Refrigeration and Air Conditioning
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Lecture No. # 04
Review of Fundamentals
1. Thermodynamics

Welcome to the fourth lecture on refrigeration and air conditioning.

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In this lecture and next one or two lectures will be reviewing the fundamentals of thermodynamics heat transfer and fluid mechanics.

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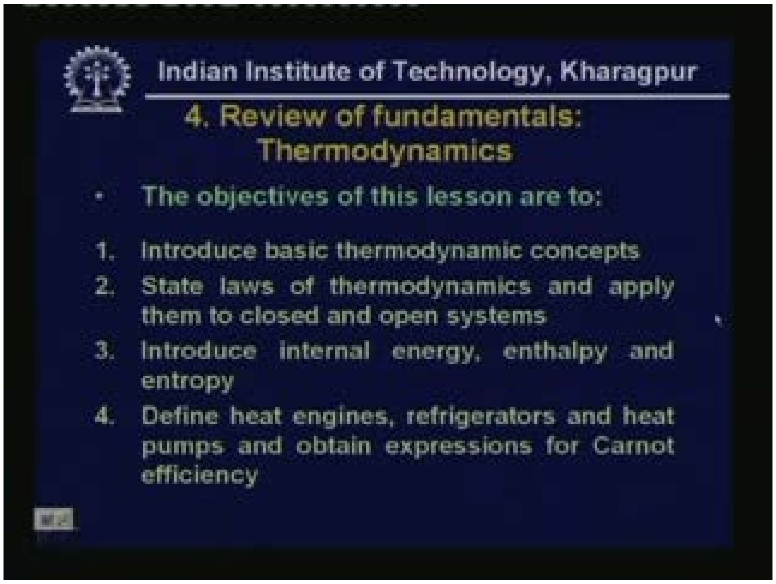

So the objectives of this lesson are to introduce basic thermodynamic concepts, state laws of thermodynamics and apply them to closed and open systems, introduce internal energy, enthalpy and entropy, define heat engine refrigerators and heat pumps and obtain expressions for Carnot efficiency of these devices.

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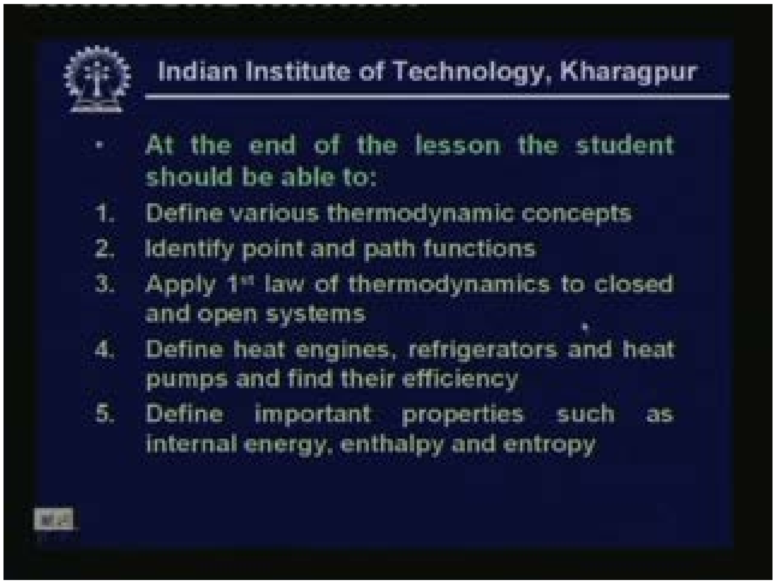

And at the end of the lesson you should be able to define various thermodynamic concepts. Identify point and path functions, apply first law of thermodynamics to closed and open systems and define heat engines, refrigerators and heat pumps and find their theoretical maximum efficiency and define important properties such as internal energy enthalpy and entropy.

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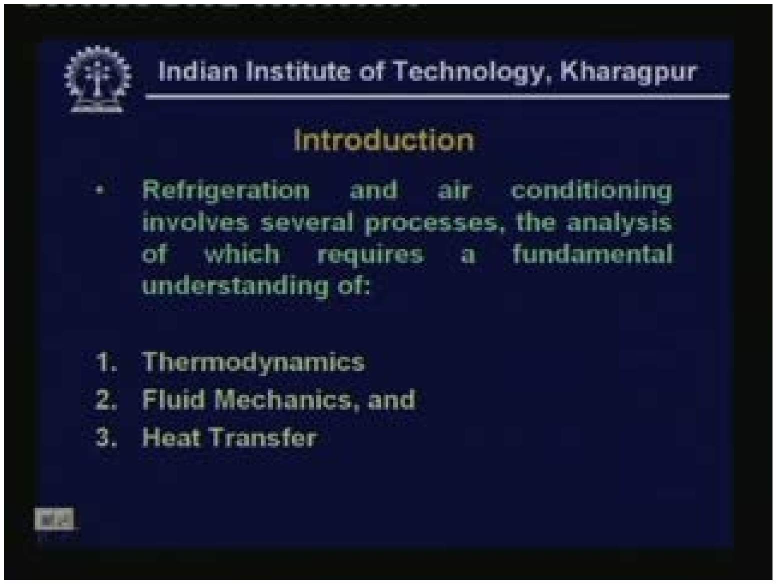

So why do we need to do the review? We know that refrigeration and air conditioning deals with several processes which involves transfer of mass momentum and energy. And all these transfers are subjected to certain fundamental laws of thermodynamics, heat transfer and fluid mechanics. So in order to understand this particular subject one needs to know the basics of these three subjects. One is thermodynamics fluid mechanics and heat transfer. I assume that you have already studied these subjects. So here the purpose is not to give a very detailed description of all these subjects. Because it is not possible. So we quickly run through the basic concepts of thermodynamics fluid mechanics and heat transfer. So for any detailed discussions you must refer to a standard text books on this subjects. So let us start with thermodynamics.

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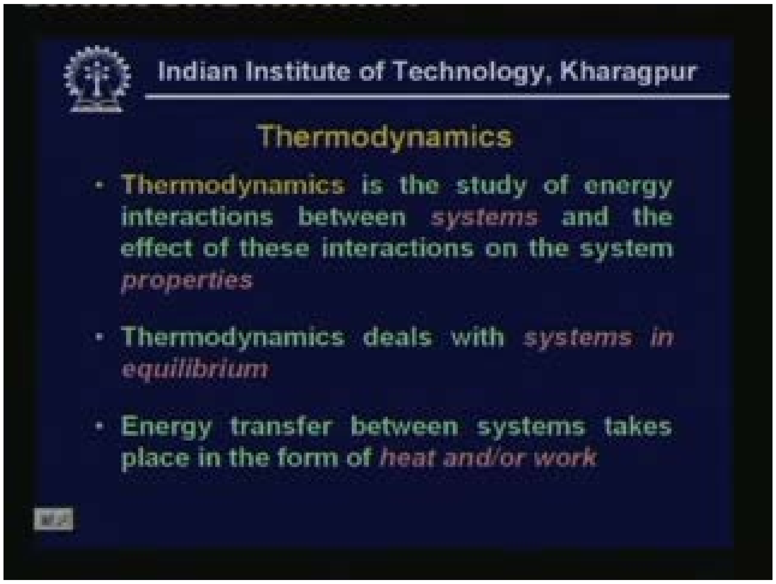

Thermodynamics is the study of energy interactions between systems and the effect of these interactions on the system properties. So we define little later what do you mean by system and how do we define properties and all. It is very important to note that thermodynamics basically deals with energy interactions. Since energy interactions exists all over the universe. Thermodynamics is a very fundamental and most important subject in engineering. And thermodynamic systems generally the subject of classical thermodynamics deals with systems in equilibrium.

What do you mean by equilibrium? Normally equilibrium means a condition of balance between opposing factions. If you have a thermal equilibrium, for example if I say that a system is in thermal equilibrium. That means there are no temperature gradients inside the system. So that there is no net heat transfer inside the system so you call that as the system in thermal equilibrium. A system is said to be in mechanical equilibrium. If there are no imbalance of forces inside the system and there is no net acceleration. So you call that system as under mechanical equilibrium and you can also call a system as in phase equilibrium if there are no phase changes taking place within the system. Similarly you can also have a system under chemical equilibrium. When there are no chemical reactions taking place inside the system and

for a system to be in thermodynamic equilibrium it has to satisfy all these equilibrium. That means for the system to be in thermodynamic equilibrium it has to be in thermal equilibrium, it has to be in mechanical equilibrium, it has to be in chemical equilibrium and it has to be in phase equilibrium.

So classical thermodynamic basically deals with systems in thermo, in equilibrium, and energy transfer. We will see little later energy transfer between systems takes place in the form of heat and work. So let us now define systems.

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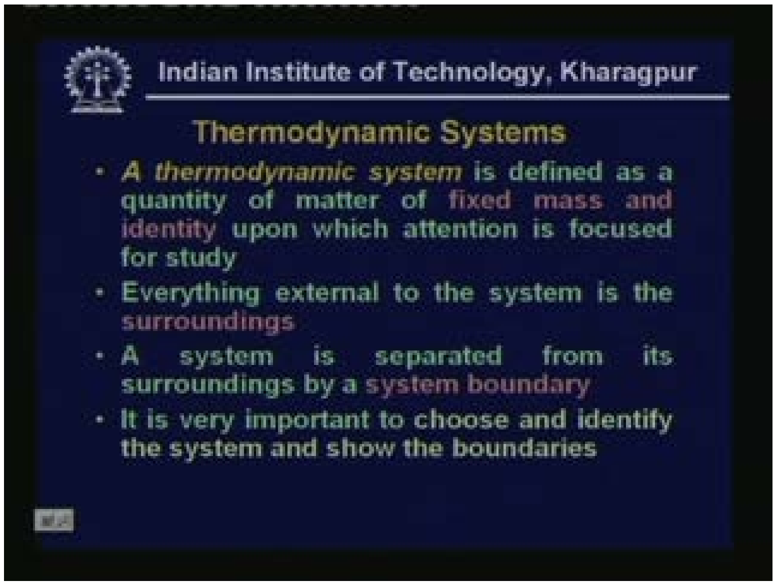

What do you mean by thermodynamic systems? So a thermodynamic system is defined as a quantity of matter of fixed mass and identity upon which attention is focused for study. So here you have to notice that the system means generally the mass is fixed and the identity is also fixed. So in very simple terms a thermodynamic system is whatever we want to study. So it can be as simple as a gas in a closed vessel or it can be as complex as a nuclear power plant. So depending upon the problem the complexity of the system will be varying and everything external to the system is called as surroundings. So you have a system and everything external to the system is surroundings. And generally a system is separated from its surroundings by what is known as a system boundary. And in any thermodynamic problems it is a, or any thermal engineering problems it is very important. And in fact it is the first step to choose and identify the system properly and show the boundaries. That means there should not be any ambiguity as far as the system and it is surroundings are concerned.

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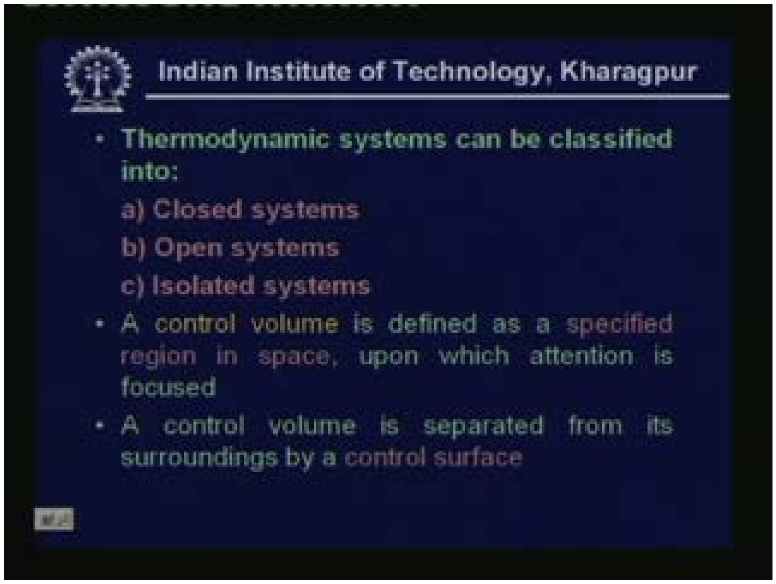

Now thermodynamic systems can be classified into three types you can have closed systems open systems and isolated systems. A closed system can have energy interaction with the surroundings. But it cannot have any mass interaction. That means no mass can enter or leave the system whereas energy can enter or leave the system. Such a system is called as a closed system.

In an open system you can have both energy as well as mass interaction. That means mass can enter or leave the system energy can enter or leave the system. So that kind of system is called as an open system.

An isolated system cannot have any interaction. That means neither mass interaction will be there not energy interaction will be there. That kind of a system is known as an isolated system.

Let me give an example if you let us say that we have a room a perfectly insulated room which tightly shut windows doors etcetera. So that no energy can enter into the room and no air can enter or leave the room. And if you take the air inside the room as the system and then it becomes an isolated system because neither air can enter nor any energy can enter into the room.

Now if you open the, if you remove the insulation then even the mass cannot enter. Some heat transfer can takes place across the walls. Then the system becomes a closed system because even the mass cannot enter early. Energy can enter early by the form way of heat. So it becomes a closed system.

Now if you keep the doors and windows open so that energy can also enter or air also can enter and leave then it becomes an open system. This is a simple example of closed open and isolated systems. Now a control volume is defined as a specified region in space upon which attention is focused. So control volume can be thought of as an open system where mass can enter or leave and a control volume is separated from its surroundings by what is known as a control surface.

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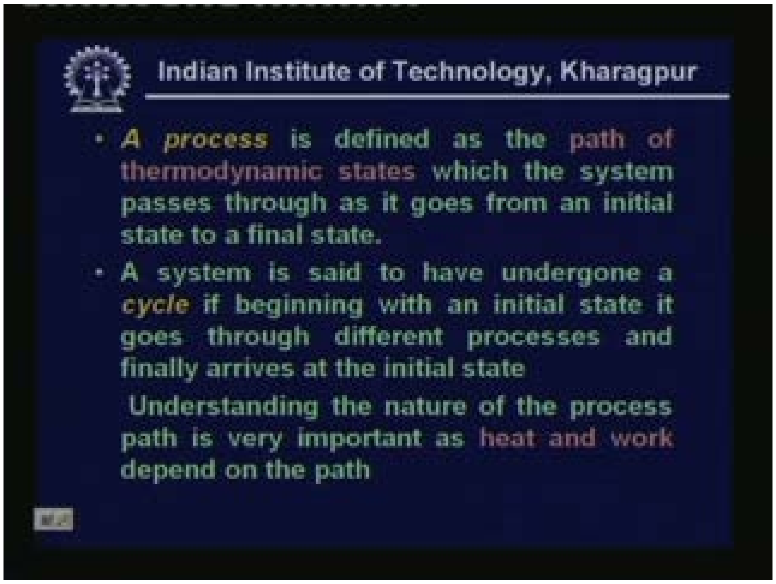

Now let us define the process. A process is defined as the path of thermodynamic states which the system passes through as it goes from an initial state to a final state. And a cycle is defined as a system is said to have undergone a cycle if beginning with an initial state it goes through different processes. And finally arrives at the initial state. That means a system passes through several processes in such a way that it finally arrives at the same initial state. So initial state and final state will be same so such a process is called as a cycle and understanding the nature of the process path is very important because we will see subsequently, that the heat transfer and work transfer depend very much on the ah process. So we have to know what kind of process is taking place .

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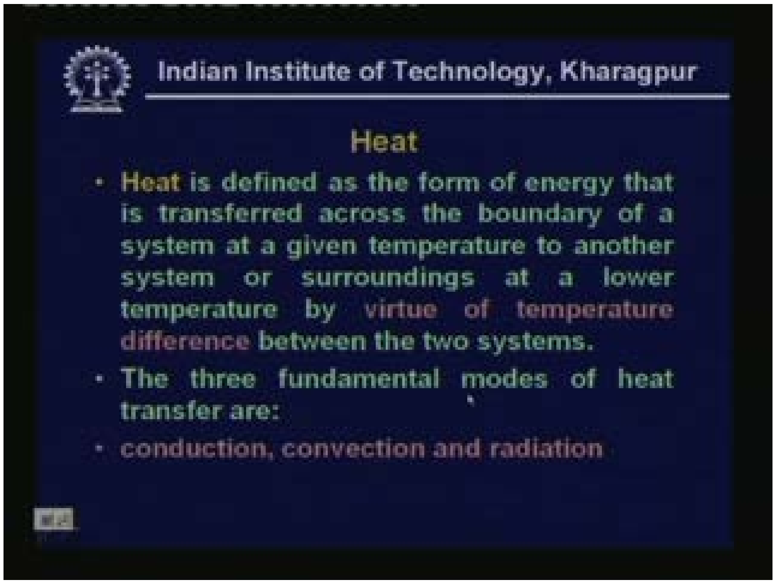

Now let us define heat so in thermodynamics heat is defined as the form of energy. That is transferred across the boundary of a system at a given temperature to another system or surroundings at a lower temperature by virtue of temperature difference between the two systems. So heat is energy transit and how does the energy transfer takes place it takes place because of the temperature difference. So if any energy transfers which involves temperature difference is called as heat transfer. And there are three fundamental modes of heat transfer they are conduction convection and radiation.

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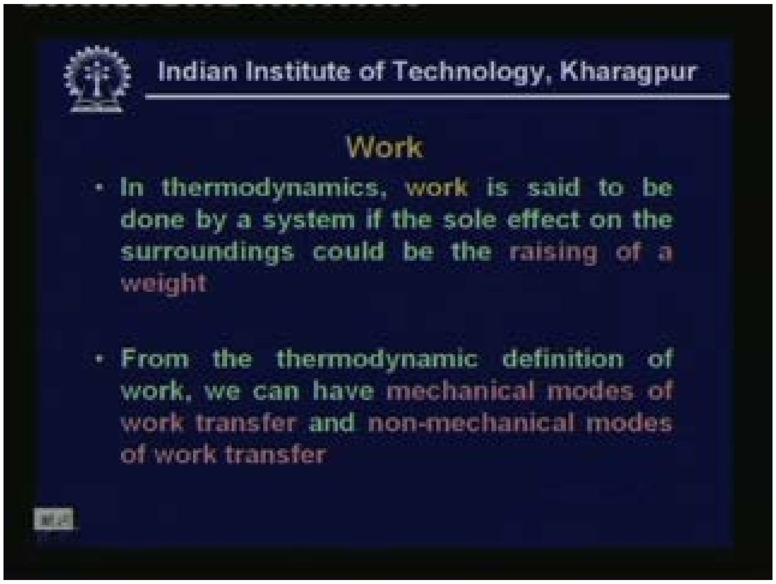

Now let us define work. In thermodynamics work is said to be done by a system if the sole effect on the surroundings could be the raising of a weight. So one thing you must notice here is it is not necessary to call something as work only when a weight is raised. Weight need not be raised but the sole effect could be the raising of a weight. So this is the thermodynamic definition of work and again you can have mechanical modes of work and non mechanical modes of work transfer.

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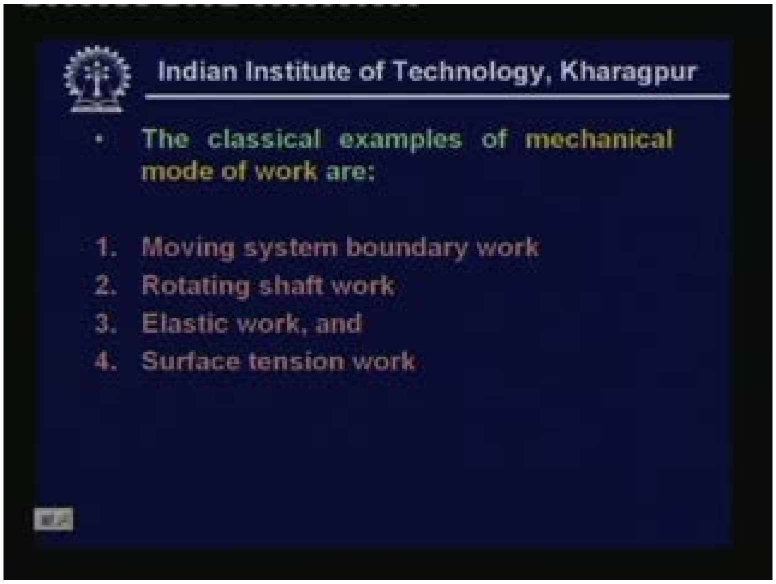

So let us look at mechanical modes of work transfer. The classical modes are moving system boundary work rotating shaft work elastic work and surface tension work. And modes of non mechanical work or electrical current flow magnetization work and chemical work had done during chemical reaction. These are some of the examples of non mechanical modes of work.

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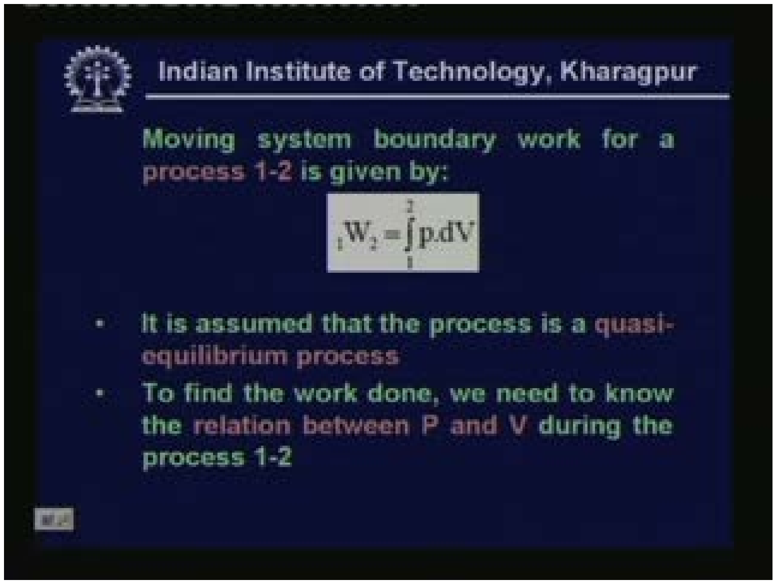

Now let us look at one of the most important modes of work. That is what is known as moving system boundary work. For example the work done at the by interface of a piston and a cylinder piston is moving and some work is being done in that process. So this is what is known as a moving system boundary work. If you are considering the gas inside the cylinder and piston as a system and for such a process the work done is given by integral p d V where p is the pressure acting and d V is the small differential volume. If you want to find out what is the work transfer during this process you have to integrate it between the initial and final states. Now this is subject to an assumption that the process is a quasi equilibrium process. Now what do you mean by a quasi equilibrium process. A quasi equilibrium process is one which moves very slowly that at every point. You know its state exactly. That means you know its properties and its path is well defined such process is called a quasi equilibrium process.

Now if you do not assume the process to be quasi equilibrium process you cannot perform the integration. Because you do not know what is the relationship between p and V during the process. So in order to perform the integration you must know the relation that means the path must be known. So this equation is for under this assumption and to find the work done. As I said we need to know the relationship between p and V during the process one to two.

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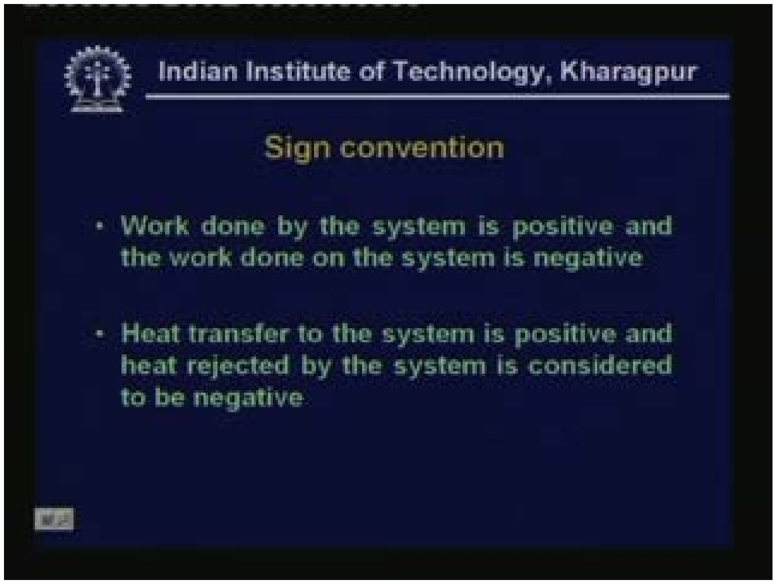

Now what is the sign convention followed generally in thermodynamics? A sign convention is like this. A work done by the system is considered to be positive and work done on the system is negative and as far as heat transfer is concerned heat transfer to the system is positive and heat rejected by the system is considered to be negative. So as far as possible we will be following the same sign convention throughout this course.

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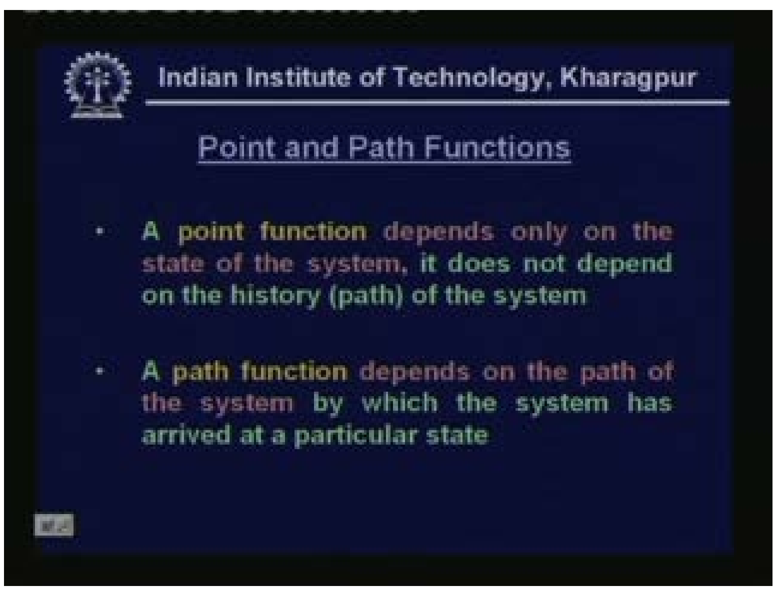

Now let us define thermodynamics functions. Thermodynamic functions can be either point function or a path function. A point function depends only on the state of the system and it does not depend on the history or path of the system. That means it depends only on the initial and final states it is independent of the path. An example of point function is temperature pressure density. These are all the examples of point functions now let us look at path function. A path function depends on the path of the system by which the system has arrived at particular state. That means in order to evaluate the path function it is not enough to know the initial and final states. You also need to know what the exact path is taken by the process. So you need to know the initial and final states as well as the path let me show the example.

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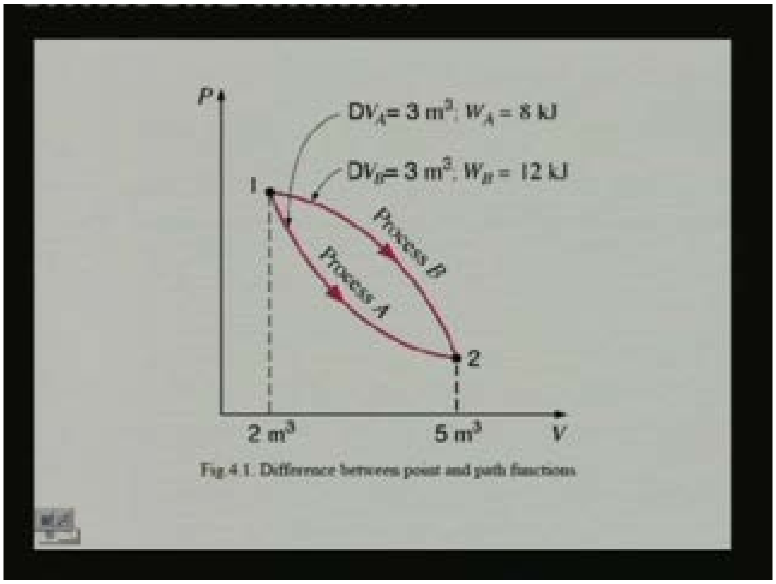

This figure here shows on P V you have volume on the x axis and pressure on the y axis. A system has under gone a process and during this process its state has change from one to two. And this change of state has occurred by two processes process A and process B. And for both the processes you will notice that the change in volume is same as three meter cube for process A as well as process B. So we, volume here is the property, since it is the property it is not dependent on path for process A or B or for any other arbitrary process. The difference in volume is same where as the work done. For example the work done in process A is eight kilo joules where as the work done in process B is twelve kilo joules. That means the work done depends not only on the initial and final states but also on the path since it is depending on the total process from one to two. So you can say that volume is a point function and work transfer or work done is a path function.

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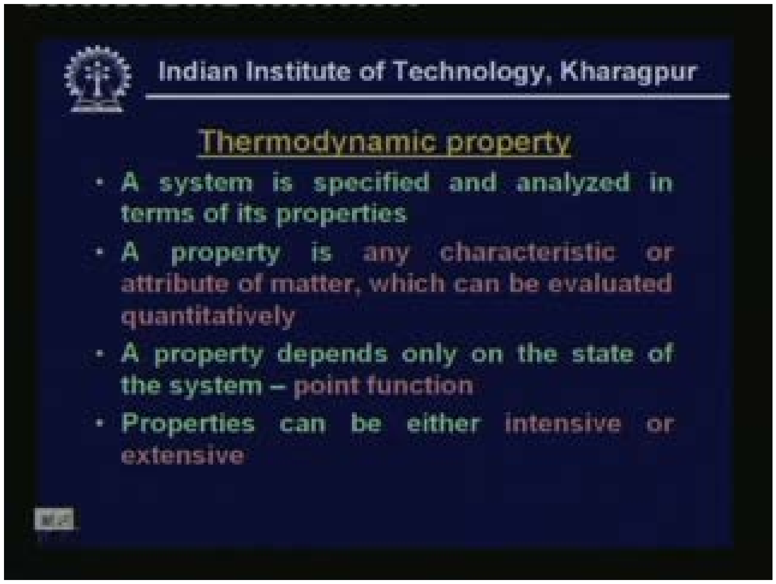

Now thermodynamic property. Let us define thermodynamic property. A system is generally specified and analyzed in terms of properties and a property is any characteristic or attribute of matter which can be evaluated quantitatively. So this is the exact definition of property and a property depends only on the state of the system. That means property has to be a point function. So all properties are point functions. And one of the peculiar characteristics of a property or point function is that their cyclic integral is always zero. So this is one of the characteristics of properties and properties can be either intensive or extensive.

An intensive property is independent of mass where as an extensive property is dependent of mass. So what are the examples of an intensive properties temperature density these are the properties which we call them as intensive properties. Because they really do not depends on the mass. For example you take a mass of one kg and let us say it has a temperature of thirty degrees. So if you divide that mass into two parts still the temperature of each part will be thirty degrees it does not become half. So the temperature is an intensive property. Other intensive properties are pressure density etcetera okay. And extensive properties are depending it on mass and one of the examples of the extensive property is mass itself or volume. For example if you half the mass then volume also becomes half. So mass volume etcetera are extensive properties and you can convert extensive properties in to intensive properties by dividing with mass. This is what you known as specific properties. For example volume is an extensive property. But specific volume which is nothing but volume per mass is an intensive property.

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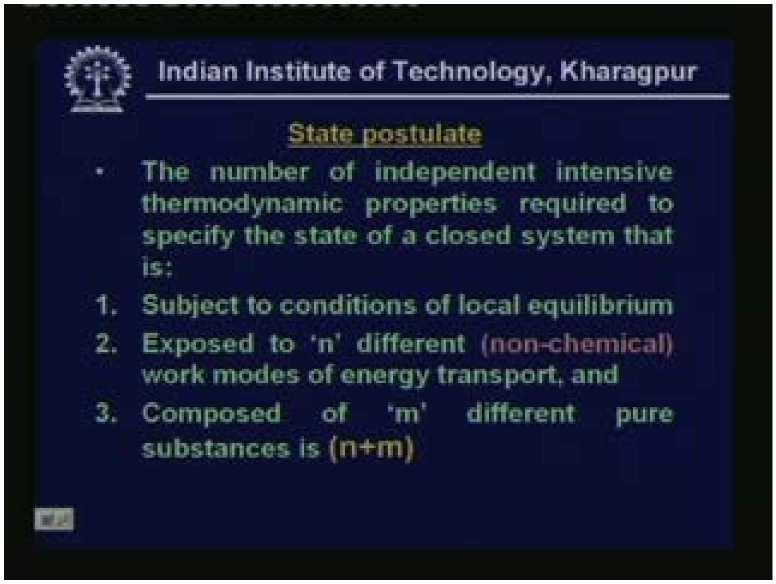

Now let us state a very important postulate called a state postulate this state postulate says that the number of independent intensive thermodynamic properties required specifying the state of a closed system. That is subject to conditions of local equilibrium exposed to n different non chemical work modes of energy transport and composed of m different pure substances is n plus m. So basically we use the state properties to find out how many degrees of freedom are required to uniquely fix the state of any system. So this is the usefulness of state postulate. Let us apply this state postulate to what is known as a simple system. Now what do you mean by simple system?

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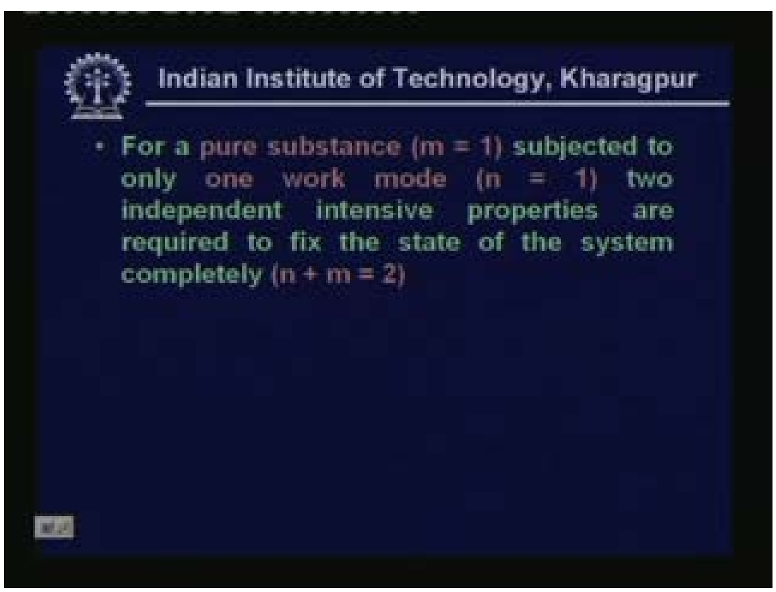

Let us take a pure substance, single pure substance. So m is equal to one and it subject to let us say only one work mode that means n is equal to one. So how many degrees of freedom are there? M plus n is two. So you have to specify two intensive properties to uniquely fix the state of this particular system. Such a system is called as simple system. And an example of a simple system is a pure gas or vapour under compression or expansion inside the piston cylinder. For example, is an example of a simple system and here the work mode is the moving system boundary work.

Now let us discuss the fundamental laws of the thermodynamics. There are basically four laws of thermodynamics. The zeroth law of thermodynamics, first law of thermodynamics, second law of thermodynamics and third law of thermodynamics. These are the most important laws of thermodynamics.

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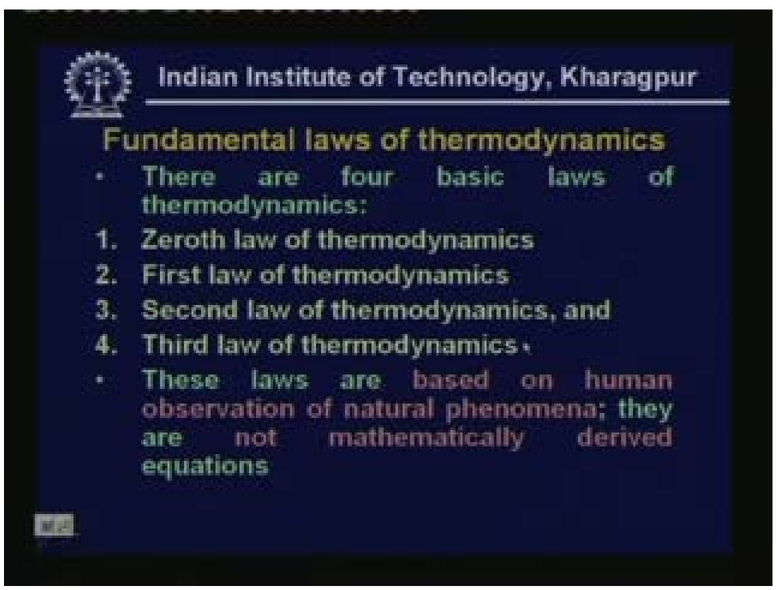

And they are not mathematically derived equations or anything they are based on our observations of natural phenomena. People have been observing the nature and the natural phenomena for centuries and based upon the observations they have arrived at these four basic laws. So they do not have any mathematical proof, then how do we know that they are right? We assume them to be right because so far nobody has observed any violations of these laws. Since you know we have not observed any violations of these laws we take them to be true and these four laws defined important thermodynamic properties.

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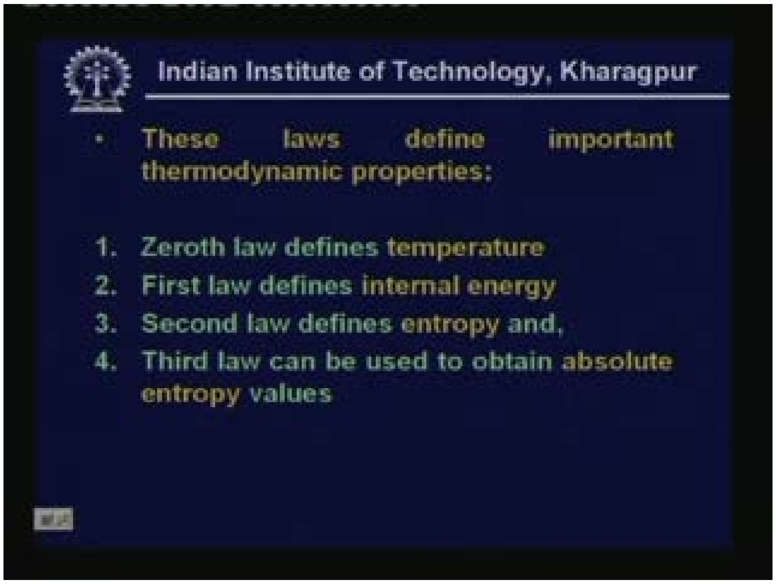

For example the zeroth law defines temperature, first law defines internal energy, second law defines entropy and third law can be used to obtain absolute entropy values. So now let us see these four laws.

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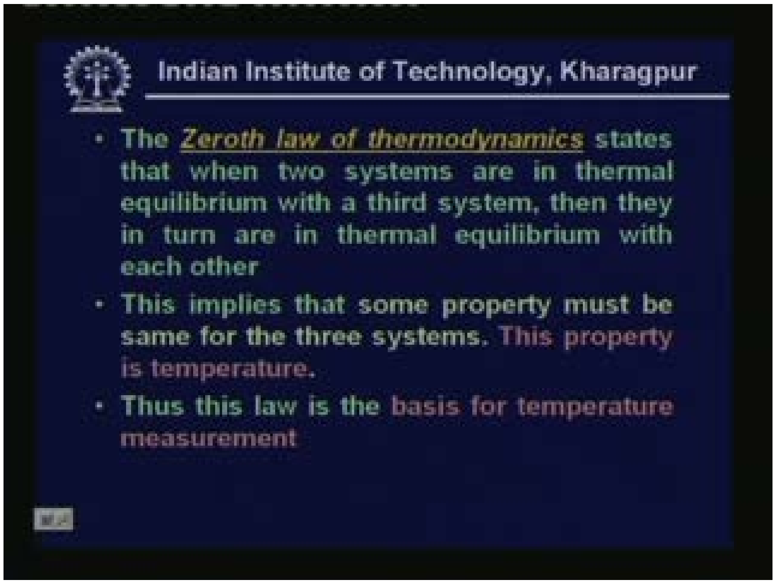

let us start with zeroth law the zeroth law of thermodynamics states that when two systems are in thermal equilibrium with a third system then they in turn are in thermal equilibrium with each other that means let us say that there are three systems a b c. A is in thermal equilibrium with b.

B is in thermal equilibrium with c that means a will be in thermal equilibrium with c so this is the in simply the zeroth law of thermodynamics.

It may look simple but it is very useful because you can draw one conclusion out of these when the three systems are in thermal equilibrium there must be at least one property which is common to all these three systems. That property is known as temperature okay. So that how the zeroth law thermodynamics by way of thermal equilibrium defines a property called temperature and this zeroth law is the basis for temperature measurement for example using thermometers etcetera.

Now let us look at the first law..

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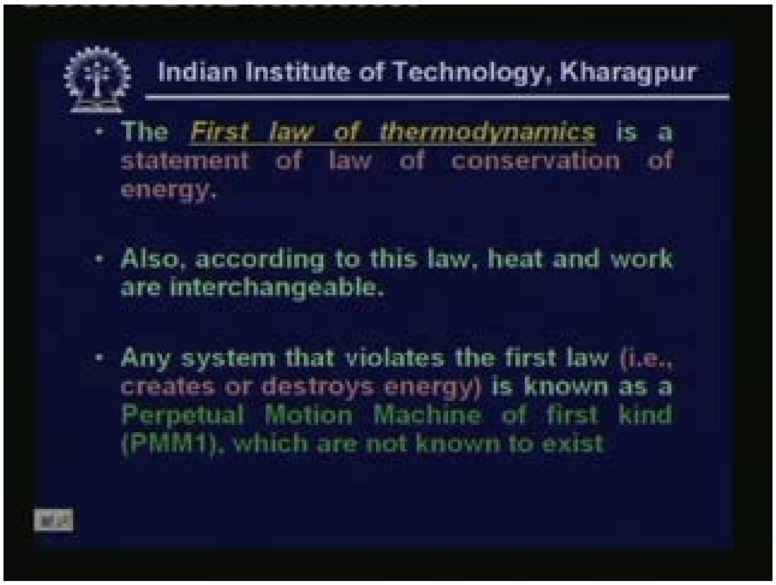

First law actually is a statement of law of conservation of energy and also according to the law heat and work are interchangeable. That means you can convert heat into work or vice a versa and any system that violates the first law that means which creates or destroys energy is known as a perpetual motion machine of first kind or PMM one. And it has been observed that PMM one does not exist that mean people have even though they have try made to several attempts nobody could create a perpetual motion machine of first kind which can create energy or which can destroy energy. Since nobody could succeed we assume that it cannot exist that means the violation of first law cannot exist so first law must be true so this is the logic. Now let us apply the first law.

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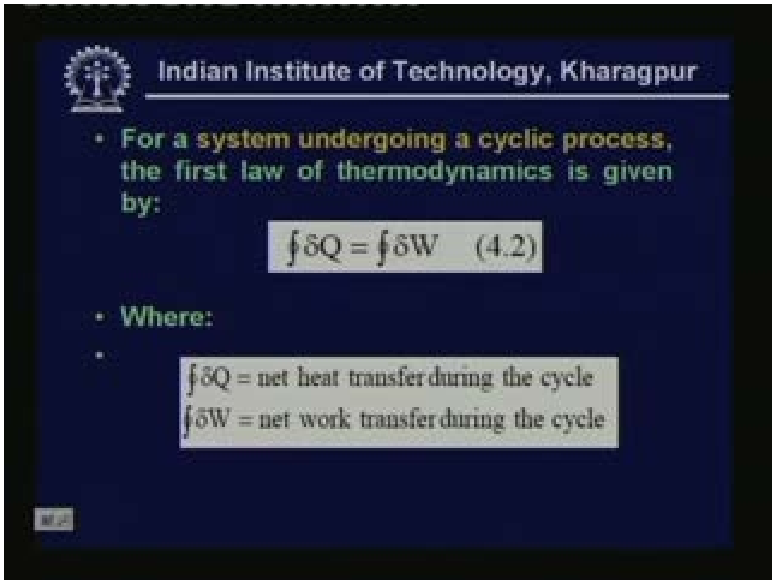

For a system undergoing a cyclic process you can write the first law of thermodynamics as cyclic integral of Do Q is equal to cyclic integral of Do W. Here what is Do Q? Do Q is the net heat transfer during the cycle and Do W is the net work transfer during the cycle.

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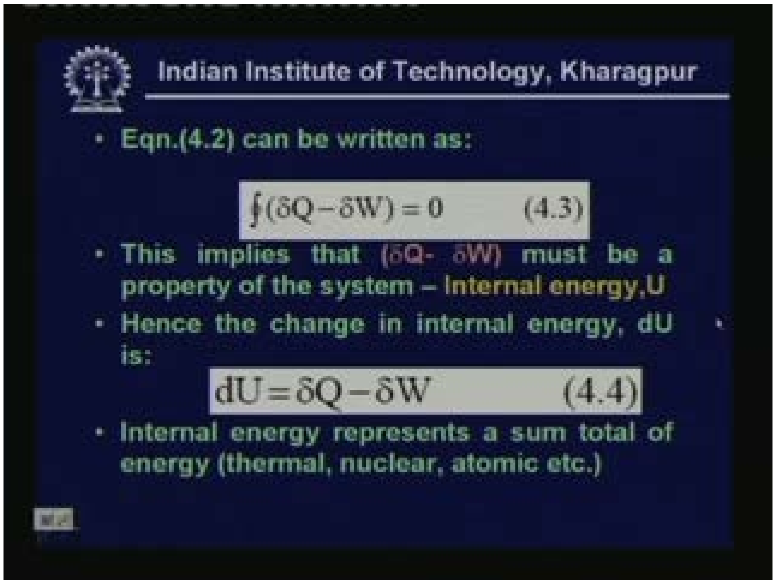

Now the same equation can be written in the form as cyclic integral of Do Q minus Do W is equal to zero. So what do we conclude out of this? This means that since the cyclic integral of Do Q minus Do W is zero that means Do Q minus Do W must be a point function. Because for all points functions the cyclic integrals are zero so Do Q minus Do W is the point function that means it must be property of the system.

So these properties known as internal energy so that how the first law defines property called internal energy. And you can write the change in the internal energy d U as Do Q minus Do W and what is physically what you mean by internal energy. Internal energy represents a sum total of all energy forms of the system. For example thermal, nuclear, atomic, vibrational, rotational etcetera.

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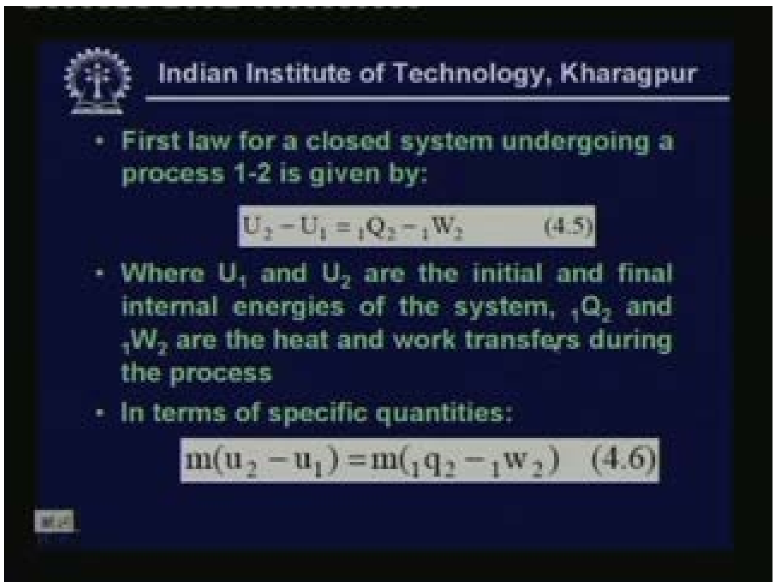

Now let us apply the first law of thermodynamics for a closed system undergoing a process one to two let us say that the system has undergone a process one to two. So what is the first law of thermodynamics for that this equation four point five actually neglects changes in kinetic and potential energy. So if you are neglecting the changes in kinetic and potential energy you can write the first law of thermodynamics as U two minus U one is equal to one Q two minus one W two where U one and U two are the internal energies of the system at the beginning and at the end of the process.

And one Q two is the net heat transfer during the process and one W two is the net work transfer during the process. So this is the first law of thermodynamics for a closed system undergoing a process the same equation can be written in terms of specific quantities. For example all that we have to do here are we had to separate out the mass. That means the total internal energy U two can be written as mass into specific internal energy u two. Similarly the total internal energy U one can be written as mass into specific internal energy u one.

So the four point five equation, four point five can be written as m into u two minus u one is equal to m into one q two minus one w two where one q two and one w two are specific heat transfer and work transfer rates.

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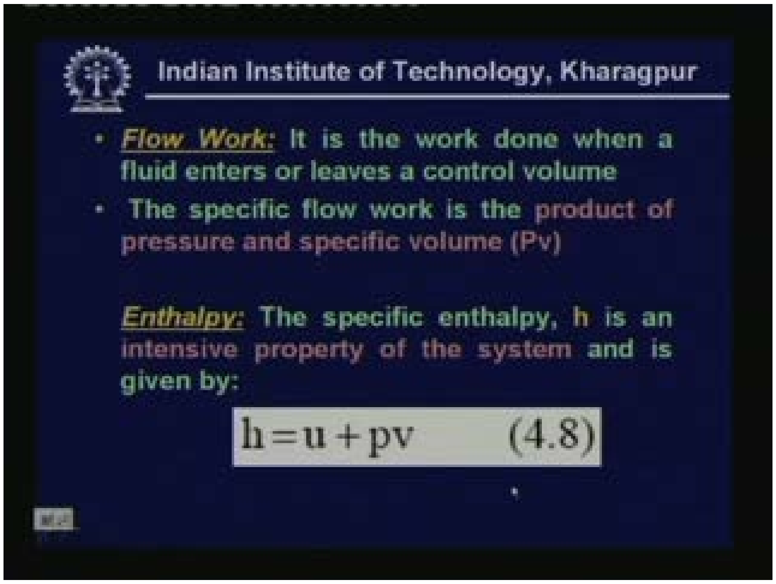

Now let us define an important parameter called flow work. So whenever a fluid enters or leaves a control volume it has to do certain work. For example when a fluid is entering into a control volume it has to do certain work again is the pressure of the control volume. There must be, there will be some fluid in the control volume which will exist some pressure. So when these fluid element from outside has to enter into the control volume it has to enter against a force because of the pressure of the control volume. So some work will be done during this process. This work is known as flow work.

Similarly when the fluid leaves the control volume it again has to do some external work against the pressure exerted by the surroundings. So again you have a flow work. So it can be shown that the flow work can be others specific flow work is given by the product of pressure and specific volume existing at a point.

Now what is the use of this flow work using this flow work and internal energy? We define a very important property called enthalpy. And the specific enthalpy a small h is an intensive property of the system. And it is given by h is equal to u plus p v that means enthalpy of a system is equal to the summation of internal energy plus flow work.

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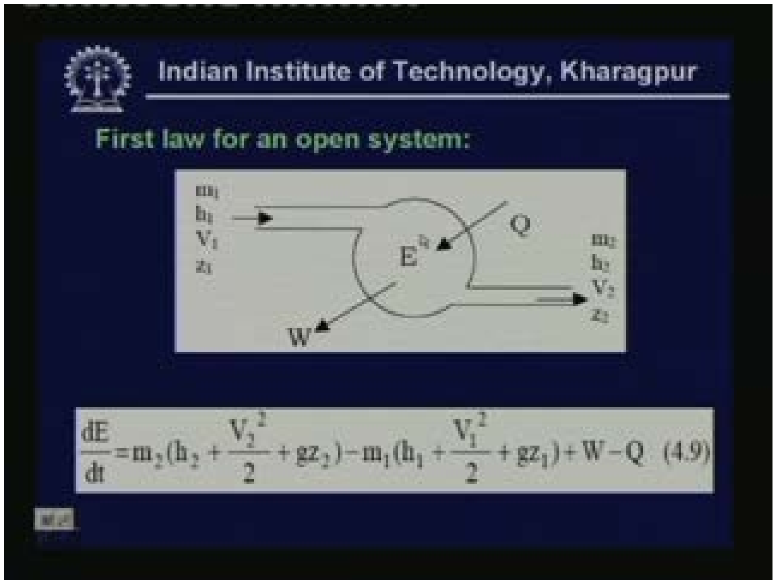

Now this figure shows the first law of thermodynamics for an open system. So here we have the system so I am showing the contro, I am sorry here we have a control volume. And I have shown the control surface or boundary of the control volume and to this control volume m one amount of mass is entering. That means a fluid is entering at a rate of m one and at that condition. That means at the inlet it has an enthalpy of h one and its velocity is V one and its height difference with reference to a datum is z one. And it is leaving the control volume at a mass flow rate of m two with an enthalpy of h two and with a velocity of v two and a datum head of z two. And E is the energy of the control volume and Q is the rate at which energy is entering into the system by means of heat transfer. And W is the rate by which work transfer is be being done that means W is the rate of work transfer and Q is the rate of heat transfer and the arrows arrow show the direction.

And if you apply the conservation of energy or first law of thermodynamics so this kind of an open system you end up with this equation. This equation on the left hand side you have d E by d t which is nothing but the rate at which the energy of the total energy of the system is changing.

So, on the right hand side you have quantities which signify the energy flux into the system net energy flux into the system for example this term. This term is the net energy flux out of the system because of the mass flow. For example if m two is zero this term will not be there so this accounts for the energy flux out of the system because of mass transfer at the outlet. Similarly this term the whole term accounts for the energy flux into the system. Because of the mass flow into the system and the W as i said is the work transfer rate and Q is the heat transfer rate. So this is the general energy equation for any open system. So here we are not assuming anything about the steady state or anything it. That means it is applicable to a steady process as well as an unsteady process. Now let us apply this to a steady process.

In steady process what happens is, the energy of the system and the mass of the system are remained constant. That means they do not vary with time that means time does not come into picture. So mass should be conserved and energy should be conserved. That means whatever mass is entering into the control volume must leave. That means m. One should be equal to m two. And since the energy total energy of the system E is constant d E by d t should be zero. Because energy is not changing its time so if you are applying these simplifications you get the first law for open system in steady state conditions.

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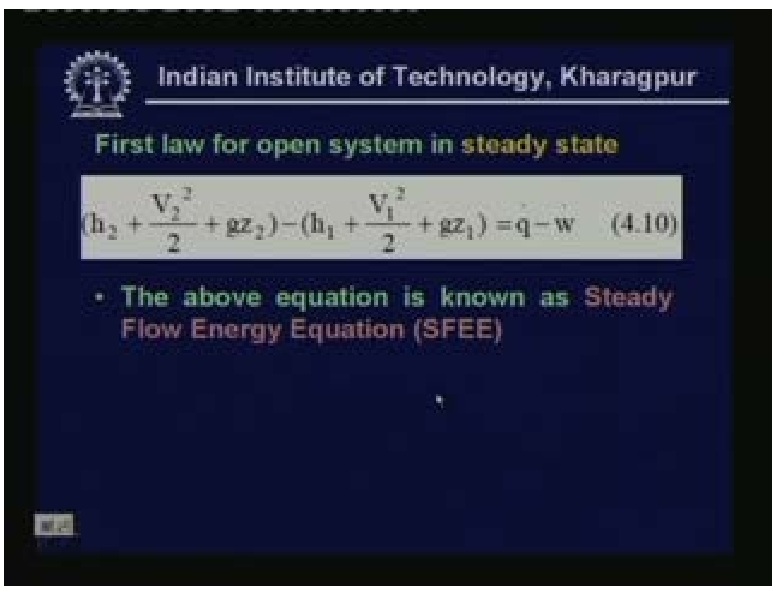

So here again you have this is the rate on the left hand side you have the net rate at which energy is entering into the system because of mass flow. And on the right hand side you have q dot and w dot q dot stands for net heat transfer rate specific heat transfer rate and w dot stands for net work transfer rate per unit mass. So this is the first law of thermodynamics for an open system in steady state and this also known as steady flow steady flow energy equation or SFEE. This is a very important equation and we will be using this equation repeatedly during this course.

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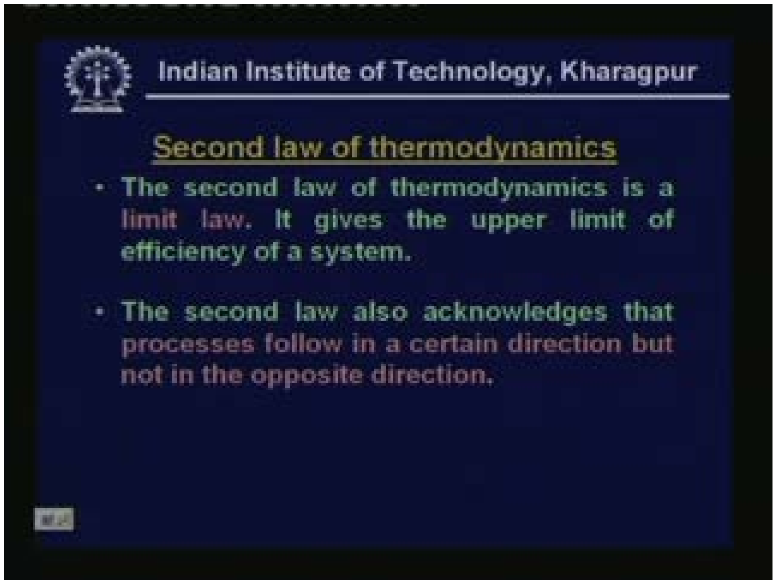

Now let us come to the second law of thermodynamics. The second law of thermodynamics is a limit law and it gives the upper limit of efficiency of the system. That means it tells you under the circumstances what is the maximum possible efficiency that you can think of. So it sets an upper limit on the possible efficiency of any device or a system. And it also decides the direction of the process. That means the second law says that certain processes takes place only in a certain direction you can they cannot take place in the reverse direction.

That means a second law sets the limit and it also sets the direction of any process. A very simple example is when you leave a cup of hot coffee this is the very common example people give for second law of thermodynamics. When you leave a cup of hot coffee on the table its temperature reduces and coffee becomes colder. So this is the spontaneous way in which the process takes place and the reverse is not possible. For example that a hot coffee cannot become hotter by taking heat from the surroundings. That means this process has only one direction okay.

It so, the arrow points in only one direction. So this is not violating. For example transfer of heat from the surroundings to the cup of coffee is not violating the first law of thermodynamics because first law of thermodynamics only accounts for the energy transfer.

So even though it is not violating the first law of thermodynamics, you know that it cannot happen. So this is the state one of the statements of second law of thermodynamics. Because it is says that a hotter body cannot became still hotter by taking heat from the surrounding.
So this is one of the directional aspects of second law and second law also defines a very important property called entropy.

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Now the second law of thermodynamics has certain statements one is what is known as Clausius' statement. So what is the Clausius' statement? It says that it is impossible to construct a device that operates in a cycle and produces no effect other that transfers of heat from a cooler body to a hotter body. What it means, is you cannot have an ideal refrigerator? For example you cannot have a refrigerator which does not take any power from the surroundings. But it is a continuously function. That means it maintains a low temperature inside without consuming any external power.
We know it is not possible. So this is in simple terms the statement of Clausius' or one of the second laws statements. Let us look at the other statement this is known as Kelvin-Planck statement of second law. This says that it is impossible to construct a device, basically an engine operating in a cycle that will produce no effect other than extraction of heat from a single reservoir and convert all of it into work. Basically what it means is you cannot have a heat

engine operating in a cyclic manner which has efficiency of hundred percent that means all cyclic heat engines will have efficiency lower that hundred percent.

How do you say that the efficiency cannot be lower than hundred percent? Because the Kelvin-Planck statement says that for a cyclic heat engine to operate the heat engine has to interact with two thermal reservoirs. That means it has to take from a high temperature reservoir and convert a part of it into work and reject the rest of it to the a low temperature reservoir. And if you are applying first law of thermodynamics to the cycle, you will find that the efficiency which is given by the work output divided by the heat input will always be less than one. Because work output will always be lower than heat input since some part of the heat has to be rejected to the surroundings. So in a nutshell the statements of second law they basically say that an ideal refrigerator cannot exist this is the statement of Clausius' and an ideal heat engine cannot exist this the statement of Kelvin-Plank.

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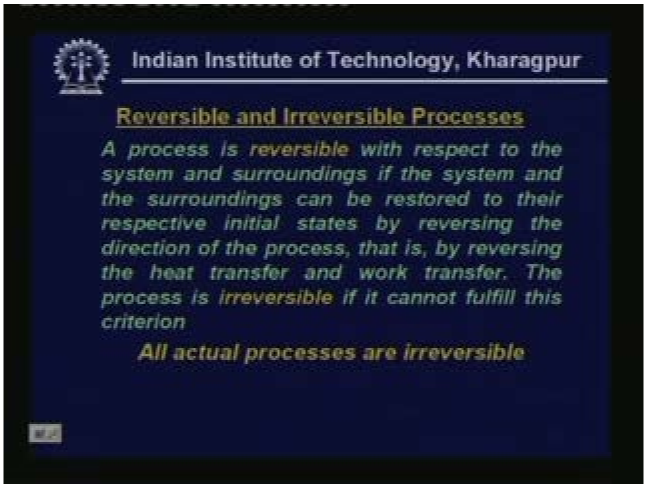

And second law of thermodynamics also introduces what is known as irreversibility and it is distinguishes between reversible and irreversible processes. So let us define reversible and irreversible process.

A process is said to be reversible with respect to the system and surroundings. If the system and the surroundings can be restored to their respective initial states by reversing the direction of the process that means by reversing the heat transfer and work transfer. The process is irreversible if it cannot fulfill these criteria. That means let us say that a system has undergone the process one to two. And now the process one to two can be said to be reversible if you retrace the path. That means to travel from two to one and arrive at one then there will not be any change either in the system or in the surroundings. Of course there will not be change in the system because you are coming back to same initial state. But there should not be any change in the surroundings also.

Even though there is no change in the system but there are change in the surroundings. Then the process is no longer reversible. That kind of a process is called as irreversible process.

And you find that all actual processes are irreversible processes now what causes the irreversibility by processes or irreversible.

There are several causes. First cause is friction you cannot avoid friction whenever you have a sliding rotating motion. So and the friction is what leads to irreversibility how does it lead to irreversibility. For example you take the mechanical, this thing a piston is moving in a cylinder and there will be friction between the piston and the cylinder. So during this process what is happening? Some mechanical energy is converted into heat because of friction. So this is the direction of the process. Now if you want to reverse it is not possible to convert all the heat into work without making any change in the system or surroundings. That means whatever the work you have lost it is lost irreversibly you cannot get back everything without making any changes in the system or surroundings.

So friction is one of the major reasons for irreversibility. What are the other reasons for irreversibility heat transfer through a finite temperature difference? We will see later that for any heat transfer to take place a finite temperature difference is required. That means heat will always flow from a hotter body to a colder body. And you cannot simply reverse the process. That means, what are heat has flown from hotter body to colder body cannot flow back without making any changes in the system or surroundings. In fact that will be a violation of Clausius' statement because Clausius' statement says that if you want to transfer heat from a lower temperature body to a higher temperature body in a cyclic manner some external work has to be done.

That means some change must take place in the surroundings. So heat transfer through a initial temperature difference an irreversible process. And another example of irreversible process is mixing, for example you are mixing two different process gases I am mixing nitrogen gas with oxygen gas then it is a highly irreversible process because I cannot simply separate them out just like that without making any change in the system or surroundings. So this is another example of irreversibility like that there are many other causes for irreversibility resistance when current flows through a conductor like that okay. Since all these cannot be avoided in natural practice all actual process are irreversible processes.

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Now let us define a heat engine. This is very important concept in thermodynamics.

A heat engine is a device that operates in a thermodynamic cycle and does a certain amount of net positive work through the transfer of heat from a high temperature body to a low temperature body. So let us look at it carefully so basically a heat engine is a thermodynamic cycle and what does it do, it does a certain amount of net positive work. That means it produces certain amount of net power work. And how does it produce? It produces by a transfer of heat from a high temperature body to a low temperature body. This is perfectly in accordance with a second law of thermodynamics as per the Kelvin-Planks statement.

What is the example of the heat engine a steam power plant is an example of a steam engine heat engine?

In a steam power plant typically water is used as a working fluid. So the working fluid water will be flowing throughout the steam power plant in a cyclic manner and during this cycle it takes heat from the boiler at a high temperature and then it converts the parts of it into work in the turbine. And rejects its remaining part in the condenser and again by it gets pumped and come comes back to the original state. So this is one example of a thermodynamic cycle. Now the other engines like i c engine for example internal combustion engine in a strict sense it is not a thermodynamic cycle because the working fluid doesn't come back to its original state.

So it is not a thermodynamic cycle it is purely a mechanical cycle because only the mechanical parts undergo cycle not the fluid. Because you take air and fuel and what you get out of the engine is not air and fuel but mixture of combustion gases. So an i c engine in strict thermodynamic sense is not a thermodynamic heat engine now.

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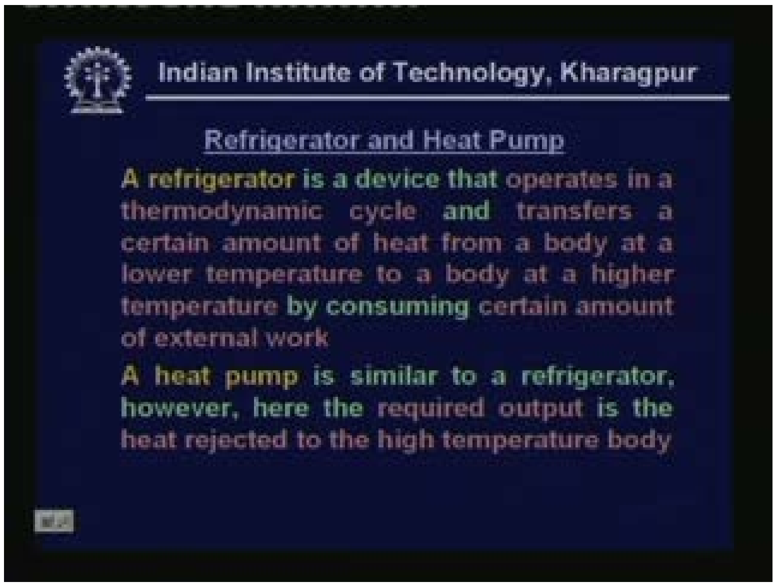

Let us look at refrigerators and heat pumps a refrigerator is a device that operates in a thermodynamic cycle and transfers a certain amount of heat from a body at a lower temperature to a body at a higher temperature by consuming certain amount of external work. I am sure that all of you know what a refrigerator is and why do we need a refrigerator. A refrigerator is used for storing food products. As I mentioned in the last class and a refrigeration system can also be used for providing cool a cold and dry air for summer air conditioning.

So basically a refrigeration system provides cooling. So how does it produce cooling what happens inside a refrigerator?

Inside a refrigerator what it does is, it takes heat from a low temperature reservoir and it pumps it to a high temperature reservoir. Now according to the Clausius' statement this cannot happen on its own. So some external work has to be done. So a typical refrigerator consumes external energy and pumps heat from a low temperature body to a high temperature body. And the useful output that we are looking from a refrigeration system is cooling effect now a heat pump is a hardware device is exactly like a refrigerator. But what is the difference between the refrigerator and heat pump is in a refrigerator we need a cooling effect whereas in a heat pump we want a heating effect.

That means in a heat pump we are not interested in the heat extracted and the heat sink. We are more interested in the heat rejected at the high temperature level. So typically if you look at the practical application point of view a refrigeration system can be used for summer air conditioning where as the heat pump heat system can be used as for winter air conditioning.

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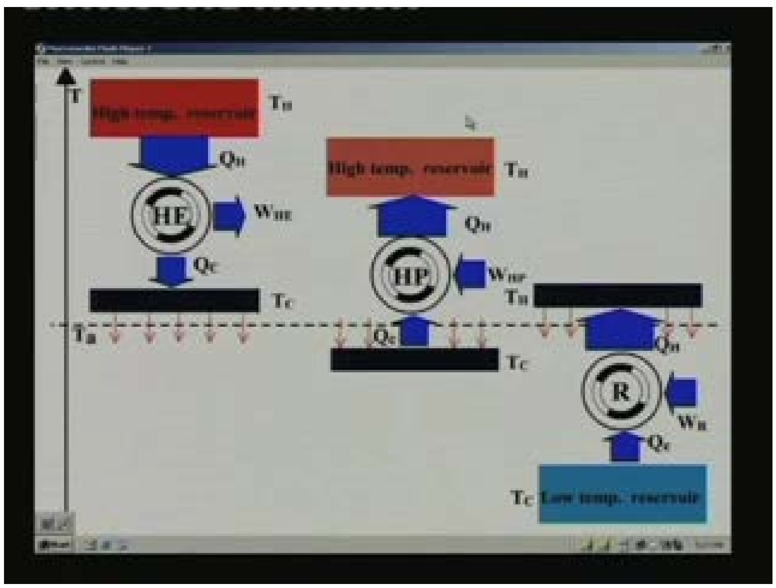

Now let me show the, let us look at this animation here, we have a heat engine, a heat pump and a refrigerator. Here H E stands for the heat engine and as I explained just now what is it doing. It is taking heat Q H from a high temperature rigid wire which is at a temperature T H and its converting a part of it into work W H E and it is rejecting rest of it. That means Q C to a low temperature heat reservoir which is at a temperature T C

In a typical steam power plant the high temperature reservoir is the boiler of the power plant and the low temperature reservoir is the condenser. Ultimately the heat from the condenser is rejected to the ambient. So here the T A shows the ambient temperature. So the condenser temperature should be slightly higher than the ambient temperature. So heat can be ultimately lost to the ambient. So it is a cyclic device that what the rotation shows and if you apply the first law of thermodynamics to the heat engine what you will find.

You will find that W H E should be equal to Q H minus Q C and if you define the efficiency as the output divided by the input then it is equal to W H E divided by Q H which is equal to Q H minus Q C by Q H since Q C is always greater than zero Q H minus Q C by Q H will be less than one.

That means the efficiency will always be less than one now let us look at the heat pump so what is the heat pump doing heat pump is basically pumping heat from a low temperature reservoir which is kept at temperature T C by consume ex by consuming external energy W H P. And it is rejecting this heat to a high temperature reservoir T H so it is taking heat from reservoir at a lower temperature P C and throwing it to a reservoir which is at a higher temperature T H.

This vertical axis actually shows the temperature that means the temperature is increasing in a vertical direction. Okay.

Again if you can apply the first law of thermodynamics to the heat pump you will find that you can define the efficiency of a heat pump as your useful output divided by the input and for a heat pump the useful output is the heat rejected to the high temperature reservoir that means Q H. And what is the heat input, what is the energy input system input to the system is in that form of work?

So the efficiency of the heat engine is nothing but Q H divided by W H P and according to Clausius' statement W H P has to be greater than zero it cannot be zero. So it has to be greater than zero means the efficiency of a heat engine cannot be infinite. Okay. It has to consume certain finite amount of energy. Now let us look at refrigerator. Refrigerator what is it doing? It is also doing exactly the same thing as heat pump. only difference is in the temperature levels. For example refrigerator low temperature reservoir is much lower than the ambient because we want to keep certain products or processes at low temperature. That is why we need a very low temperature T C.

So this refrigeration system, a cyclic refrigeration system, what it does is it takes heat Q C from the low temperature reservoir consume some external energy W R and rejects this Q C plus W R to a high temperature sink which is a T H. And ultimately this will be rejected to the ambient. For example in typical refrigerator the refrigerated space inside the refrigerator is your low temperature reservoir and the condenser which is kept outside is your high temperature reservoir.

So you know that inside it will be cold and outside that is the condenser will be hot then ultimately heat from the condenser will be rejected to the surroundings. So in this animation actually shows the temperature levels. For example in a heat engine the high temperature T H will be much larger than the T H of the heat pump which is larger than the T H of a refrigerator. Similarly the T C of the refrigerator which will be much colder than the T C of heat pump which will be colder than the T C of a heat engine.

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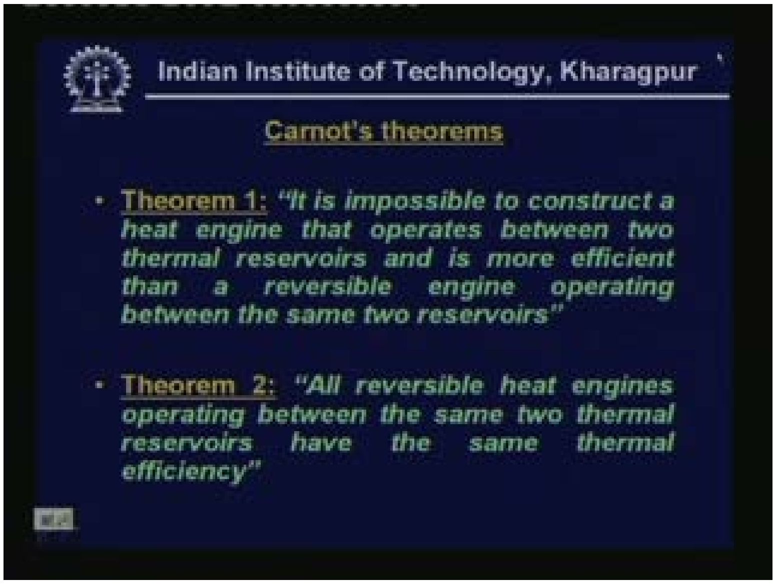

Now let us look at important theorems called Carnot's theorems. The Carnot has, he is a French scientist a very famous and his one of the founding fathers of the subject of thermodynamics and he has studied the heat engines extensively and he has put forward two propositions or two theorems. What is the theorem? One theorem says that it is impossible to construct a heat engine that operates between two thermal reservoirs and is more efficient than a reversible engine operating between the same two reservoirs. In simple words let us say that we have two thermal reservoirs. One high temperature reservoir and a low temperature reservoir and between these two reservoirs just now I have shown you the heat engine two heat engines are operating let us say.

And one heat engine is reversible and the other heat engine is irreversible. Now what is mean by reversible heat engine? An engine is said to be reversible if all the processes are completely reversible. Any cyclic process will have several individual processes and for the complete cycle to be reversible. All these individual processes have got to be reversible. So a reversible heat engine consists of all reversible processes and again this reversibility should be both internally reversible as well as externally reversible. So such a heat engine is called as a reversible heat engine. So between two temperature reservoirs we have one reversible heat engine and one irreversible heat engine.

The Carnot's first theorem says that the efficiency of an irreversible heat engine will always will lower than the efficiency of a reversible heat engine. That means the maximum efficiency is possible only with a reversible heat engine operating between the same two temperature levels.

So this is the first theorem of Carnot. Now let us look at the second theorem of Carnot. Second theorem of Carnot says that all reversible heat engines operating between the same two thermal reservoirs have the same thermal efficiency.

That means, I will again, let us take the example of two thermal reservoirs and let us say that n numbers of reversible heat engines are operating between these two reservoirs. And the Carnot's second theorem says that all these n reversible heat engines will have exactly the same efficiency. That means the efficiency of a reversible heat engine is not the function of how the cycle is constructed or anything as long as it is reversible. But it is a function of only the temperatures of the reservoirs. That means it is reversible heat engine efficiency depends upon the high temperature reservoir. It is the temperature of the high temperature reservoir and the temperature of the low temperature reservoir. It is only the function of these two temperatures and nothing else.

This is the very important theorem and we will see what the consequence of this is. So these two theorems whatever have been stated now they are for the heat engines. You can derive or you can formulate Carnot's theorems for refrigerators as well as heat pumps exactly on the similar lines.

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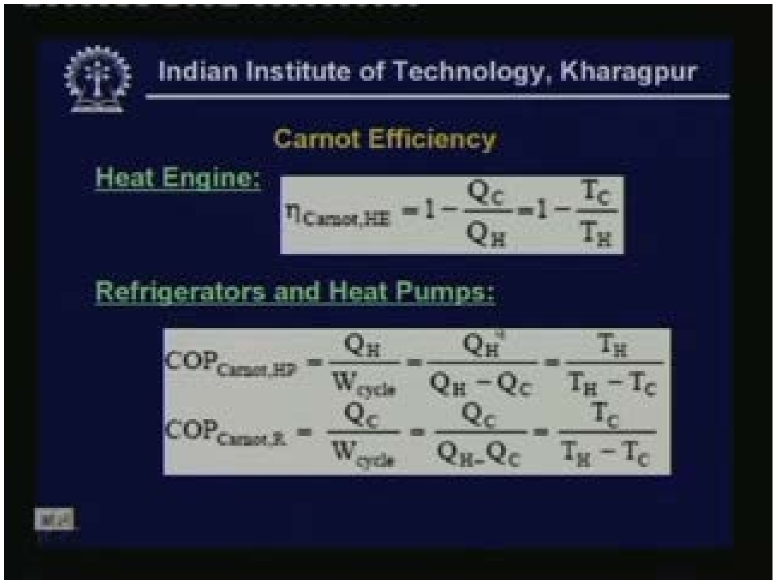

Now let us see what the consequence of Carnot efficiency for a heat engine is. The Carnot efficiency is the maximum possible efficiency. That means the efficiency of the reversible heat engine operating between the two temperatures reservoirs is given by the Carnot efficiency and Carnot. And if this is equal to one minus T C by T H where T C is the low temperature heat sink temperature and T H is the heat source temperature.

That means the maximum possible efficiency of a heat engine operating between heat source at temperature T H and heat sink at temperature T C is given by one minus T C by T H. Now what conclusions you can derive out of these. For example you can conclude that the efficiency increases as the T H increases. That means higher the temperature of the heat sources you get higher efficiency. And another conclusion is that the efficiency increases as T C is reduced. That means the lower the temperature of the heat sink higher will be the efficiency. And what is the maximum possible efficiency if you have a heat source which has the temperature of infinity and then you get maximum possible efficiency of one or if you have a heat sink whose temperature is zero Kelvin.

Then again you get, you can get an efficiency of one. But we know that you do not have a heat source whose temperature is infinity nor do you have a heat sink whose temperature is zero degrees Kelvin absolute. So since these two are not possible that means the efficiency of heat engine will always will be less than one. Efficiency of a reversible heat engine itself will be less than one. That means all actual heat engines will be less than must less than one. So this is the consequences of the Carnot's theorem. And in deriving this equation we had to apply the first law of thermodynamics. Because all heat engines have to obey the second law of thermodynamics.

It does not mean that they can violate first law of thermodynamics. So for any process or for any cycle to be feasible, it has to obey both first law of thermodynamics as well second law of thermodynamics.

And the efficiency here is derived by applying both these laws. Now let us look at what is the maximum possible efficiency for a refrigerator and heat pump operating between two temperature reservoirs T H and T C. In case of refrigerators and heat pumps normally we do not use the term efficiency. We use the term called coefficient of performance. In short it is COP C stands for coefficient O stands for of and P stands for performance. So the efficiency of any refrigerator or heat system is derived is defined in terms of COP's. Now COP of Carnot heat pump that means the COP of a reversible heat pump operating between two temperatures T H and T C is given by T H divided by T H minus T C. And the efficiency of a Carnot refrigerator is given by T C divided by T H minus T C. And again these are derived by applying both first law as well as second law of thermodynamics and you can see here that the COP is defined as the required output divided by the effort that you are putting in. For example in case of heat pump the required output is heating output Q H and the effort is work input to the system. So the COP is defined as Q H divided by W and in case of refrigerator the required output is cooling output. So we are writing it as Q C. And the required effort is work input. So we are writing COP as Q C by W and it is very easy to show that the COP of a heat pump will be equal to COP of a refrigerator plus one from these equations.

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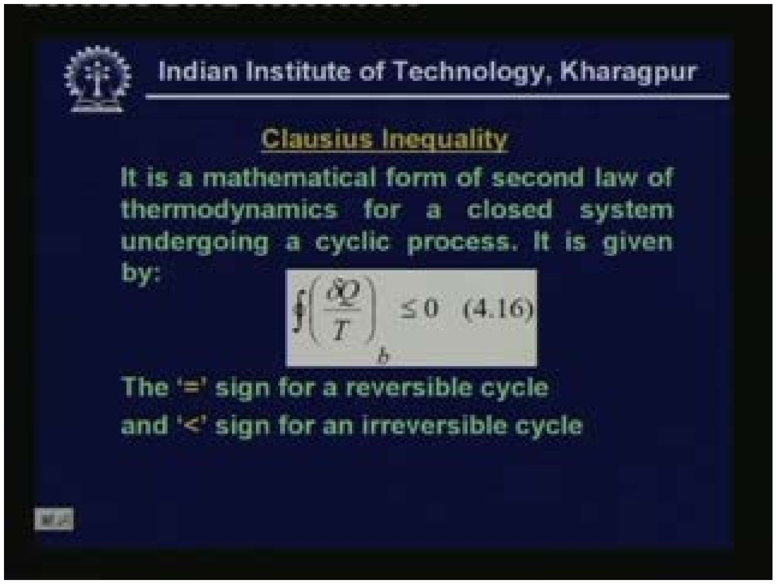

Now let us define a very important inequality called as Clausius inequality. This is in fact a mathematical form of second law of thermodynamics for a closed system undergoing a cyclic process. This is proposed by Clausius and it is known as Clausius inequality and it is simply given by the cyclic integral of Do Q by T is less than or equal to zero. So this is what is known as Clausius inequality applies to a closed system undergoing a cyclic process. Now what is Do Q? Do Q is the heat transfer rate at the boundary. The subscript b stands for the boundary. That means heat interaction is taking place near the boundary and T is the temperature at which heat transfer is taking place. So Do Q is the heat transfer of the boundary and T is the temperature at which heat transfer is taking place.

So the Clausius inequality says that if you integrate this quantity Do Q by T is over the boundary for the entire cycle its value will always be less than or equal to zero. And this less than sign applies for irreversible cycles and equal to sign applies for reversible cycles. That means for a reversible cycle the cyclic integral of Do Q by T will always be equal to zero. Whereas for a irreversible cycle the cyclic integral of Do Q by T always be less than zero Clausius. Based on this he has arrived at a very important conclusion.

I have mentioned that one of the characteristics of point functions is that their cyclic integral is zero. So according to the Clausius inequality the cyclic integral of Do Q by T for a reversible process is zero. That means Do Q by T for a reversible process must be a point function that means it must be a property of a system and this property is known as entropy. And the Clausius inequality can also be used for deriving the efficiencies of the Carnot heat pump for heat engine or refrigerator.

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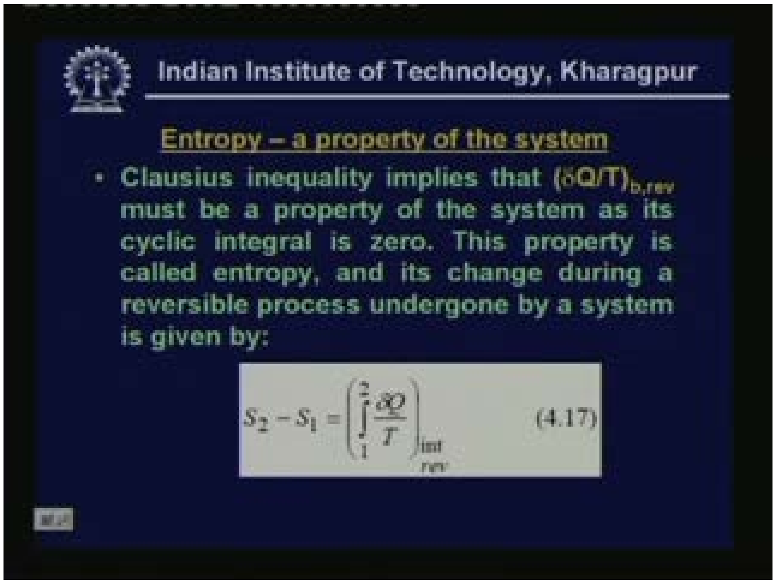

So this is the summary of what are I have been telling you entropy Clausius has derived this property based on this inequality and this property is called as entropy and the entropic change of a system during a process. For example if the process is reversible is given by this equation that means S two minus S one is equal to two integral of Do Q by T and internal reversible means that this processes has got to be internally reversible. So if you want to find out the entropic change during an internally reversible process you have to integrate the quantity Do Q by T from the initial state to the final state.

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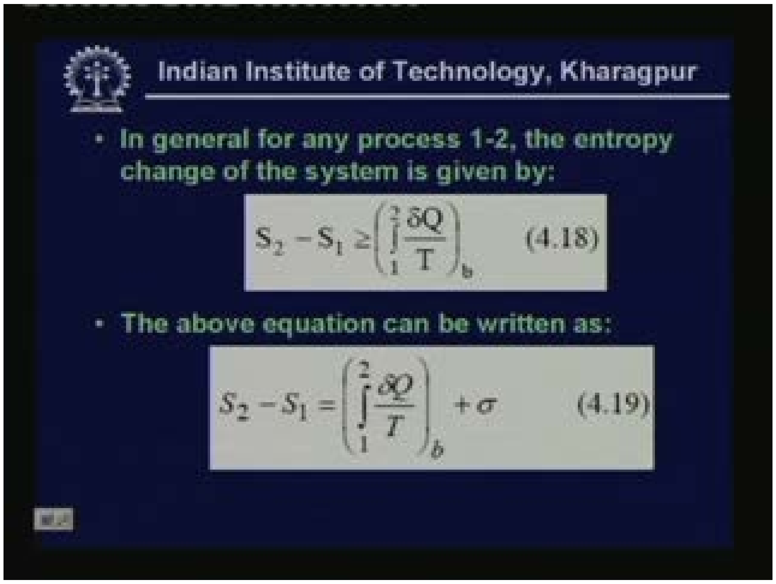

And in general for any process that means for reversible as well as irreversible processes you can write what is known as an entropy balance equation. For example equation four point one eight where the entropic change S two minus S one will always be greater than or equal to cyclic integral of Do Q by T evaluate evaluated at the boundary. And again this greater than sign holds good for an irreversible process and equal to sign is good for a reversible process. So this is again follow up of whatever we have concluded in the earlier slide that means for a reversible process S two minus S one is a cyclic integral of Do Q by T. Whereas for a irreversible process entropic change will always be greater than the cyclic integral I mean integral of Do Q by T for the process one to two.

And this above equation that means four point one eight can also be written in this form that means you can also write this as you eliminate the greater than sign and write this as S two minus S one is equal to integral Do Q by T from one to two plus sigma. Okay. And sigma is what is known as entropy production parameter and for a reversible process if you compare the earlier equation with this you know that for a reversible process sigma has got to be zero. So for a reversible process S two minus S one is equal to integral Do Q by T where as for an irreversible process S two minus S one has got to be greater than Do Q by integral of Do Q by T that means sigma has to be greater than zero. So sigma can be either greater than or equal to zero and it can never be less than zero. Okay.

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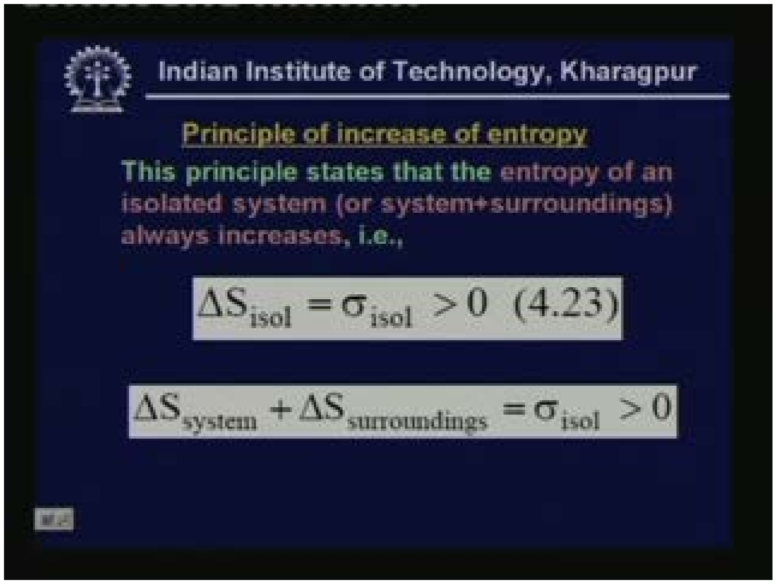

Now this gives a very important conclusion or you can derive an important principle known as principle of increase of entropy. These principles states that the entropy of an isolated system always increase. So that is what is shown in the equation four point two three that means entropy of an isolated system will never reduce. And it will always increase so this actually defines the direction of the process which an isolated system can undergo. And what is the example of an isolated system if you take the system plus surroundings itself as a combined system then it becomes an isolated system. That means an isolated system can be an isolated system in itself or a system plus surroundings.

So if you are writing that entropy balance equation for a system plus surroundings then also you get the same conclusion. That means entropic change of the system plus entropic change of surrounding will be equal to sigma of combined system. And which will always be greater than zero this is a consequence again of the fact that in actual practice all the processes are irreversible processes you cannot have a completely reversible processes. So all these by irreversible processes generate entropy so one thing I would like to point out here is that with the quantity energy which was defined by the first law of thermodynamics is a conserved quantity.

That means energy can be neither destroyed nor created. So energy of an isolated system for example if you take an isolated system its energy will always remain constant. Because an isolated system can neither take energy nor give energy because there do not be any energy interaction. That means its energy should always remain constant. So this is the first law of thermodynamics for an isolated system. Whereas the second law of thermodynamics for an isolated system that means which says that entropy of the system should always increases. That means entropy is not conserved quantity entropy of an isolated system always increases this does not mean that entropy of a system has to increase. You must make a distinction between system and isolated system. For example if you look at the system plus surroundings the entropy of a system can reduce by if it is rejecting heat to the surroundings let us say then its entropy reduces. At the same time the entropy of the surrounding will increase because it is taking the heat from the system so the system is losing entropy and the surrounding is gaining entropy. But the sum total of the entropic change that means entropy reduction in the system plus entropy increase in the surroundings should always be greater than zero.

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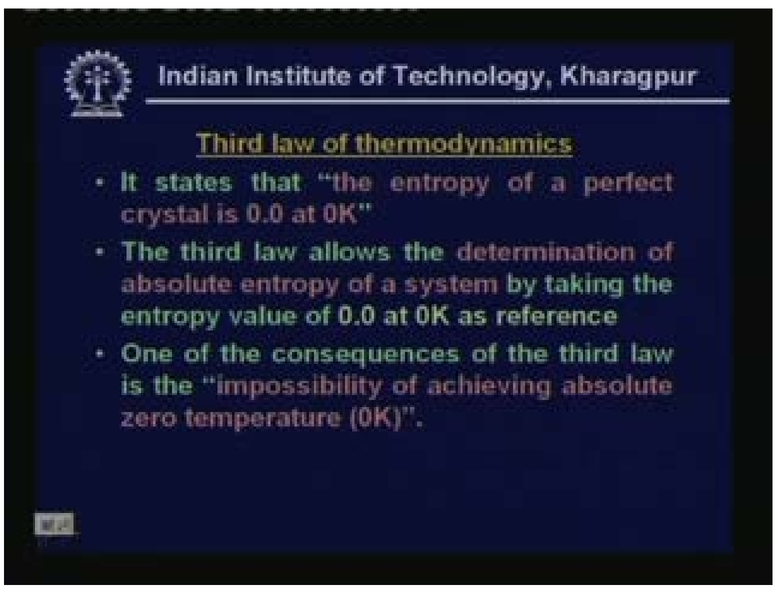

This is the principle of increase of entropy now let me quickly define the third law of thermodynamics. The third law of thermodynamics states that the entropy of a perfect crystal is zero at zero degree Kelvin that means at absolute zero temperature a perfect crystal will have zero entropy. This actually brings out another aspect of second law of thermodynamics namely that of order and disorder. We will see you might have read in thermodynamics that entropy is also a measure of disorder a highly disorder system will have higher entropy compared to a highly ordered system. So the entropy is an indication of a disorder and at zero degree centigrade or zero degree absolute theoretically all the motions seizes so there won't be any disorder due to motion. And for a per perfect crystal even the arrangement will also be perfect so a perfect crystal is a perfect example of order.

Since it is perfectly in order its entropy will be zero so this is a consequence of third law of thermodynamics. Now of course at zero degree Kelvin if you achieve that which is not possible you will find that other materials will have nonzero entropies that means positive entropies.

Now what is the use of the third law of thermodynamics? The third law of thermodynamics can be used for determining the absolute entropy of a system by taking the entropy value of zero at zero degree Kelvin as the reference. So this is the major use of third law of thermodynamics and it can also be shown that by using the air consequence of the third law thermodynamics is that it is not possible to achieve absolute zero degree centigrade. I mean sorry absolute zero degree Kelvin zero Kelvin is not possible to achieve this is one of the consequences of the third law of thermodynamics.

I forget to mention one thing here I have given the expressions for Carnot heat engine efficiency and Carnot refrigerator efficiency and Carnot heat pump efficiency and we have seen that all these are functions of temperature and that units of temperature there must be absolute. That means you must use absolute temperatures scale there to obtain the efficiencies of Carnot heat engine refrigerator and heat pump. You cannot use the degree centigrade or degree Fahrenheit you must keep this in mind. So this by completes this portion completes half of the thermodynamics and we have to look at how to evaluate the thermodynamic properties and what are the different thermodynamic processes how do we evaluate the thermodynamic process etcetera. And these portions we will discuss in the next class.

Thank you.