Aircraft Propulsion
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Lecture 01
Basic Thermodynamics: Review

Welcome to the class. This is the first class what we are going to see in this class is all about the basic thermodynamics basically, it is all about a review of the thermodynamics. Let us see first the terminologies which are very basic in the course of thermodynamics.

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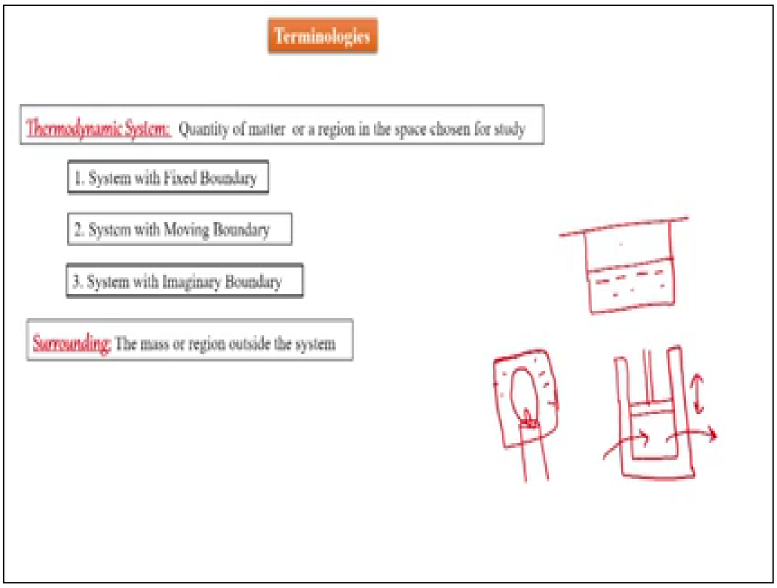

First is we have to define what do we mean by thermodynamics system. Thermodynamic system is defined as quantity of matter or a region in the space chosen for study. So we basically are interested in specific region or we are interested in specific mass amount of mass about which we are going to have interest for which we are going to study. So, that mass or that region is called as thermodynamic system.

So then we have few types of systems what we are going to define and based upon the boundary of the system, system with fixed boundary. So let us consider a point that we have a pot in which we have water and we have kept a lid in the pot. So this is a system which has air plus water and this is fixed with the boundary surface this is called as the system with fixed boundary.

Then we will have system with moving boundary. So, in case of system with moving boundary. We can consider a piston cylinder arrangement where are we have a cylinder and that cylinder is fitted with a piston inside. And if we can supply heat or we can take away heat from the gas which is placed inside then accordingly Piston can move up or down. In such case the boundary of the system is moving.

So this is also system where we are focused on certain mass inside the piston and cylinder arrangement where one of the boundaries is moving. So, this is example of system with moving boundary. We might encounter a situation where we will have a system and then we have to define boundaries for the system. As an example, we can case take an example of candle where we have Flame of the candle and then we define this region as our system if we define this region as our system that we are defining this as our region of interest for thermodynamics studies.

Hence such system which does not have fixed boundaries and where user defined the boundaries with their we can see it as these are the imaginary boundaries and they are not physical boundaries of the system. Then by defining the boundaries of the system we are defining certain region or by focusing upon certain mass. We are focusing certain mass of the system. However, then it comes that we are excluding certain mass and we are excluding certain volume.

So, the volume or mass which is not considered which remains outside the system is called as surrounding. So, everything outside the system is called as surrounding. So now these two are the basic things related to thermodynamics. Having said this now we will see what are the different types of the system. So, first type of the system is closed system. Now, let us see the types of thermodynamic systems.

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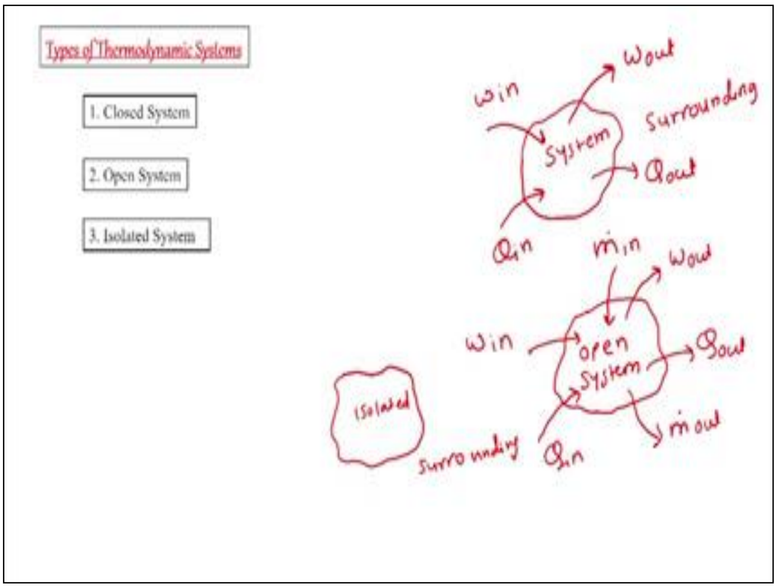

So first is closed system. In case of our closed system suppose this is our system of our interest and then and then this is surrounding in case of closed system we can have certain heat going out of the system certain heat coming into the system. We might have W out of the system. We might have W in to the system but we will not have mass entering into the system. The system which can have interaction with the surrounding in the form of heat and work only is a definition of closed system.

Then we will have open system. In case of open system again we will consider an open system and in case of open system, we will have certain work which is delivered by the system. There might be certain work input to the system. There might be also heat input to the system and there might be heat output from system or system might reject certain amount of heat but apart from that there might be certain mass m dot entering into the system. There might be certain m dot or mass leaving out of the system.

In such case where system can have interaction with the surrounding from the perspective of mass heat and work is called as open system. And we have many such examples in engineering which are open systems, which have something like heat exchangers. We have we are compressor, pumps, turbines. These are the examples of open system. In case of closed system, we have piston and cylinder arrangement which is not having any valves or rather if at all any valves they are closed.

And such system would be example of closed system. Then we have an isolated system in the isolated system. We have only system and surrounding and there is no work interaction. There is no heat interaction and then there is no mass interaction between the system and surrounding in such case system is called as isolated system. The best example for isolated system is thermos flask. So these are basically the types of thermodynamics systems.

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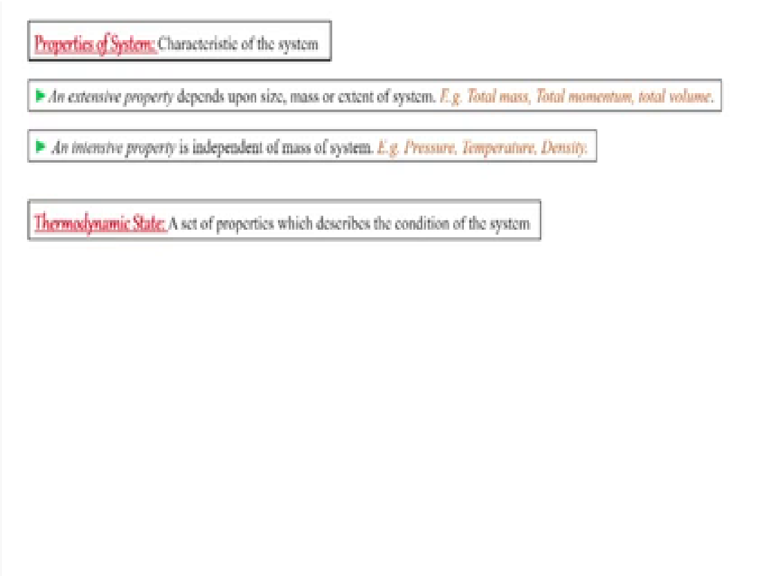

Then we have next part to study is properties of system. So we will define properties of system. We have to define what do you mean by property of a system? So property of a system is characteristics of the system basically, why do we do need to do this. Suppose we are interested to study thermodynamic behaviour of a system. Then we have to describe the existing state of the system and then we might need to understand the change in state of the system.

So, for that we have to describe the existing position or existing state of the system, so this characteristic of the system helps us to define the existing state of the system. So the properties are the characteristics which help us to define the state of the system. But then within the properties there are again 2 types and there is an extensive property which depends upon mass and extent of the system. So the extensive property example is total mass, total momentum and total volume.

So we have some properties which are helping us to describe the state of the system, but they need the extent of the system or they also need what do you what is the size of the system. But then there are certain properties which are independent of the mass and size of the system or extent of the system such properties are called as intensive properties of the system. And we know the famous example is pressure.

Also, we have temperature and density. Further any specific property of the system is intensive in nature something like specific enthalpy, specific entropy, specific internal energy and all these properties would become intensive properties of the system. Then as what we said that we need the properties of the system to describe a particular state of the system and that particular state of the system is called as thermodynamic state.

So set of properties which help us to describe the condition of the system is called as thermodynamic state. So we will suppose we are dealing with a piston and cylinder arrangement and then in the piston and cylinder arrangement we have gas which is suppose at 12 bar pressure and 500 degree Celsius then these two things which is 12 bar and 00 degree Celsius are basically the properties of the system which is gas which we are using to describe the state.

Upon certain interaction with the surrounding this suppose next state of that gas is 10 bar and 400 degree Celsius then the 10 bar and 400 degree Celsius is next state of the same system so these are the ways by which we define or describe the condition of the system. Then we basically have to define equilibrium. Here we are basically in thermodynamics mainly dealing with the equilibrium of the system.

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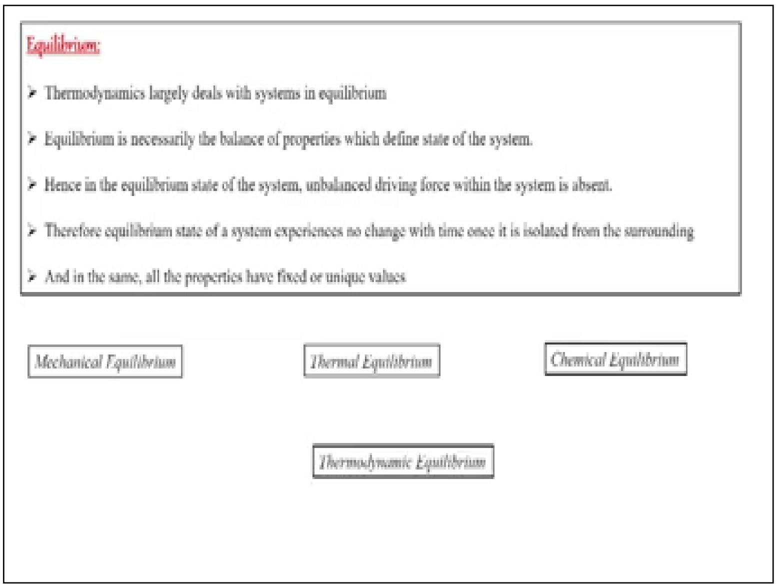

So thermodynamics largely deals with equilibrium of the system and equilibrium is necessarily balance of properties which are used to define the condition or state of the system. Hence equilibrium state of the system when it is achieved then we will not have any unbalanced force within the system which will change the properties of the system. So once we have defined an equilibrium once and equilibrium is achieved. By the system then there is no change in the properties or any property of the system since there is no driving force.

What are the basic driving forces, which we would know if there is non-uniformity in pressure within the system then there will be flow from high pressure to low pressure region if there is density change or density variation within the system then there is flow from high density part to low density part, if there is variation between term in the temperature of the system then there is flow of heat from high temperature to low temperature.

So, this flow of mass or heat is mainly occurring due to the presence of the some driving force and that driving force is absent when we say that system has reached equilibrium. So, once we have got system in equilibrium. It is all properties are fixed then there are internally many equilibrium which are defined and first equilibrium is mechanical equilibrium. Here system is said to be in mechanical equilibrium once the mechanical forces are balanced within the system.

So, there is no unbalanced force mechanical force for this is term or for this we have pressure is uniform within the system. Then we have thermal equilibrium and in case of thermal equilibrium. There is no temperature variation within the system. Then chemical equilibrium then there is uniform composition of the system. Once we have pressure uniformity. Once we have temperature uniformity and once we have basically composition uniformity. Then system is said to be achieved the Thermodynamic Equilibrium.

So system needs to bring needs to be brought to thermodynamics equilibrium for the understanding. And Thermodynamic Equilibrium will be achieved when we have mechanical equilibrium, thermal equilibrium and chemical equilibrium. Then next part to discuss is thermodynamic process.

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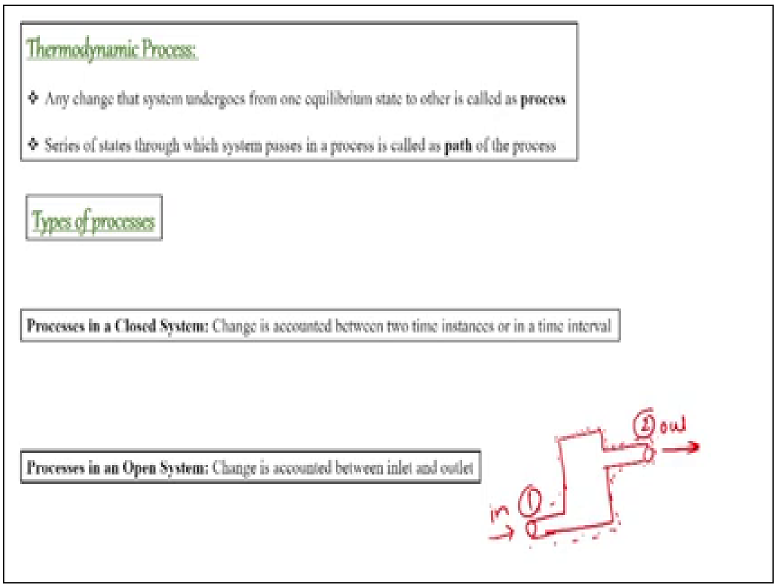

So, any change that system undergoes from one equilibrium state to other equilibrium state system undergoes. So when system undergoes from one state to other state in the previous example, we had said that there is a gas in a cylinder which are certain pressure and temperature at an instance and after certain instance there is certain other pressure and certain other temperature.

So, the first state of system and second state of the system, they are basically different in such case system has undergone a process and this is what we are calling it as a thermodynamic process. Where system undergoes from one state of equilibrium to other state of equilibrium and the final destination which system has basically achieved before that equilibrium to achieve system has undergone through various destinations or various milestones and those all milestones are basically the intermediate thermodynamics states which system would have in equilibrium.

And all such states if we join and we say that this is the path which the system has followed to execute a particular process. So these are there two things which are related with change in state of the system. Then we have types of processes. The first type is something like suppose we are considering processes in a closed system. So when we are considering process in a closed system, then basically we are looking into two different time instances.

As what again, we will refer back to our previous example, where we have said that there is a piston cylinder arrangement in which there is gas. That gas has certain pressure and certain temperature and then there was certain interaction of work and heat between the system and surrounding and then the gas has attained certain else pressure and certain else temperature and this certain else pressure and else temperature certain else instance for the same mass.

And then that certain else pressure and temperature is what the next state of the system's. Initial and final they are the same they are the states of the same system, but there are two different instances. When we are looking for the processes in open system, we have to consider an example here that there is certain inlet and certain outlet for one system. This is system of our interest and for this system this is in and out and this is station 1 and station 2.

The system has certain mass entering in at station one, so that mass has certain property. And there is certain mass which is leaving at station 2 and that has certain property. So while analysing the open system we consider that the properties at station 1 and we will consider properties at station 2 then this is what the change in the conditions which mass has undergone and these will be used for analysing the open system.

So, here practically while considering processes in the open system. We are looking at two different stations maybe at the same instance. So we are looking at the same instance, but at two different locations while understanding the process which is undergoing in which is undergone by the open system.

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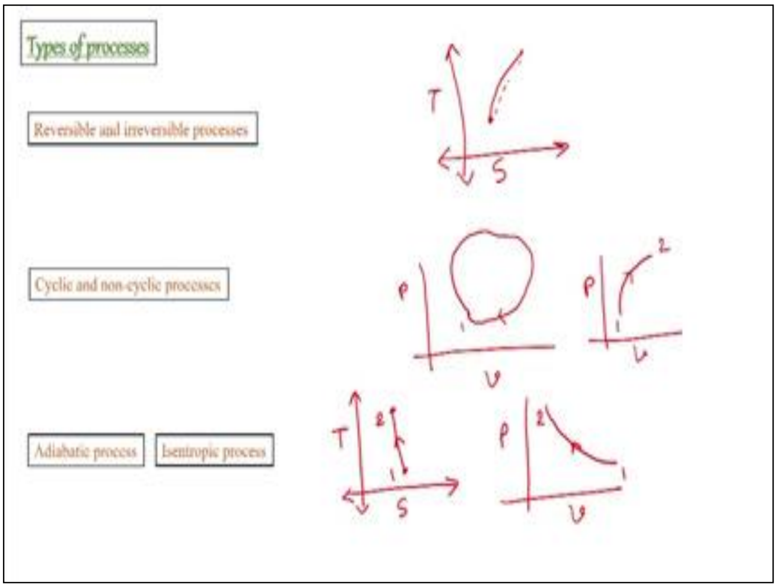

Then there are other types of processes. First is a reversible process and an Irreversible process system is said to be undergone and Irreversible process when system cannot come back to its original state by the same path. So if we try to draw a PV for TS diagram suppose we are trying to draw a TS diagram and System is going from one state to other state and then in such case. We do not know what are the what is the path followed by the system then in such case system will undergo an irreversible process.

It says it cannot come back to the same state by the same path. But if we know then the system has undergone certain process and then system can come back to the same state then we can draw a firm line between the two states where system is said to be in equilibrium at all points and such process where system is guaranteedly coming back to original state by the same path is called as a reversible process.

Then we have cyclic or non cyclic process. In case of cyclic process suppose we will take a PV diagram and then system is at state one which is having certain pressure and certain temperature system has undergone multiple changes and system has come back to the original or initial pressure and temperature then since system has come back to the original state it is called as cyclic process. If system does not come back to the original state which was one and goes back to state 2 it does not come back to state 1 so this is a non cyclic process.

Then we have adiabatic process or isentropic process. Adiabatic process is a process in which there is no heat interaction of the system or with the system and between system and surrounding. So but if the process is executed reversibly and reversible adiabatic is also termed as isentropic process, so if we try to plot TS diagram for an isentropic process, TS diagram becomes vertical.

If we are at state 1 then we will go to state 2 with constant entropy and it becomes straight vertical line, but if we try to draw a PV diagram for isentropic curve, then we will have a curve of this kind in case of state 1 to state 2 so it becomes isentropic compression and if we want to do expansion 2 to 1 become the expansion process, which is isentropic.

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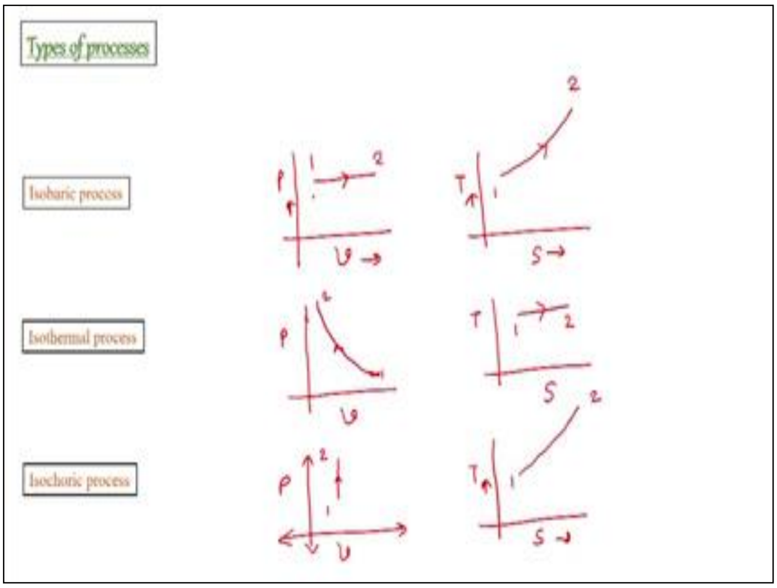

Having said this we have next which is an isobaric process. So isobaric processes as the name suggest is the process where pressure kept constant. So if you try to plot PV diagram then the process 1 to 2 is the isobaric process where pressure is constant. Otherwise if we try to plot TS diagram for the same isobaric process suppose. We are considering heat addition between 1 to 2 this process is like this and if you are considering heat rejection and the processes 2 to 1.

Then we have isothermal process as the name suggest isothermal process is a process in which temperature of the system is going to remain constant. So if we plot TS diagram then the process 1 to 2 is having constant temperature such it's a horizontal line so that horizontal line represent the isothermal process. But if we try to plot PV diagram for the isothermal process, then it would look like similar to the isentropic curve and then that curve will have negative slope as 1 to 2 which is compression process or 2 to 1 which will be expansion process.

Then we have isochoric process as again the name suggest we will have isochoric means volume constant process so it becomes 1 to 2 process, which is a complete vertical line on PV diagram. So the TS diagram for constant volume process would be similar to that of constant pressure process but it will be more steeper. So this is 1 to 2 processes for heat addition or there can be 2 to 1 process for heat rejection in constant volume sense. So as the name suggest we have different processes which system would undergo.

Now let us see some laws of thermodynamics. So we have first 0th law of Thermodynamics and 0th law of thermodynamics states that if system A is in thermal equilibrium with system B and system B is separately in thermal equilibrium with system C then system A and C are said to be in thermal equilibrium.

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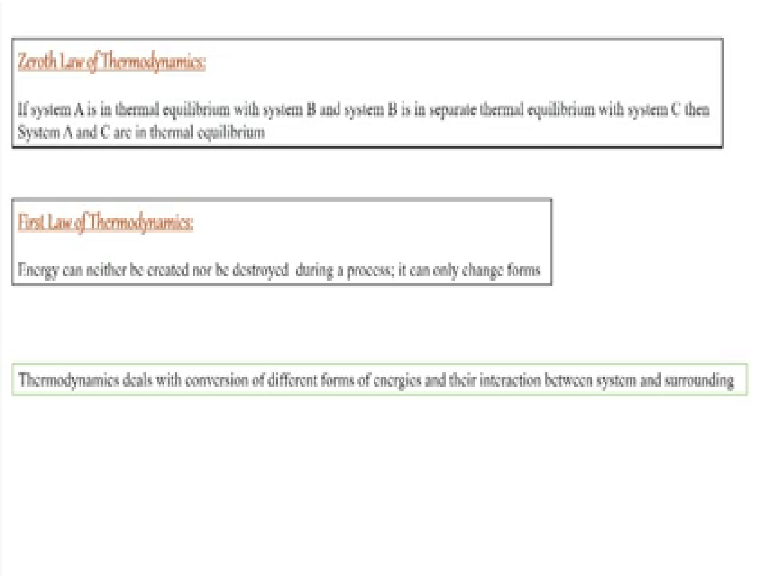

Basically 0th law of thermodynamics has one clear hint that temperature is property of the system and then this is the definition for the temperature at this is the definition for thermal equilibrium. Then we have first law of thermodynamics, which is basically energy conservation principle it states that energy can neither be created nor be destroyed in a process but one form of energy gets converted into other.

Then this law of energy conservation has many implications in understanding the system and it helps us by having its mathematical formulation available in the format of energy conservation equation. Basically thermodynamics in general deals with different forms of energies and their interaction with the system and surrounding we have basically different forms of energies.

The forms of energies something like work and heat, work and heat are two different forms of energy, then we will have some mechanical work with electrical work and we have shaft work and these are different kind of works, which are there then we have heat as again a form of energy. We have kinetic energy and potential energy and then we have internal energy. So there are different forms of energies which are involved in thermodynamics of a system whenever we are dealing with understanding of a system.

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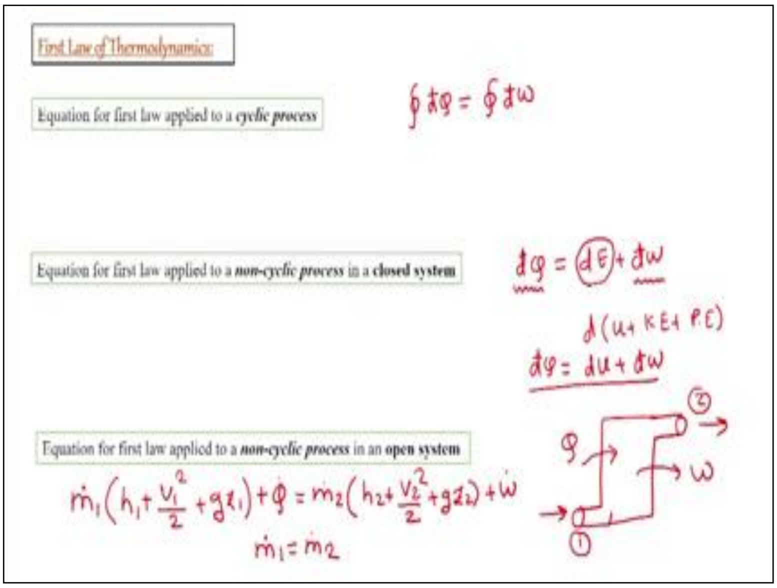

Then first law of thermodynamics when we apply for the cyclic process it state that

$$\oint đQ = \oint đW$$

This is the mathematical statement of first law of thermodynamics for the cyclic process, which is undergone by the system maybe it is closed or may be it is open. Then we have equation for non cyclic process and suppose in the closed system in the differential form state that

$$đQ = dE + đW$$

It states that if Q amount of heat is supplied from the surrounding to the system and system does dW amount of work and rest of the energy change of the system dE where E is total energy of the system which will have three energies basically d of internal energy, there is kinetic energy and there is potential energy.

$$dE = d(U + K.E + P.E)$$

So, when we are not considering any Kinetic and potential energy in first law of thermodynamics for closed system will be

$$đQ = dU + đW$$

So, this an expression for first law of thermodynamics applied to non cyclic process in closed system. And then we have non cyclic process in open system again understand the similar example where we have certain mass which is entering into the system and certain mass amount which is leaving out of the system from station 2 and in station 1 we have entry of mass into the system then we can write down the equation as suppose then there is certain work done by the system there is some heat addition to the system.

Then if you consider all then equation becomes

$$\dot{m}_1\left(h_1+\frac{V_1^2}{2}+gz_1\right)+\dot{Q}=\dot{m}_2\left(h_2+\frac{V_2^2}{2}+gz_2\right)+\dot{W}$$

this is the steady flow energy equation and since we are telling that this is a steady flow energy equation that is

$$\dot{m}_1=\dot{m}_2$$

Since there is a steady state the same amount of mass flow rate is taking place at the inlet and also at the outlet this is the equation for non cyclic process for an open system.

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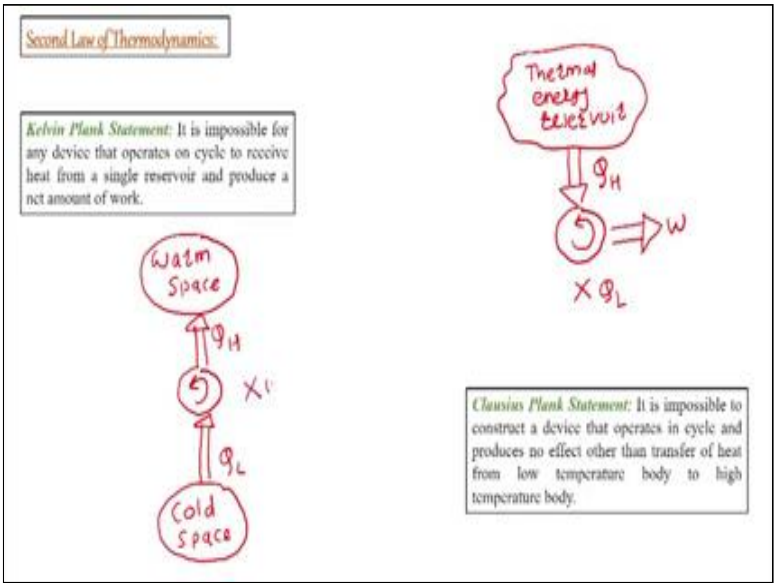

Then we have second law of thermodynamics basically it has two statements and the first statement is Kelvin Planck statement which state that it is impossible for any device that operates on a cycle to receive heat from a single reservoir and produce a net amount of work. So practically if we have a thermal, energy reservoir and that thermal energy reservoir is interacting with a system which is undergoing a cyclic change and then we say that it is giving Q amount of heat and system is doing W amount of work where no heat is rejected.

So, if no heat is rejected then Kelvin-Planck statement says that it is impossible to construct such a device which operates in cycle and interacts with only one reservoir. But then there is a second statement which is Clausius Planck statement which states that it is impossible to construct a device that operates in a cycle and produces no effect other than transfer of heat from low temperature body to high temperature body.

Practically it says that there is a warm space and there is a cold space. And among these two spaces. There is a system which is undergoing certain changes for that and with as an effect of those of cyclic changes. It is taking QL amount of heat from the cold space and putting Q H amount of heat in the warm space, but it does not interact with surrounding or anything and gets any work input. So this is impossible from the perspective of Clausius statement.

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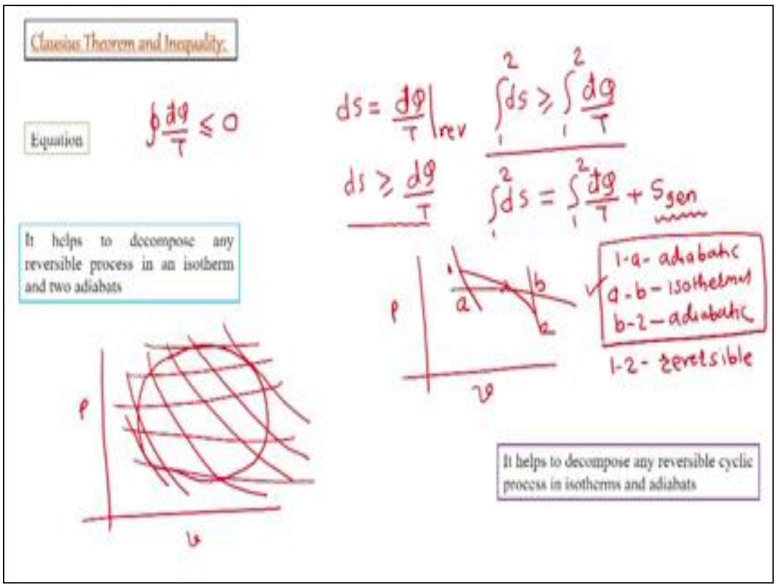

Having said that we have Clausius inequality and Clausius inequality state that

$$\oint \frac{đQ}{T} \leq 0$$

this is for cyclic process but if there is a reversible process then it is states that

$$dS = \frac{đQ}{T}|_{rev}$$

where second law of thermodynamics states that entropy is a property of system as what we have seen 0th law has a corresponding temperature as property of a system.

First law has correspondence with internal energy or enthalpy of the system is the property of the systems and then second law of thermodynamics tell that entropy is the property system. So, for reversible process change in entropy is equal to $\frac{dQ}{T}$ but if it is irreversible process,

$$\int_1^2 dS \geq \int_1^2 \frac{đQ}{T}$$

but then we have to integrate it from state 1 to state 2 for the system and otherwise

$$dS \geq \frac{đQ}{T}$$

And if we are interested to find out total change in entropy of the system, then we have to integrate and find out what is the dS but for the irreversible process in a system we have

$$dS \geq \frac{đQ}{T}$$

So,

$$\int_1^2 dS \geq \int_1^2 \frac{đQ}{T}$$

But for such irreversible process

$$\int_1^2 dS \geq \int_1^2 \frac{đQ}{T} + S_{gen}$$

S_{gen} → Entropy generated.

So this is Clausius inequality. This Clausius inequality helps us to decompose any reversible process into multiple isotherms and adiabats. So, consider that we have a PV diagram where system has undergone a process 1 to 2 then this process 1 to 2 is any arbitrary reversible process and this arbitrary reversible process can be decomposed into multiple things multiple processes. So this is 1 to 2, 1 to a a to b and b to 2. 1 to a is an adiabatic process, 1 to 2 is an adiabatic process.

So a to b is an isothermal process and b to 2 is again an adiabatic process. So, this is the process which is a general reversible process got decomposed into 3 processes which have 2 adiabats and 1 isotherm and this is what we are telling that we have help from Clausius inequality that it helps us to decompose a reversible process into multiple things. Basically we try to see here that the work and heat interaction in the actual process 1 to 2 is same if we do not consider 1 to 2 and if we consider the other 3 set of processes which system actually undergoes between points 1 to 2 system states 1 to 2.

Other thing which we get help is we can decompose cycle into multiple isotherms and adiabats as this is a non cyclic process similarly if we have a cyclic process, then the cyclic process can again be decomposed into multiple processes which are isotherms and adiabats. So, this is an adiabatic process and isothermal process. So we can now say that the area under the isotherms and adiabatic processes is same as the area under the closed cyclic process.

So, we can state that this part can be dealt with this isotherm so this adiabats but this adiabat and this isotherm and the isotherm this becomes if a number a, b, c and d. So, we got a, b, c, d as one patch and other patch here like that and there is other patch here so like that we can decompose complete cycle into multiple isotherms and multiple adiabats. And we have advantage of such decomposition of cycle which is a closed cycle which is basically due to the fact that system has undergone a process and came back to its original state. And such cyclic process gets decomposed into multiple adiabats and multiple isotherms.

So now let us see the thermodynamics cycles which are basically the cyclic processes composed of different processes individually with different characteristics first cyclic process, which you would consider is Carnot cycle. Actually importance of this cyclic processes is that some of the cyclic processes have engines based on their thermodynamics characteristics.

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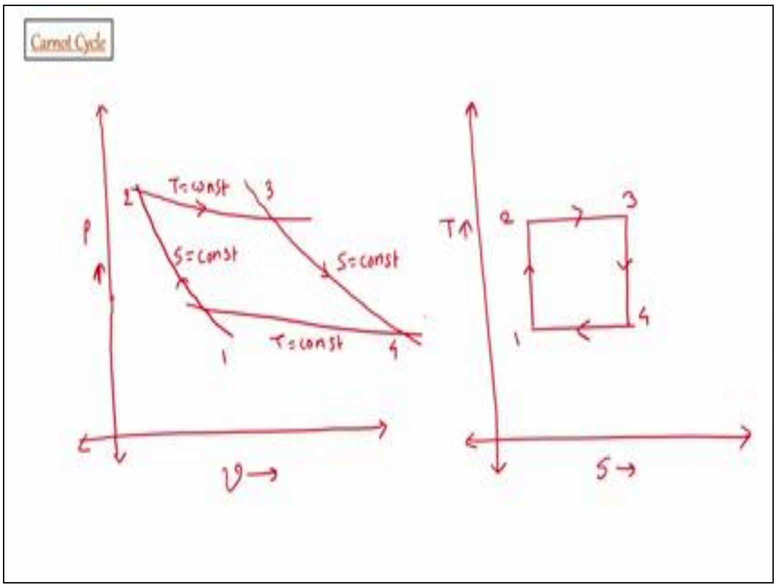

So first cyclic process which you would consider is a Carnot cycle, so let us draw the PV diagram and TS diagram for the Carnot cycle. So, here we will have first PV diagram. Pressure on y axis volume on x axis and as per the PV diagram of this cycle we have process 1 to 2 as the isentropic compression process 2 to 3 isothermal heat addition, process 3 to 4 as isentropic expansion and process 4 to 1 as isothermal heat rejection.

So, these are the processes which are basically comprising of which is constituted towards the formation of Carnot cycle, so let us draw the TS diagram for carnot cycle. And here we have temperature on y axis and entropy on its x axis process. 1 to 2 is practically entropy constant cycle process. So this process 1 to 2 is isentropic process. It is a vertical line 1 to 2, process 2 to 3 is isothermal process. So it is a temperature constant line. So, it will be a horizontal line in 2 to 3 process.

And then 3 to 4 is again entropy constant line which will again be a vertical line in the TS chart and again process 4 to 1 is again temperature constant line which would be horizontal line in case of TS diagram. So this is Carnot cycle. Now, this cycle is an ideal cycle where all processes are reversible.

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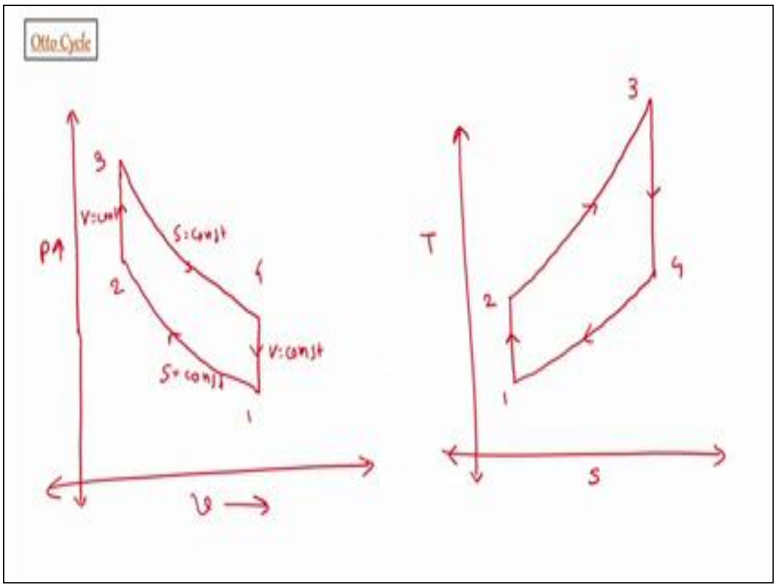

Now let us move to the next cycle which is Otto cycle. We are interested to see this specific part in the overview of thermodynamics because this cycle constitutes the engines which are the complementary engines towards our gas turbine. Otto-cycle is basically leading to SI engine, which is a spark ignition engine. So PV diagram or in our case we call it as petrol engine, PV diagram for Otto-cycle is comprised of first 1 to 2 is isentropic compression, 2 to 3 is constant volume heat addition, 3 to 4 is isentropic expansion and 4 to 1 is again constant volume heat rejection.

So, this is entropy constant. This is volume constant. This is entropy constant 3 to 4 and 4 to 1 is again volume constant. So this diagram on TS chart would look like this where process 1 to 2 is isentropic site will be a vertical line. 2 to 3 is constant volume heat addition so this is constant volume heat addition 2 to 3, 3 to 4 is isentropic process expansions this is 3 to 4 and 4 to 1 is again constant volume heat rejection.

So Otto-cycle basically is having constant volume heat addition and constant volume heat rejection. So based upon this there is design of SI engine or petrol engine.

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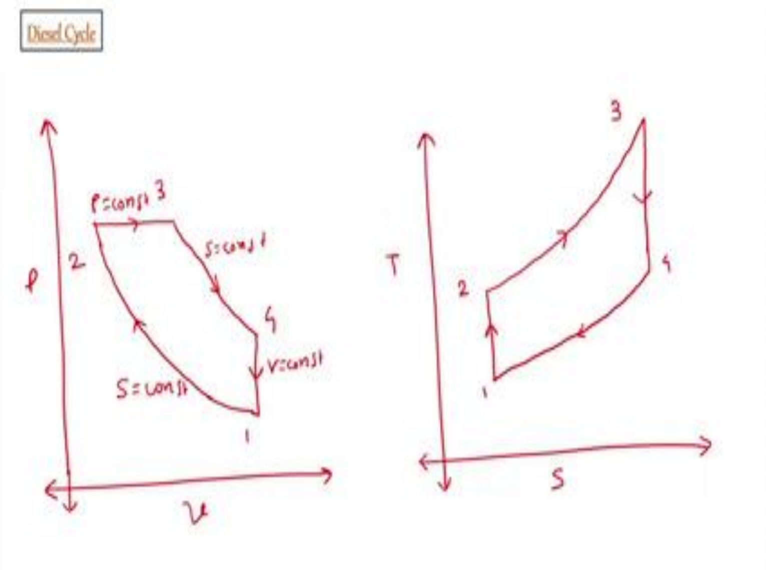

Then next is the Diesel cycle. So for diesel cycle we also know that there is diesel engine and it is also an internal combustion engine. And PV diagram for this diesel engine is like this where we have first 1 to 2 process is same as isentropic compression then at 2 we have constant pressure heat addition from 2 to 3. 3 to 4 is isentropic expansion and 4 to 1 is constant volume heat rejection.

So this is entropy constant. This is pressure constant heat addition. This is entropy constant expansion. And this is volume constant heat rejection this is diesel cycle. And so diesel cycle on TS chart would look like this where 1 to 2 isentropic process 2 to 3 is constant pressure heat addition. 3 to 4 is constant is isentropic expansion. So it is a vertical line and then we have 4 to 1 as constant volume heat rejection.

These are the 4 processes which constitutes the diesel cycle. So we know that we use diesel as a fuel for Diesel cycle and petrol is the fuel for Otto-cycle, but there are many other variants which can be used for petrol engine basically can have other fuels like CNG or LPG or biogas. The there are new kinds of bio diesels which can also be thought in the blending or in isolated usage for the diesel cycle.

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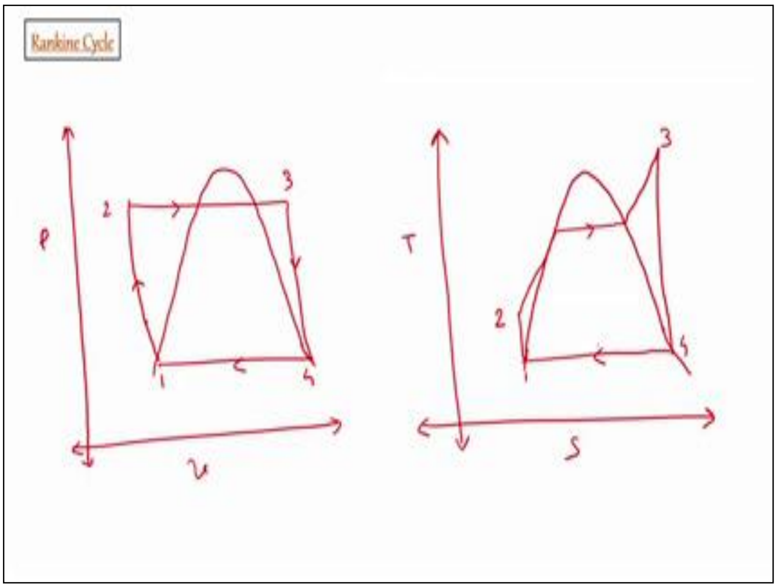

Then we have Rankine cycle and this Rankine cycle, we know here working medium is water and this water is used in 2 phase, this cycle uses 2 phase material while doing the work. So, the PV diagram for this cycle basically needs first to draw the phase change dome. Then 1 to 2 is isentropic, 1 to 2 is basically isentropic compression. But since we are dealing with liquid so we will not see much compression, but there will be much pressure rise and 2 to 3 is constant volume heat is constant pressure heat addition.

Then 3 to 4 is isentropic expansion and 4 to 1 is the constant pressure heat rejection. And TS diagram for this would be seen again leading the dome where 1 to 2 is basically. Isentropic compression 2 to 3 is constant pressure heat addition and 4 to 1 is constant pressure heat rejection. So this cycle is giving us a thermal power plant, which is steam power plant and steam power plant has water as working medium which is in liquid state in the 1 to 2 process which will get converted into vapour state in the process to 2 to 3.

For 3 to 4 again we will have water in the vapour state but 4 to 1 again there is a phase change. So, this is a basic cycle which is again used for electricity generation or in olden days it was used for locomotives where engine which is steam engine which was based upon this cycle.

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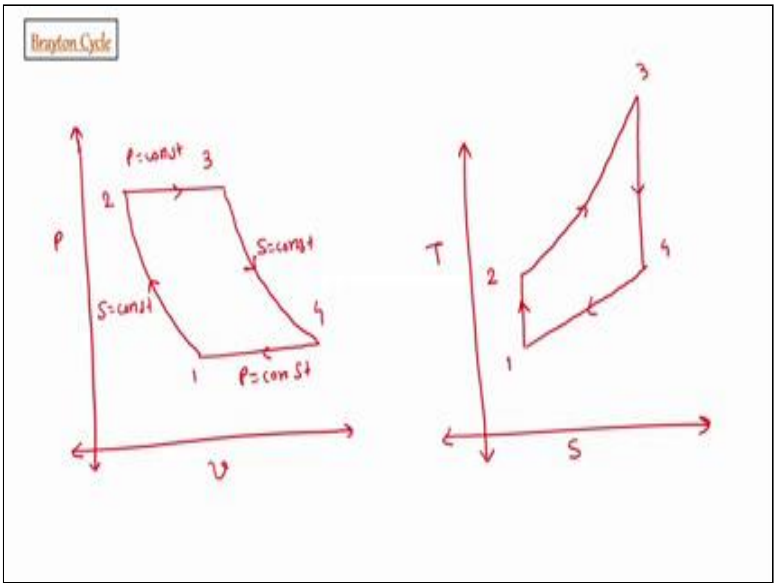

Now the last cycle which is of our interest is Brayton cycle and Brayton cycle is a cycle upon which we have our gas turbine power plant based upon PV diagram for gas turbine power cycle is like this we have 1 to 2 isentropic compression and 2 to 3 constant pressure heat addition, 3 to 4 isentropic expansion and 4 to 1 is constant pressure heat rejection. So this is pressure constant process. This is entropy constant process 1 to 2. This is pressure constant process 2 to 3.

And this is entropy constant process 3 to 4 then we have TS diagram. And TS diagram states that we have 1 to 2 isentropic compression than 2 to 3 constant pressure heat addition 3 to 4 isentropic expansion and 4 to 1 we have heat rejection. So there is basically Brayton cycle which is generally used in the gas turbine power plant. So these cycles basically constitutes different engines then they can be internal or external combustion engines or they can have single or multiple components to consider the engine.

But the idea is to use the heat and reject the head so that we can have net work which will be done in the thermodynamic process where we have different working mediums. This is how we complete the review of thermodynamics where we have learnt basic terminologies of thermodynamics and then we have seen what are the processes which would be important for us and we have seen the laws of Thermodynamics.

And now we have seen that there are cycles upon which engine are based. Now, we will take only Brayton cycle here onwards for further discussion. Or we might take some other cycle for comparison? In the case of our course, thank you.