily write an energy balance for the surface shown here, it is receiving G amount of energy and on the steady state, this should be called the total amount of radiation energy emitted by this plus total amount of convection energy lost by this. So here, all these G and E, they can be written in flux mode or they can also be written in heat rate mode. We shall be discussing in detail about each of them later on in week number 9.

(Refer Slide Time: 57:50)



The third mode of heat transfer is the convective heat transfer, which talks about the energy transfer due to random molecular motion; which is diffusion and macroscopic motion of fluid called advection. We are particularly concerned about convective heat transfer at the interface of a solid and a flowing fluid, just like the situation shown here. You have a heated solid plate maintained at certain temperature and a fluid is flowing over this.

As the fluid is flowing over this, it will pick up energy from this. That is the fluid molecules which are very close to the surface, they will try to attain the solid surface temperature that is T_s, while the fluid itself may be coming with some free stream temperature, T_∞. So, as we are moving away from this in this direction, the temperature of the fluid will keep on reducing. Finally it will reach this free stream temperature. Thereby it creates this particular zone of rapid temperature gradient which is called the thermal boundary layer.

Convection is a very involved subject. The total convective heat transfer associated with this situation or the convective heat flux is found to be

$$\dot{q}_{conv}" \propto (T_s - T_\infty)$$

converting this to equality, we can write

$$\dot{q}_{conv}" = h(T_s - T_\infty)$$

I have earlier used this h to indicate specific enthalpy, but in this course we are not going to talk about enthalpy anymore. And therefore this h is a constant of proportionality which is also called the convective heat transfer coefficient. As in this course, we are going to talk only about conduction and radiation; we are not going to discuss anything about the convective heat transfer. But this convective heat flux equation may be repeatedly coming to picture.

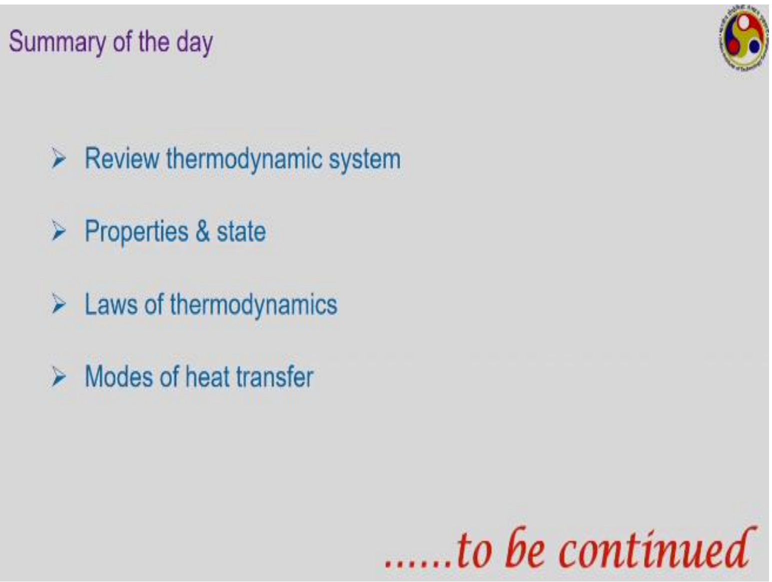
So, we have to understand that, the convective heat transfer will be coming into equation whenever we are talking about a fluid flowing over a solid surface, at least for the perspective of this present course. Whenever we are facing a situation that a fluid is flowing over a solid surface, then we have a convective heat transfer and corresponding heat flux can be calculated in this way.

Or, if our interest is to calculate the corresponding convective heat transfer or rate, then that will be equal to

$$\dot{q}_{conv} = hA_s(T_s - T_\infty)$$

Where A_s is the area of the plate. This equation we have to use repeatedly.

(Refer Slide Time: 01:00:33)



So this is where I would like to keep the introduction of the day, where we have just briefly reviewed the thermodynamic system, and the concept of properties and state; and different laws of thermodynamics. We have seen that the Zeroth law of thermodynamics gives us the concept of temperature, first law tells us how to calculate the magnitude of heat transfer, and second law tells us the direction of heat transfer. But none of the laws of thermodynamics tells anything about the time scale associated with heat transfer or the modes of heat transfer.

So we have briefly reviewed the modes of heat transfer. Out of which the convective mode of heat transfer we are not going to discuss any further, but both conduction and radiation will be discussed in details. So, I shall be keeping today's lecture here itself. A few further introductions to these modes of heat transfer and also some discussion about associated dimensions and some numericals associated with each of the modes of heat transfer will be discussed in the next lecture. Till then, you please review this particular week's lecture, and if you have any query, please write back to me. Thank you.