Concepts of Thermodynamics
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Lecture – 59
Otto Cycle

Today, we will start discussing about thermodynamic cycles. We all appreciate that this is a fundamental thermodynamics course, and cycles are mostly discussed in applied thermodynamic courses, where cycles are related to sudden practical applications; having said that we must also appreciate that cycles are very much fundamental through thermodynamics and need not necessarily be related to some specific applications. So, thermodynamics cycles are related to situations when you start a process with a given thermodynamic state, and then after a sequence of process you come back to the same state same thermodynamic state, and thus you complete the thermodynamic cycle.

So, this being of extreme fundamental important in thermodynamics, this also has its implications from a practical point of view. And in this course, we will briefly touch upon some thermodynamic cycles which are immensely fundamental on one side, and at the same time they have relevant practical applications.

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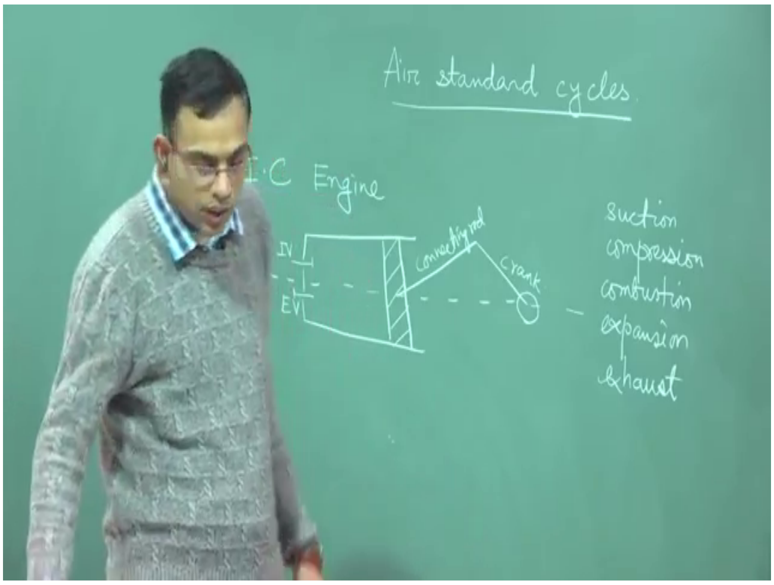

So, we will start with air standard cycles. So, before understanding what are these, I will try to give you a practical example in engineering. And this example concerns something called as internal combustion engine; example, IC for Internal Combustion. So, let us imagine that there is a cylinder with two valves. And then there is a piston, piston cylinder arrangements have been discussed in details in this course. So, you are familiar with this, except for the fact that this cylinder has certain provisions of taking in and throwing out the fluid which is contain within the cylinder. So, it is a cylinder in which mass of the fluid that is been circulated can be variable.

So, this cylinder is having a piston. This piston in turn reciprocates through a mechanism called as crank connecting rod mechanism. So, what is that mechanism? So, there is a shaft that is a cylindrical piece of rod like this which in a section will show like this circle. And there is a there is a link this is called as crank, and this is called as connecting rod, a rod that connects the crank to the piston.

Now let us say that this cylinder takes in air fuel mixture, a mixture of air and fuel it could also take only air, but let us take a particular example when it takes a mixture of air and fuel. So, how does it take that air and fuel? So, there is a suction valve that opens up, and air and fuel mixture is drawn into it. So, after this suction, then what will this, what will happen to this air fuel mixture, then this air fuel mixture will be compressed.

So, when the air fuel mixture is compressed, the whole objective will be to raise its pressure and temperature. So, once it is compressed, the same air and fuel which was inducted, but it is in a highly compressed situation, and remember that when it is compressed the inlet valve which was kept open during suction that is completely closed. So, the cylinder is blocked, and air cannot move out during the compression. So, during this compression, the gas mixture is compressed to a large extend and then let us say there is a ignition or sparking.

So, what I am saying is what commonly occurs in petrol engines, in petrol driven vehicles. So, once that combustion take places, there is a release of energy. And with this release of energy, heat is available to the air fuel mixture. Now, with this thermal energy it as a capacity to do work, so then it will undergo an expansion. And during that expansion, there will be a spontaneous revolution. So, if this if there is an expansion, this crank will also rotate, and then this crank shaft will rotate. So, there will be a spontaneous generation of power. So, this is called as expansion stroke or power stroke.

So, what we have seen is like we have first seen suction, then we have seen compression, I am just telling you the mechanical steps, then combustion, then expansion. And after expansion you are left products of combustion from which work as been extracted, so you can leave that and bring in fresh products of combustion with renewed potential of doing work because of the chemical energy.

So, after the combustion and expansion, all the chemical energy in the fuel is utilized to do work, and then you require fresh air fuel mixture to run the show. So, after expansion what you then do is so there is an inlet valve and there is an exhaust valve. So, you open the exhaust valve, and then products of combustion leave the chamber and then again phase suction starts. So, these are the process which are happening. And this is very much typical to a petrol engine.

In a diesel engine, what you do, the basic difference is that instead of pushing an air fuel mixture you suck air and compress air, but the compression is so great that at a very high level of compression of air, if you inject fuel, ignition will start taking place. So, air will be compressed instead of an air fuel mixture. So, these are technicalities related to practical situations what will be compressed or what will be sucked in, whether it is air or air fuel mixture, all these things, but intrinsically these are the common processes which take place no matter whether it is a petrol engine or a diesel engine. Nowadays the traditional distinction is gone because you can have multipoint fuel injection in modern engines, no, irrespective of what is the fuel by which it runs.

So, it is possible to have combinations of different technologies to run an auto mobile. So, traditionally whatever used to be the mechanism of a the running system of a petrol engine things have involved considerably, but no matter what is the detail, this is what is the suction, compression, combustion, expansion, exhaust, these are the broad steps that will take place.

So, once you have that, the question is how to make a thermodynamic model out of this. What is represented by this is a mechanical model, that means you have a mechanical system which takes into account some induction of either air or air plus fuel, then there is combustion, expansion and then exhaust. So, it completes a mechanical cycle. Question is does it complete a thermodynamic cycle? The answer is no. Why it does not?

Constitute a thermodynamic cycle? because in a thermodynamic cycle you should have the same fluid that is being continuously circulated.

Now, here you have a variable mass within the system which gets circulated, and therefore, it is not given control mass system or even a given flowing system that is a constant mass or a constant rate of mass that is being transported within the system constituting the cycle. So, then we can say that it is better to call it a mechanical cycle, but not a thermodynamic cycle. But it is possible to imagine an equivalent thermodynamic cycle which grossly represents this behaviour and which does not take into account also the variable chemical composition of the working fluid.

So, what it takes into account is that the working fluid is simply air with a constant property that circulates; it is of fixed mass and composition. And then it constitutes a thermodynamic cycle which is different from what is physically happening here, but is a gross representation of the thermodynamic phenomena taking place in this. Not just these it could be other applications which I will talk about later on. It could also be instead of internal combination engine, it could be a gas turbine which is a different examples, I will come to that later on.

But irrespective of what is the practical scenario, if you consider air of fixed mass and composition constituting the thermodynamic cycle with certain processes, then we call it an air standard cycle. So, the air standard cycle is a thermodynamic cycle which is used to mimic certain practical industrial processes.

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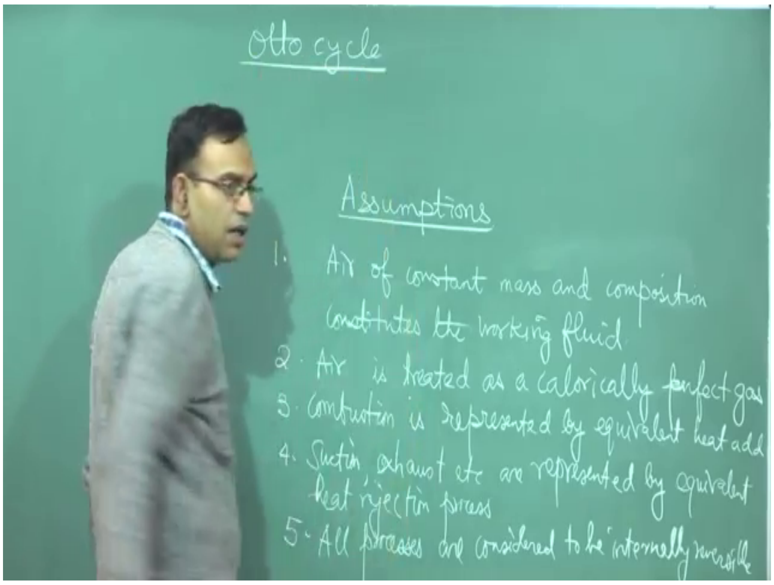

So, because it is idealized cycle, it will have certain assumptions. What are the assumptions? So, let us first note down. Number 1, air of constant mass and composition constitutes the working fluid. So, it may be constant mass and composition, but the temperature range is quite large. Why the temperature range is quite large? The temperature range is quite large because after combustion there is a rapid increase in temperature of the working fluid.

So, the question is over such a great range of temperature, it would not actually be legitimate to consider air with constant C p and C v, but the air standard cycle is a simplified version of the reality when it considers air to be a calorically perfect gas with that means, ideal gas of constant C p and C v. Air is treated as a calorically perfect gas ok.

Then this combustion, combustion cannot be represented in a thermodynamic cycle. The reason is that combustion is a complicated process where the chemical composition gets altered and with such alteration in chemical composition you now more can consider the working fluid to be or fixed chemical composition. So, what you do is you treat combustion as an equivalent effect. The equivalent effect is heat addition. So, the combustion is represented by equivalent heat addition.

Then you cannot also take into account suction, exhaust, etcetera, because that will change the mass of the system. So, suction, exhaust, etcetera are represented by equivalent heat rejection process, are represented by equivalent heat rejection process. We will see later on that what is the specification of this heat rejection process, it depends on whether it is an internal combustion engine or a gas turbine, based on that the heat rejection process either it could be a constant volume or a constant pressure process. And finally, all processes are considered to be internally reversible.

This is a sort of obvious assumption because if the process is not internally reversible it cannot be represented by a continuous process diagram. And therefore, you cannot draw say p V diagram or TS diagram of such processes. So, once you draw p V diagram or a T S diagram with a continuous line, it must be an internally reversible process; otherwise the intermediate state points are not defined.

So, with this assumptions we will learn two important air standard cycles, which are relevant to internal combustion engines. The first is Otto cycle a classical air standard cycle that is used to model the petrol engine. So, I would erase the assumptions and for all this cycles what I will do is we will identify the processes and try to draw the processes schematically in pressure versus volume or temperature versus entropy diagram.

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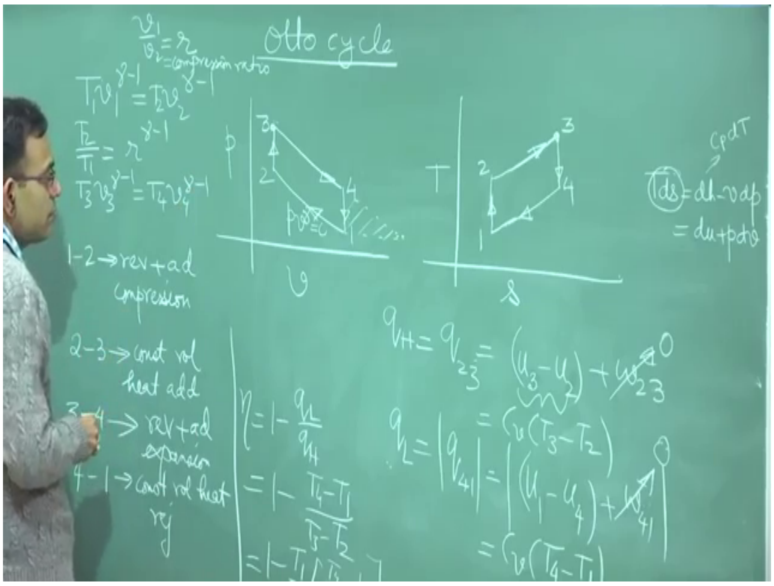

So, we will make p V diagram and T s diagram. So, we will start with compression ok. So, because suction is sort of neglected, we do not take suction into account, we will model it by a heat rejection process. So, the first component of the real process which we want to model thermodynamically is the compression process. So, 1 to 2 reversible plus adiabatic compression, so all processes are reversible internally reversible. So, compression is also internally reversible, but it could be any general reversible polytropic process. For air standard cycles representing the internal combustion engines, we take these as reversible and adiabatic process. So, if there is a compression, then the obvious conclusion is that the pressure should increase and the volume should decrease.

Then 2 to 3 constant volume heat addition ok. So, let me draw the same thing in the T S diagram together that will make it very interesting. So, compression reversible adiabatic compression, what do you think at the end of the compression, first of all reversible adiabatic means isentropic. So, at the end of the isentropic process, what will happen to the temperature, will it increase or decrease? So, for all these basic questions, the focus should be thermodynamics, not the practical situation.

So, we can use this Tds equal to dh minus vdp or du plus pdv whatever. So, Tds is 0 for reversible adiabatic process. So, dh is equal to vdp, dh is cp dt for an ideal gas so that is equal to vdp. During the compression process pressure is increasing, so v dp is positive. Therefore dt is positive, so that means, temperature will increase, it will be like this 2 to 3 constant volume heat addition. So, the heat addition in the Otto cycle is modelled as a constant volume process. Why it is modelled as a constant volume process? See the cycle as something to do with practicality also in the petrol engine the combustion on or the sparking is also instantaneous. During that process the working fluid does not have chance much of a chance to change its volume, so that is why it is a constant volume heat addition during which the pressure will increase.

Can you tell why this point 2 does not go to volume equal to 0? It stops somewhere where the volume is highly compressed, but not equal to 0. So, the reason is that in the diagram that I viewed to begin with you have a piston and you have a cylinder, the there should be a little bit of clearance between the piston and the cylinder to avoid direct metal to metal contact and to accommodate the valves, the inlet and the exhaust valves. So, this is volume is called as clearance volume. All these things you will learn in more details in applied thermodynamics courses, but I want to give you a practical prospective to the thermodynamics that we are studying.

Then 3 to 4 is reversible adiabatic expansion which is the power stroke reversible plus adiabatic expansion. So, in the T S diagram expansion should be opposite to compression; p V diagram also like that. And 4 to 1 this we have said to complete the cycle, we must have a process from 4 to 1 we have neglected the suction and the exhaust. So, we will replace that why constant volume heat rejection process. So, 4 to 1, we will have constant volume heat rejection.

Now, why constant volume heat rejection? It could also be constant pressure heat rejection. So, add it being constant pressure heat rejection, the advantage would be that you could have got more power out of the system that would have been advantage. Why? Because if it is a constant pressure heat rejection the process would go up to this, and then you would have add this heat rejection processes. So, this extra area under the p V diagram you will get as work, which would have been good.

But the problem is that in this case the stroke volume, the piston stroke in here the it is the difference between V 1 and V 2 in that case would have it would have been more. And with this greater amount of stroke volume, you will require a longer cylinder that will make your car or any auto mobile more bulky, because it as to accommodate a larger cylinder. So, for compactness of auto mobiles which run on these thermodynamics cycles, we never imagine that there is a constant pressure heat rejection for those cycles, but constant volume heat rejection.

So, we will quickly work out the thermal efficiency of this cycle. So, what is the heat addition? You apply the first law of thermodynamics in which process your heat rejection from 1 to 2. So, q 1 2, this is u 2 minus u 1 plus w 1 2; w 1 2 is 0, because sorry, I am very sorry it is q 2 3 heat addition not 1 2, 1 2 is compression. So, heat addition is 0 in 1 to 2.

Heat addition takes place in 2 to 3, q H which is q 2 3 that is u 3 minus u 2 plus w 2 3; w 2 3 is 0 because it is a constant volume process. And u 2 minus u 2 for constant C v, it is C v into T 3 minus T 2. This is q H. What is q L? q L is, see when you write the efficiency 1 minus q L by q H, you have to keep in mind that q L and q H are magnitudes of heat transfer not with sign, this you have to be very careful.

So, q H is mod of q 4 1 so that is mod of u 4 minus u 1 plus w 1 4 right or basically mod of u to be technically correct. The end state is 1; the beginning state is 4. So, mod of u 1 minus u 4 plus w 4 1, because u 4 is greater than u 1, this is an this w 4 1 is 0, because it is a constant volume heat rejection process. So, this is C v into T 4 minus T 1 ok.

So, the efficiency is equal to 1 minus q L by q H is equal to 1 minus T 4 minus T 1 by T 3 minus T 2. So, this is 1 minus you can write as T 1 by T 2 into T 4 by T 1 minus 1 divided by T 3 by T 2 minus 1 ok. So, now, you can write T 1 v 1 to the power gamma minus 1 is equal to T 2 v 2 to the power gamma minus 1 right. This process 1 to 2 is p V to the power gamma equal to constant, where gamma is the ratio of specific heats.

So, T 1 v 1 to the power gamma minus 1 is equal to T 2 v 2 to the power gamma minus 1 right. So, you can write T 2 by T 1 is v 1 by v 2 to the power gamma minus 1 and v 1 by v 2 is defined as r, which is called as compression ratio, compression ratio. So, T 2 by T 1, so this is compression ratio, so T 2 by T 1 is r to the power gamma minus 1. Similarly, T 3 v 3 to the power gamma minus 1 is equal to T 4 v 4 to the power gamma minus 1 right.

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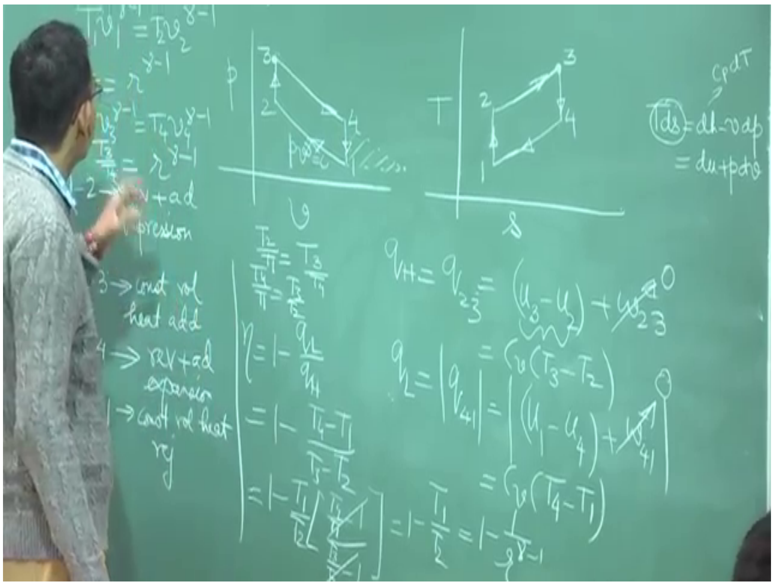

So, you have T 4 by T 3 or T 3 by T 4 is equal to v 4 by v 3 to the power gamma minus 1 v 4 is equal to v 1 and v 3 is equal to v 2. So, this is also r to the power gamma minus 1. Therefore, you have T 2 by T 1 is nothing but T 3 by T 4. So, you can write T 4 by T 1 is equal to T 3 by T 2. So, T 4 by T 1 being T 3 by T 2, these two terms simply cancel. So, this becomes 1 minus T 1 by T 2 and T 1 by T 2 is 1 by r to the power gamma minus 1, so 1 minus 1 by r to the power gamma minus 1 ok.

So, technically if you increase r the efficiency will increase with r right, but you cannot indiscriminately keep on increasing r, because indiscriminately if you increase r the temperature will spontaneously raise to an extend that automatic self combustion will occur. So, you cannot really it is already a air fuel mixture. So, you cannot really indiscriminately increase r. So, the efficiency of this cycle is limited by r. Anyway we stop here today. And in the next lecture, we will study some other air standard cycles.

Thank you very much.