Introduction to Aerospace Propulsion

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Module No. # 01

Lecture No. # 17

Gas and vapor power cycles, Otto cycle, Diesel cycles, Dual cycles

Hello and welcome to lecture 17 of this lecture series on introduction to aerospace propulsion. In the last several lectures, we have been discussing about many of the fundamental aspects of thermodynamics. We have understood what are the different laws of thermodynamics and what are the different technical terms associated with thermodynamics.

So, starting from today's lecture, what we shall do is, to use some of the thermodynamic principles that we have understood in the last few lectures and apply them to an actual process or to different processes. So, application of thermodynamics is what we shall be doing in the next several lectures.

We have got an introduction to various laws of thermodynamics and also towards the - I think the last 2 3 lectures, we have also been discussing about the - Carnot cycle which happens to be an ideal cycle which has all the processes which are totally reversible. We shall continue our discussion on cycles and what we shall discuss today is, basically on gas power cycles, as well as on vapor power cycles little later.

So, we shall be discussing about what are the different forms of cycles which have been proposed over the years. Some of them are very widely used and some of them though seem to be very promising has not really been implemented in practice and we shall also be discussing some of these cycles in the next few lectures.

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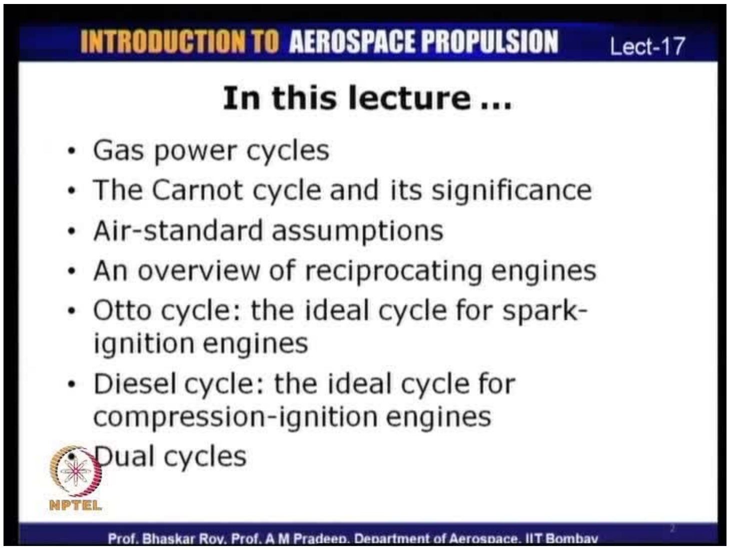

In today's lecture, what we shall be discussing is basically on we shall get introduce to gas power cycles. We shall start our discussion with little more discussion on Carnot cycle which we have already discussed little earlier and we shall also see what the significance of the Carnot cycle is. We shall then, discuss about what are known as the air standard assumptions.

Then subsequently, we shall have a very quick overview of reciprocating engines and then, we will discuss about the Otto cycle which is the ideal cycle for spark ignition engines. Then, we shall also discuss about the second important cycle which is a diesel cycle which happens to be the ideal cycle for compression ignition engines.

Towards the end of the lecture, we shall discuss about dual cycles which are basically having some similarities with both Otto as well as diesel cycles. During this discussion we shall not be discussing the Otto cycle in too much detail because we shall take up discussion in Otto cycles a little later on when we talk about piston engines.

So that is when we shall discuss lot more in detail about the Otto cycle. These are some of the topics that we shall be discussing in today's lecture and we shall begin with some understanding of what we mean by gas power cycles.

In many of the lectures we have discussed, we have normally assumed that the working medium is air and we have also assumed that air is behaving like an ideal gas; so that we could apply many of the ideal gas laws to air. That is one of the assumptions which we shall also make in today's discussion but, what we shall be looking at are actual cycles which have been used over the past many years. Of course, some of the cycles which have only been proposed but, have not really been implemented due to practical limitations.

Now, we know that Carnot cycle is the most efficient cycle basically because all the processes which constitute a Carnot cycle are totally reversible cycle, which means they are both internally as well as externally reversible cycle. So, what is the importance? Why do we need to discuss about the so called gas power cycles?

Well, power cycles form a very important component in engineering analysis as aerospace engineers or as mechanical engineers, we have all dealt with power cycles or we deal with power cycles on a day to day basis. For example, all automobiles operate on some sort of power cycle; it could be either an Otto cycle or a diesel cycle depending upon whether it is driven by petrol or by diesel. Similarly, aircraft engines also operate on a certain power cycle which is known as the brayton cycle and so on.

So, it is important for us to understand the significance of these power cycles basically because, they form a very important aspect of day to day operation especially in the engineering sense. We shall be discussing primarily about the idealized versions of the cycles. We shall not be really taking up the actual cycles.

Actual cycles are little different from the idealized cycles but, thermodynamically we can approximate all real cycles to their idealized versions and therefore, which makes thermodynamic analysis of such systems very simple, which is why we will take up only the ideal cycle analysis during this course. During ideal cycle analysis, we shall also be discussing about a several variety of cycles; some of them I had already mentioned in the contents for today's lecture. We shall be discussing about two of the cycle; Otto cycle, the diesel cycle and the slight variant of these known as the dual cycle.

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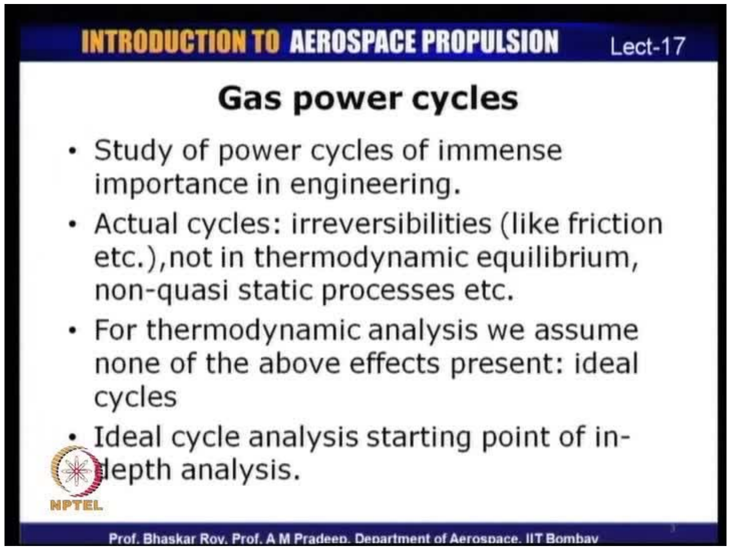

As I have mentioned, study of power cycle obviously is of immense importance and which the reason is why we are taking up this topic in today's lecture. All actual cycles basically are effected by irreversibilities like friction and other aspects of irreversibilities. Actual cycles do not have thermal equilibrium throughout their process and obviously they are non-quasi static processes. That is one of the reasons; well, this is the reason why actual cycles have efficiencies which are lower than that of their ideal versions.

For thermodynamic analysis which we shall be carrying out today, we shall be assuming that none of these effects are present; that is there are no irreversibilities and that the cycle is in thermodynamic equilibrium and that process is quasi static. With these assumptions, we have a cycle which is basically an ideal cycle.

So, what is the significance of such an analysis because all the processes are idealized you have no irreversibilities and so on which really does not happen in day today life. Well, that is very much true that such irreversibilities do not occur in day to day life but, what is important to understand is that idealized cycles or ideal cycle analysis forms the basis or starting point of a detailed analysis. That is if you can analyze an ideal cycle then, we should be able to get some idea of what the actual cycle is going to be about because we also know, what irreversibilities that are present.

Based on our ideal cycle analysis it should be possible for us to understand the real cycle in a better way and also take steps so that we can try and improve the performance of real cycle. So that is where ideal cycle analysis plays a significance role.

The other important difference between an ideal cycle and a real cycle is that an ideal cycle obviously, there are no irreversibilities whereas, in a real cycle you have all kinds of irreversibilities but, there is also a difference between the ideal cycle and the Carnot cycle. Though the Carnot cycle by definition is an ideal cycle, all ideal cycles which we are going to discuss today are not the Carnot cycle in one sense or the other.

The basic difference is that all the ideal cycles we shall be discussing today are internally reversible and not externally reversible, which means that it is possible that there could be irreversibilities outside the cycle whereas, Carnot cycle on the other hand is both an internally as well as an externally reversible cycle and that way a Carnot cycle qualifies to be what is known as a totally reversible cycle whereas, the ideal cycle analysis we shall be carrying out today are not totally reversible.

This means that the efficiencies of these ideal cycles will still be lower than that of the Carnot efficiencies but, the efficiency of the ideal cycles will be higher than that of the corresponding real cycles but, all of them are still less than Carnot cycle. Basically because, in ideal cycle analysis we are only assuming that the processes are internally reversible and there is still a possibility of external irreversibilities occurring.

Therefore, the thermal efficiency of an ideal cycle in general will be less than that of totally reversible cycle operating between the same temperature levels but, the thermal efficiency of ideal cycles is higher than that of actual cycles and so that is one of the differences between the actual and the ideal cycles.

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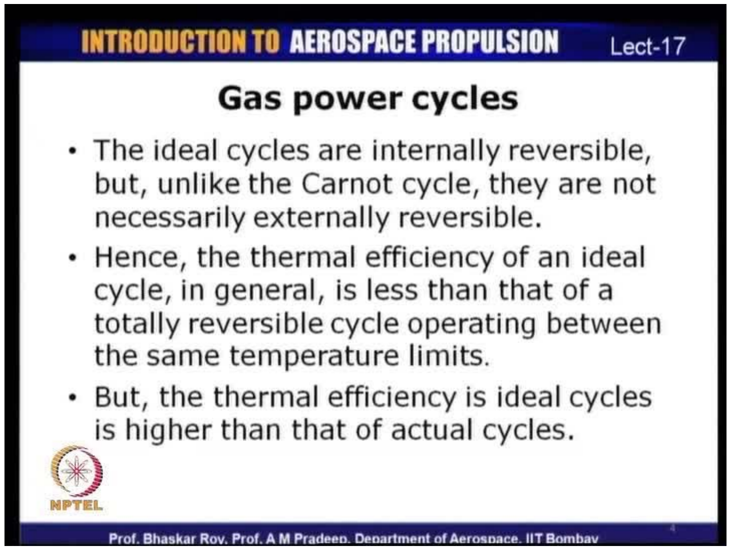

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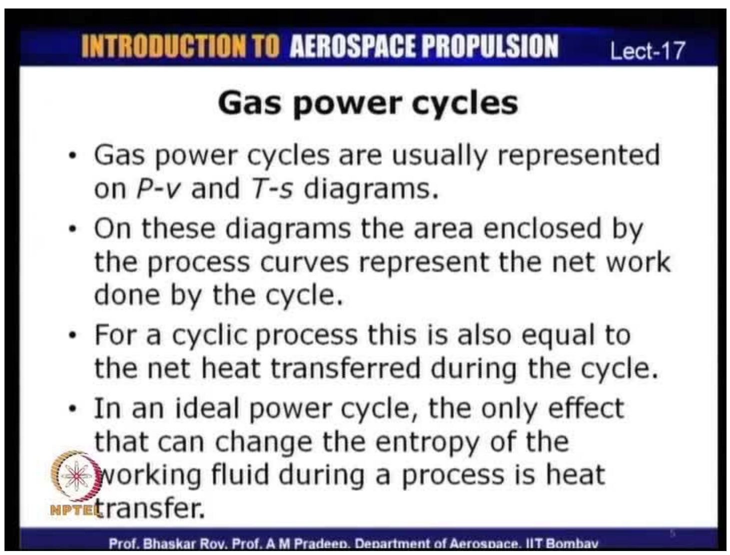

What we shall do today is that we shall be representing the different gas power cycles on P-v and T-s diagrams; that is pressure-volume and temperature-entropy diagrams. We have already discussed that the area enclosed between the P-v and T-s diagrams basically represent the net work done by the cycle. So, gas power cycles as we have discussed in last few lectures, we usually represent them on the pressure-volume or the temperature-entropy coordinates or sometimes we represent them in both of them and it really helps us in analysis of the cycles. We also discuss that on these diagrams whether it is the pressure-volume or temperature-entropy the area under the curve basically represents the net work done by the process and because these are cyclic processes net work done will also be equal to the net heat transferred that has taken place during this process. Therefore, area under the curve on a P-v diagram or on a T-s diagram basically represents the network output of this particular cycle.

In these gas power cycles, when we assume that it is basically that the cycle has a whole is basically a closed system in some sense or the other; in which case the only effect that can be lead to an increase in entropy is basically heat transfer which we have also discussed earlier on entropy. It can be increased in 2 mechanisms either through heat or through mass, entropy does not change during a work interaction process. In these cyclic processes basically entropy increase is account or entropy change is accounted for only because of heat transfer either to the system or from the system.

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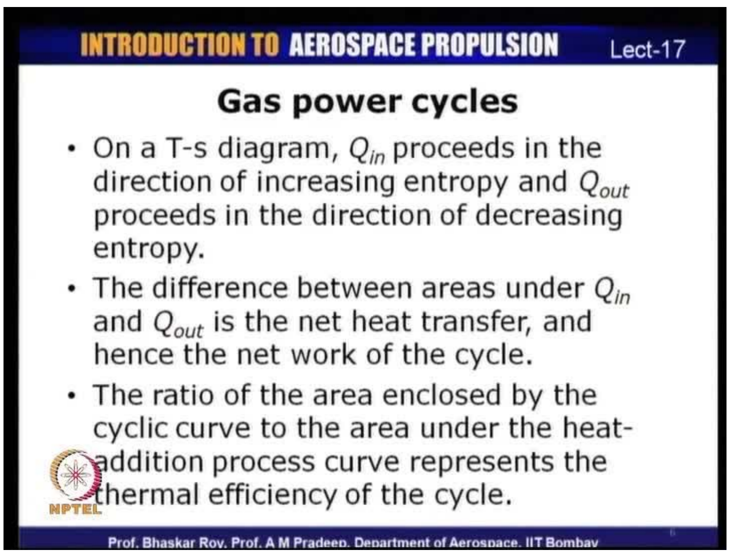

On P-v and T-s diagram, it helps us a lot in understanding the performance or in carrying out thermodynamic analysis of these different gas power cycles. So on a T-s diagram for example, if you look at T-s diagram, the heat transfer Q in basically proceeds in a direction of increasing entropy which is something we have also discussed earlier that Q in will obviously or increase in entropy is basically because of heat transfer to the system and Q out or heat transfer from the system proceeds in the direction of decreasing entropy.

The difference in areas under Q in and Q out is the net heat transfer on a T-s diagram. Therefore, net heat transfer will also be equal to net work done by the cycle because it is a cyclic process and delta Q is equal to delta W. So, the ratio of area enclosed by the cyclic curve to the area under the heat addition process basically represents the thermal efficiency because thermal efficiency is W net by Q in. Since W net is equal to Q net, the ratio of the area under the cyclic curve which is equal to Q net which is in fact equal to W net to the area under the Q in process.

That is the heat transfer in to the system basically represents the thermal efficiency of this particular cycle, which means that any process or any change that we make to the cycle which leads to an increase in this ratio; that is ratio of the area between the cycle or area enclosed by the cyclic curve to the area under the Q in process is basically thermal efficiency. So, whatever change you make if that leads to a change in this ratio, it can lead to a corresponding change in the thermal efficiency which could either be in increase in efficiency or it could also be a decrease in the efficiency.

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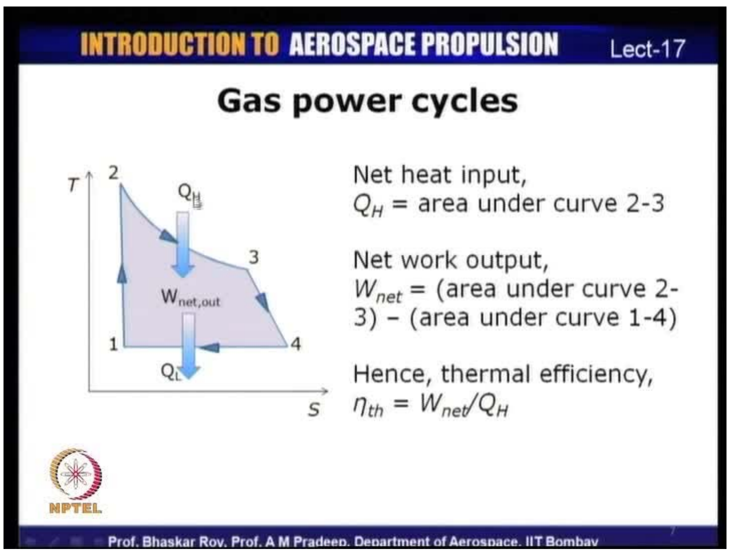

So just to explain that point through an illustration, what we have here on a T-s diagram is a cyclic process which is shown by this processes 1 2 3 and 4. This process the cyclic process is shown on T-s coordinates and it is some arbitrary power cycle and the net heat input is taking place through let us say this process 2-3.

Let us say the heat transfer is at a rate of Q h and therefore, area under Q 3, area under 2-3 is basically heat input to the system and net work output is basically the difference between area under the curve 2-3 and area under curve 1-4. This means that the shaded area is basically the net work output of the cycle; therefore, thermal efficiency is W net out divided by Q h or Q in. Therefore, whatever changes we make to a cycle if that affects this ratio, that is ratio of the area under the curve to the heat input curve, then that basically can lead to a change in the efficiency of this cycle.

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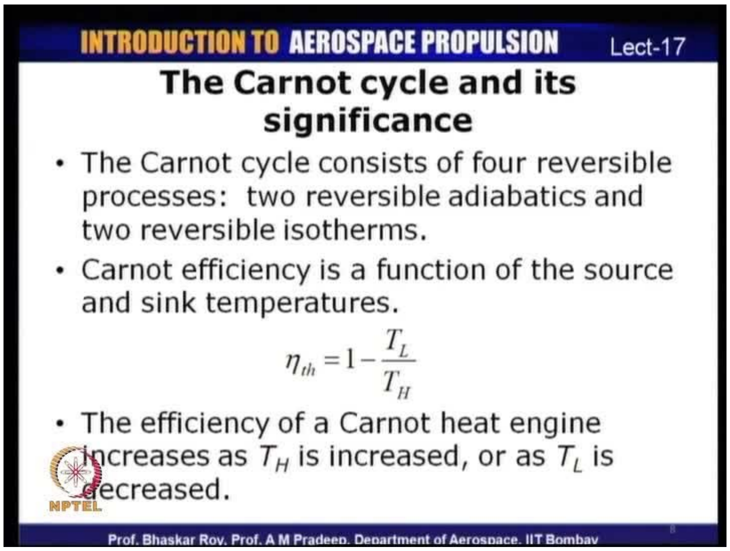

We have discussed a lot in detail about the Carnot cycle and we have seen that Carnot cycle is a cycle which consists of processes which are all internally and externally reversible consists of 2 adiabatic isothermal processes and 2 adiabatic to entropy processes. Basically you have a Carnot cycle consisting of all the 4 processes, which are reversible isotherms and reversible adiabatics which means, there are 2 isothermal processes and 2 isentropic processes in a Carnot cycle. Efficiency of a Carnot cycle as we have discussed is the maximum that any cycle can have and also efficiencies of all reversible cycles operating between the same temperature limits are the same, these are consequences of the Carnot theorem.

As we have discussed, Carnot cycle is an idealized version of any power cycle and so what is a significance of a Carnot cycle at all because all the processes as we know are in fact irreversible and therefore, their efficiencies can never be equal to that of the Carnot efficiency. But Carnot cycle basically helps us in identifying the maximum efficiency that particular cycle can achieve when it is operating between two temperatures - sources and sink.

Therefore, Carnot efficiency helps us in identifying or benchmarking the efficiency level to which a particular power cycle can reach and that is primarily the significance of the Carnot cycle because we know that, our heat engine let us say is operating between a temperature source of T h and a sink of T l so, what is the maximum efficiency that you can get, so that is defined by the Carnot cycle.

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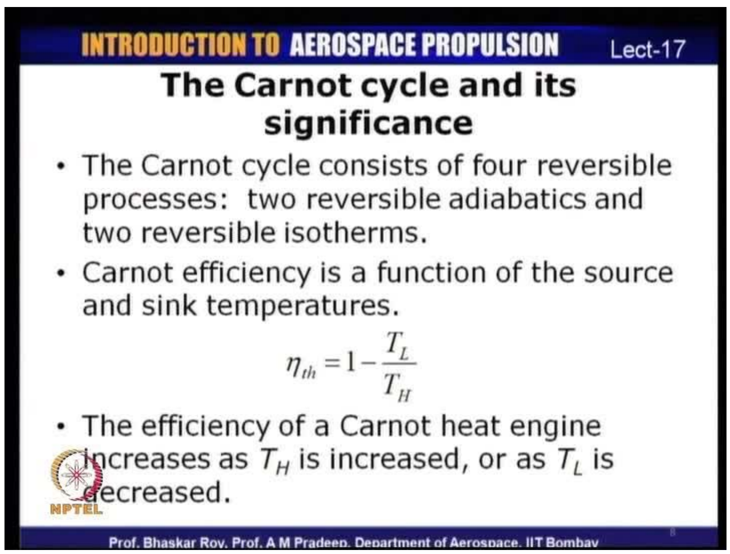

Carnot cycles help us in understanding that this is the limit to which we can extend the performance of actual heat engines. So Carnot cycle or Carnot efficiency is basically a function of the source and sink temperatures and therefore, as you increase the difference between T h and T l the efficiency also increases.

So that is another hint that a Carnot cycle gives on how to improve the efficiency that as you increase the temperature between the source and the sink then the efficiency of that cycle is bound to increase because the Carnot efficiency also increases as you increase the difference between T h and T l.

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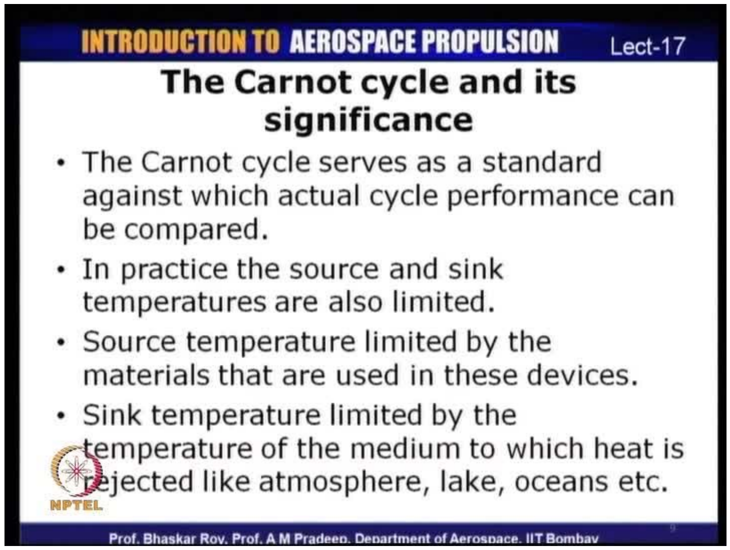

So, Carnot cycle basically would serve as a standard against which actual cycle performance can be compared but, we know that in actual practice the source and sink temperatures are limited basically because the source temperature is limited by the materials which are used in these power cycles. So, you would always be limited by a certain temperature beyond which the materials which constitute the cycle cannot withstand such temperatures.

The maximum temperature is limited because of that and the sink temperature on the other hand, though ideally you could go up to zero kelvin that is the lowest temperature possible but, the sink temperature in actual practices is limited because of the medium to which the heat is to be rejected like the atmosphere or to a lake or an ocean.

So, the sink temperatures are also limited and so are source temperatures, which means that there is a certain inherent limitation in the maximum Carnot efficiency that itself can be achieved by a certain cycle because the source and sink temperatures are limited because of practical issues.

On the other hand, Carnot efficiency or Carnot cycle analysis helps us in identifying what can be done to improve the performance of actual cycles and to what extent can we extend the performance of actual cycles. We will always be referring to Carnot efficiency as the standard to which other efficiencies or cycle efficiencies can be compared to and as I had discussed in the beginning of today’s lecture that we shall always be comparing or we shall always be assuming that air is going to be the working medium in all these cycles.

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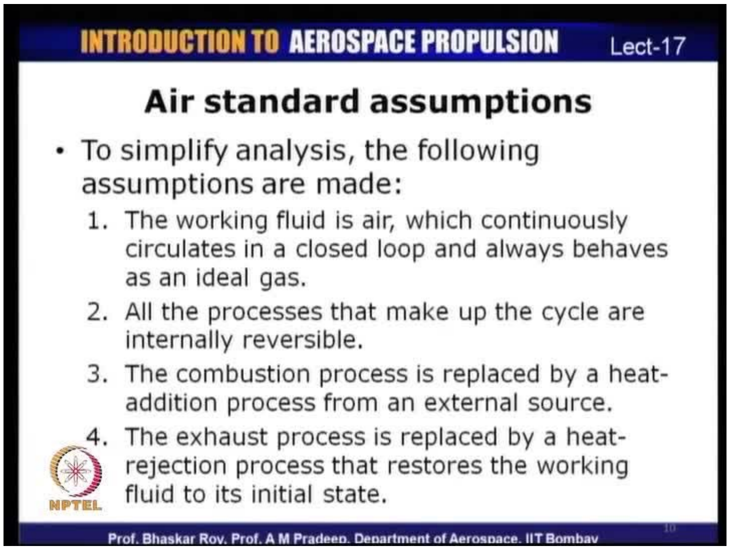

Though in actual cycles, the working medium is not really air beyond after combustion it also has constituents of the combustion products. So that can actually make the analysis quite complicated but, for the ideal cycle analysis that we are going to discuss today we shall be assuming that air is the working medium and also that air behaves like an ideal gas.

These are certain assumptions which we shall be making while carrying out the cycle analysis; these are basically referred to as the air standard assumptions. So we shall look at what are the different assumptions which we shall be basically assuming to simplify the analysis. The air standard assumptions are the following. The first on the primary assumption is that, the working fluid is air which continuously circulates in a closed loop and always behaves like an ideal gas. So that is the main assumption that constitutes the air standard assumptions.

Then, all the processes that make up for the cycle are internally reversible, that is the second assumption. All the processes, which form a part of the cycle, are internally reversible but, not necessarily externally reversible.

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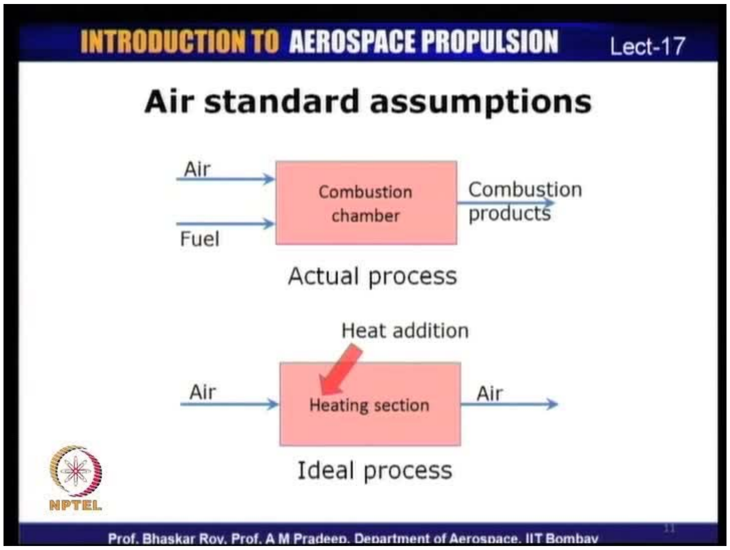

The combustion process is replaced by a heat addition process from an external source and the exhaust process is replaced by a heat rejection process that restores the working fluid to its initial state. So we shall be replacing the combustion process as discussed here by a heat addition process. The actual process would basically constitute of air and fuel which either is mixed before the combustion chamber or mixes within the combustion chamber; then what comes out of the combustion chamber or the combustion products which will in addition to air also constitute of the combustion products.

This in our analysis we shall be replacing by the following. So we shall assume that it is air that is coming into a certain heating section and it is air that leaves out of the heating section. What is happening in inside the heating section is that there is heat addition taking place which means, temperature of the air across the heating section changes; so the constituent or the other properties of air remaining constant will just assume that there is a heat addition taking place and that results in a change in temperature of air between inlet and outlet of the heating section. So, this is the third and assumption that constitute the air standard assumptions.

The fourth assumption is that, we can actually make a similar assumption for heat rejection process that there is certain heat rejection process which results in temperature of air coming back to where it was at the beginning of the process.

We shall have a very brief overview of reciprocating engines because what we shall be discussing today are cycles on which reciprocating engines operate and so it is necessary for us to understand certain basic terminologies associated with reciprocating engines. So, detailed analysis of this will be taken up little later on in the lecture. In later lectures, were we shall be discussing lot more about the practical implementation of many of these cycles. In today's lecture, we shall be limiting our discussion to ideal cycle or the idealized versions of the Otto and the diesel cycles.

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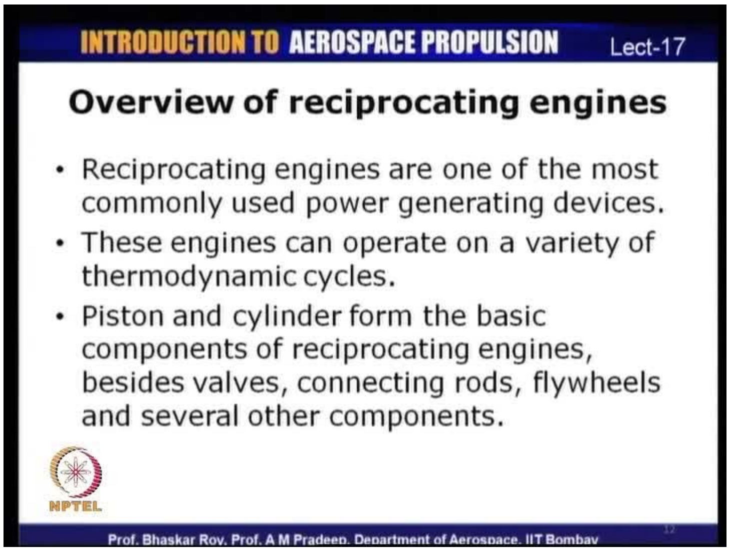

We already know that reciprocating engines form one of the most commonly used power cycles; reciprocating engines are one of the most commonly used forms of power generating devices. There are different engines which operate on different thermodynamic cycles and the common feature between all these cycles is that all of them constitute a piston and cylinder assembly. So, piston and assembly cylinder form the basic components of the reciprocating engine besides this there are of course, other components like valves connecting rods, flywheels and several other components which we will not be discussing today.

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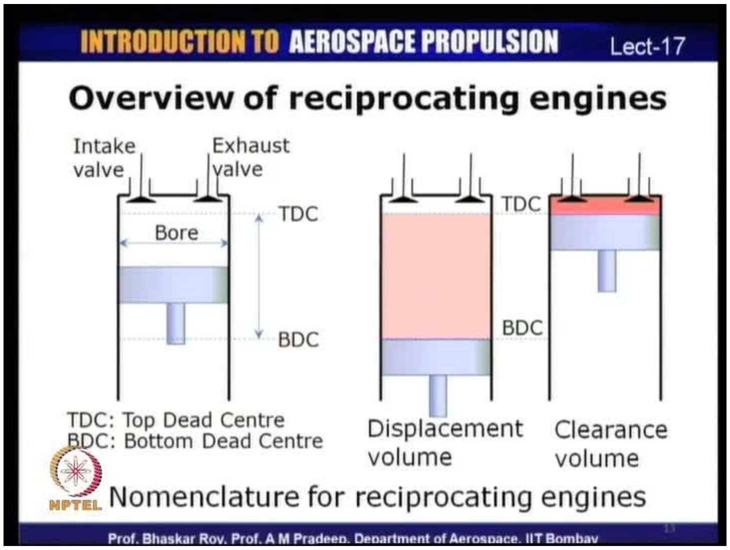

Basically reciprocating engines constitutes the following components; so reciprocating engines constitutes of a piston and cylinder as you can see here (Refer Slide Time: 24:14), this is the piston and this is the cylinder. So the cross sectional area of the cylinder is basically referred to as the bore of the cylinder or the diameter of the cylinder.

The piston basically move between two distinct points which are known as the Bottom Dead Center that is the point, the bottom most point to which the piston can move and Top dead Center is the top most point to which the piston can move. Difference between the top Dead Center and the Bottom Dead Center is basically known as the stroke of the cylinder. Of course, you have intake valves and exhaust valves which of course do not form any part of thermodynamic analysis.

So Top Dead Center is the maximum height to which the piston can move or that is the region or at the point when the piston has reached TDC that is when we have the minimum volume within the cylinder. When the piston reaches BDC that is when we have maximum volume within the cylinder. If the piston is at the BDC then, the volume within the cylinder is basically the displacement volume and as the piston reaches TDC the volume which is left inside the cylinder is known as the clearance volume.

You can see that the piston does not move all the way up to the cylinder head, it leaves a small volume between the piston and the cylinder head which is known as the clearance volume. So these are some of the terms, there are many other terms which will also be discussed later on in the course when we take up more detailed analysis of reciprocating engines.

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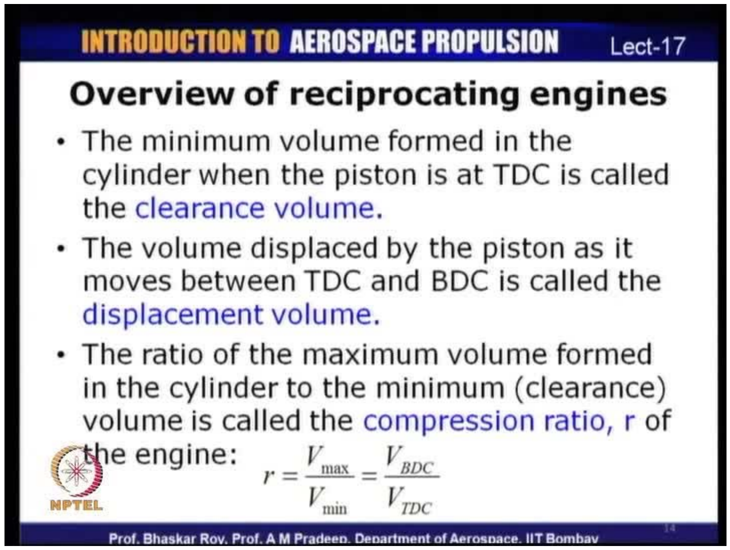

So the minimum volume that is formed in the cylinder when the piston is at TDC is known as the clearance volume. The volume displaced by the piston has it moves between TDC and BDC is known as the displacement volume. The ratio of the maximum volume within the cylinder to the minimum volume is known as the compression ratio r; so we will represent compression ratio here today by r. So, r is basically the ratio of V max to V min which is volume at BDC to the volume at TDC.

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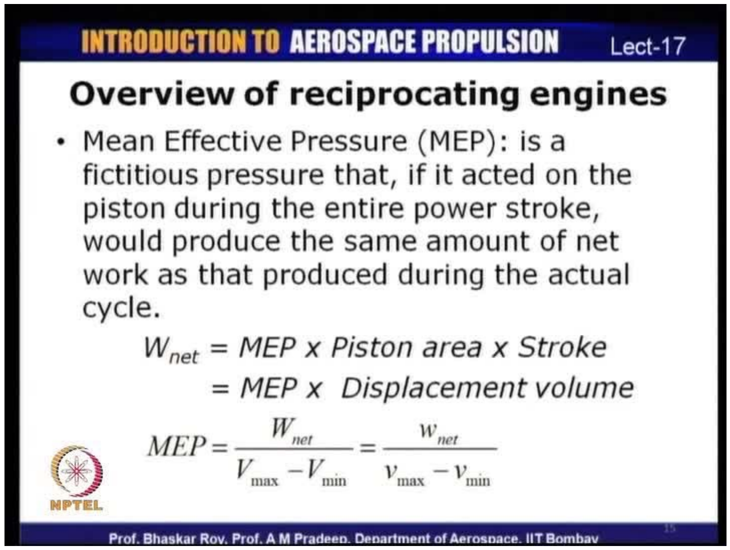

The other important term that we will need to understand is what is known as the mean effective pressure which is basically a fictitious pressure that if acted on the piston during the entire power stroke would basically produce the same amount of net work as produced during the actual cycle. So, net work output is equal to the product of the mean effective pressure to the piston area and the stroke, which is basically mean effective pressure in to the displacement volume.

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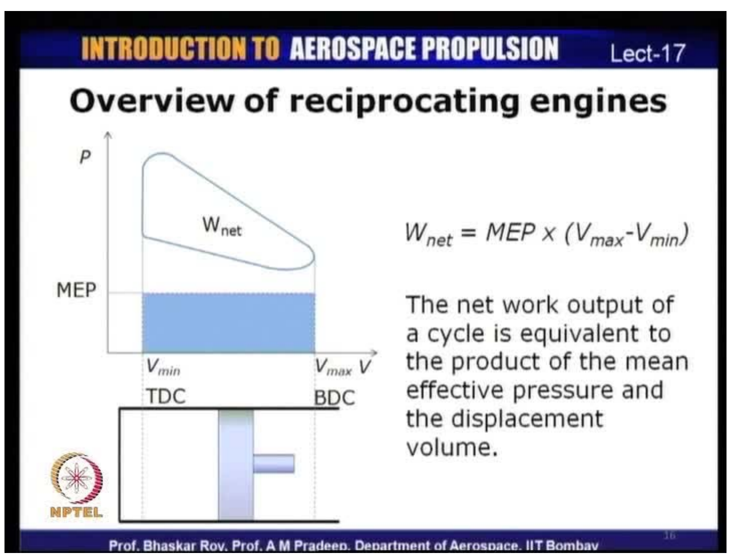

So, mean effective pressure can be explained by the following P-v diagram. Here we have a cycle, which is some power cycle which generates a certain net work output. The area between the mean effective pressures is basically the fictitious pressure which when acted upon the cylinder during the power stroke produces the same work output as that of the actual cycle.

If we know the area between this which is enclosed within this cycle which is basically equal to W net, we have an equivalent area here which is between V max and V min. So the fictitious pressure corresponding to that area is equal to mean effective pressure. Therefore, W net is the net work output is equivalent to product of any MEP which is Mean Effective Pressure and the displacement volume that is V max minus V min. Therefore, as the piston moves from BDC to TDC that is, when it displaces a certain volume which is known as the displacement volume.

So the fictitious pressure, which when multiplied by this displacement volume is basically equal to the mean effective pressure. Now that we have understood some of these basic terms associated with reciprocating engines which is what we had just an overview of reciprocating engines and as I mentioned we will take up lot more discussions on this, later on in the course.

We shall now start cycle analysis of some of the cycles and we shall basically be discussing about two cycles in today’s lecture: one is known as the Otto cycles which forms the basic thermodynamic cycle for spark ignition engines and then we shall take up discussions on the diesel cycle which is the basic thermodynamic cycle for compression ignition or diesel engines.

So basically, there are two classes or types of reciprocating engines, one is known as the spark ignition engine and the other is a compression ignition engine. A spark ignition engine is one in which combustion is initiated on a fuel and air mixture using a spark plug.

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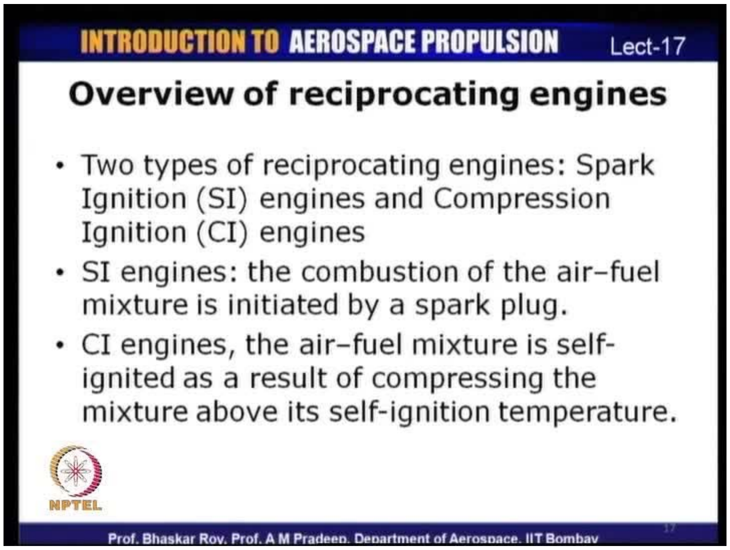

So spark ignition engine is one in which, we initiate combustion to the fuel air mixture using a spark plug were as in a compression ignition engine air fuel mixture is self-ignited as a result of the high compression which takes place. That is compression is taken to a point beyond the self-ignition temperature so that the air fuel mixture ignites on its own.

Basically for spark ignition engines, the basic thermodynamic cycle which is spark ignition engines operate is known as the Otto cycle. So we will first have discussion, we will understand what is an Otto cycle and we will limit our discussion to only ideal cycles. So, Otto cycle is the basic thermodynamic cycle of spark ignition engines.

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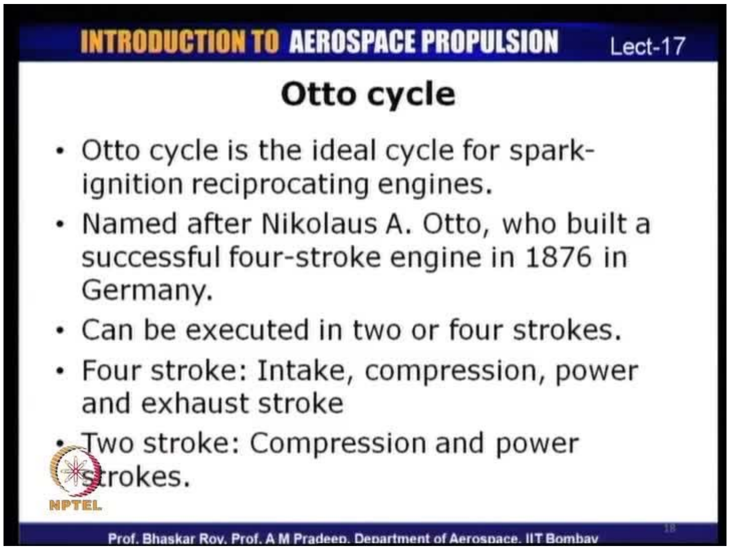

The basic cycle was of course, discovered long back in the 1876 by gentleman name Nikolaus Otto. It was in 1876 that Nikolaus Otto developed the first spark ignition engine. As we know today, spark ignition engines are very widely used in automobiles and which is why it is important for us to understand the basic thermodynamic cycle of spark ignition engines. So, Otto cycle basically is the ideal cycle for SI engines and it is basically named after Nikolaus Otto as I mentioned.

Otto cycle can be executed in two or four strokes. If it is a four stroke engine, it basically has four different processes or strokes which are basically the intake stroke, the compression stroke, power stroke and the exhaust stroke. The same cycle can or the Otto cycle can also be operated in a two stroke mode wherein, we have only compression stroke and the power stroke, that is intake and compression strokes are combined, the power and exhaust strokes are combined. So, it is possible also to operate Otto cycle either as a four stroke mode or as a two stroke mode, which again as I mentioned will be discussed little later.

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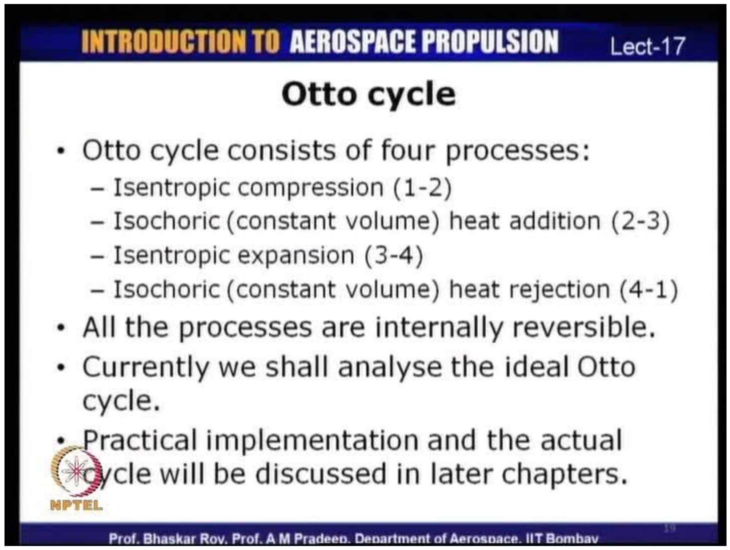

So, Otto cycle basically consists of four processes. Otto cycle begins with an isentropic compression process and then there is an isochoric or constant volume heat addition process followed by an isentropic expansion process and a constant volume heat rejection process. All these four processes are internally reversible.

As we have discussed in the beginning of the lecture, all these different processes are only internally reversible they are not externally reversible like a Carnot cycle which is why Otto cycle always have efficiencies less than that of Carnot cycle. In today lecture, we will only be discussing about the ideal Otto cycle, actual Otto cycles are quite different from the ideal cycle but, it is of course, possible for us to make comparisons between the ideal cycle and the actual cycle which again will be discussed little later.

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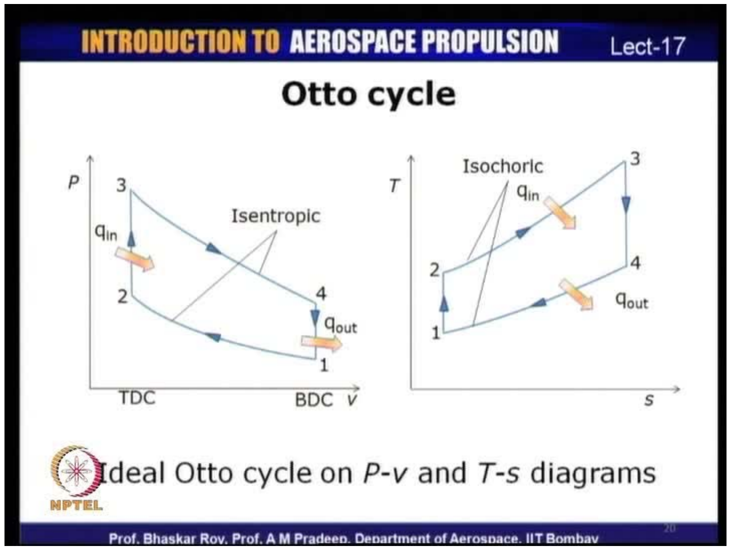

Let us look at the ideal Otto cycle in terms of P-v and T-s coordinates. I mentioned that Otto cycle consist of four processes, it starts with an isentropic compression. So, on a P-v diagram you can see this process 1 to 2 is an isentropic compression process. Heat addition takes place at constant volume, volume is a constant followed by isentropic expansion process; 3 to 4 is expansion but, isentropically process 4 to 1 is constant volume heat rejection.

The same process on the T-s diagram, first process is isentropic compression which is why you have a vertical line constant; entropy 2 to 3 is constant volume heat addition, q in takes place during process 2-3, process 3-4 is isentropic expansion and process 4-1 is constant volume heat rejection. So, this is ideal cycle as seen on ideal Otto cycle on P-v as well as T-s diagrams the real cycle of course, real cycle can only be approximated in some way to that of the ideal cycle there could be some differences between the real and the ideal cycles.

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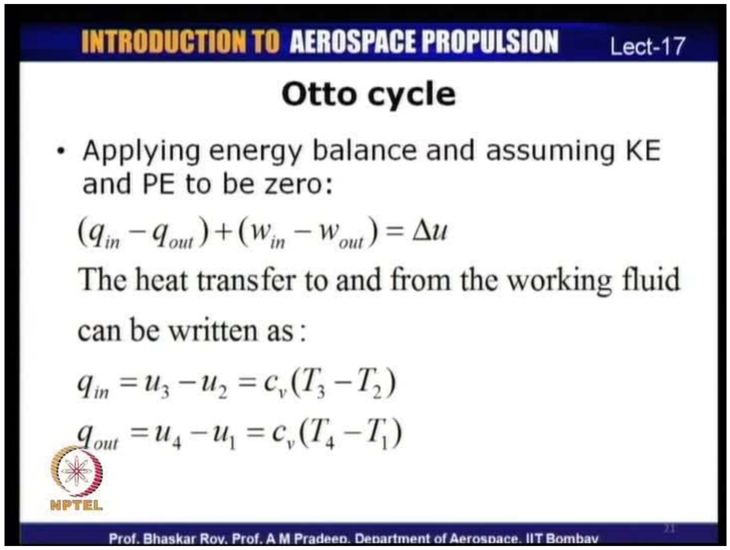

If we now try to apply the energy equation for these cycles, basically our aim is to derive an expression for the efficiency of the ideal Otto cycle. So what we shall be doing is to apply the energy equation for the cycle and find out the heat and work interactions which will basically give us an expression for the efficiency of an Otto cycle. If you apply the energy balance which we will assume that kinetic and potential energy to be zero said delta q plus w delta is equal to delta u, that is q in minus q out plus w in minus w out is equal to change in internal energy.

Now, if you look at the heat transfer to or from the working fluid, q in is taking place during the constant volume process between process 2 and 3 or states 2 and 3 therefore, q in is u 3 minus u 2 it is constant volume and therefore, q in is equal to c v into T 3 minus T 2.

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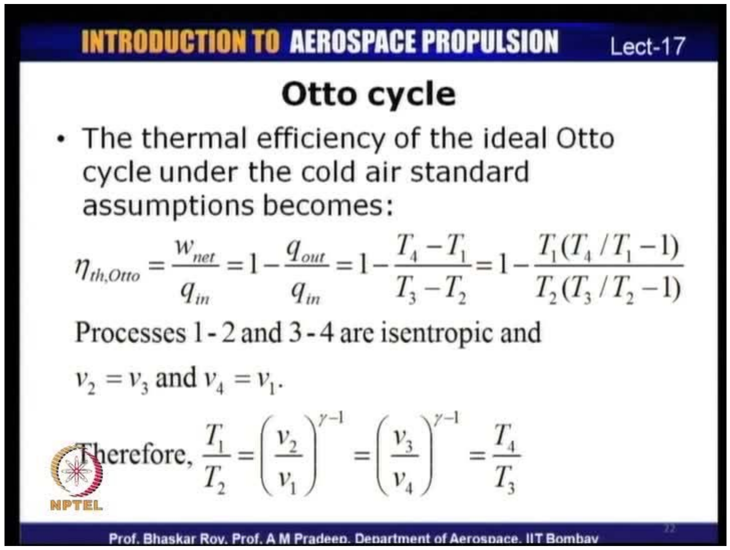

Similarly, q out is again a constant volume process which is u 4 minus u 1 which is equal to c v times T 4 minus T 1. Therefore, thermal efficiency of an ideal Otto cycle with the cold air standard assumption is basically w net by q in that is 1 minus q out by q in which is 1 minus T 4 minus T 1 by T 3 minus T 2, c v gets cancelled out because of the cold air standard assumptions where we assumed that c v does not change which is equal to 1 minus T 1 times, T 4 by T 1 minus 1 divided by T 2 times, T 3 by T 2 minus 1.

We have already discuss that processes 1-2 and 3-4 are isentropic and also that v 2 is equal to v 3 because process 2-3 is constant volume and v 4 is equal to v 1 because process 4-1 is also constant volume. Therefore, the ratio T 1 by T 2 is equal to v 2 by v 1 raise to gamma minus 1 which is equal to v 3 by v 4 raise to gamma minus 1 and which is in fact equal to the temperature ratios T 4 by T 3.

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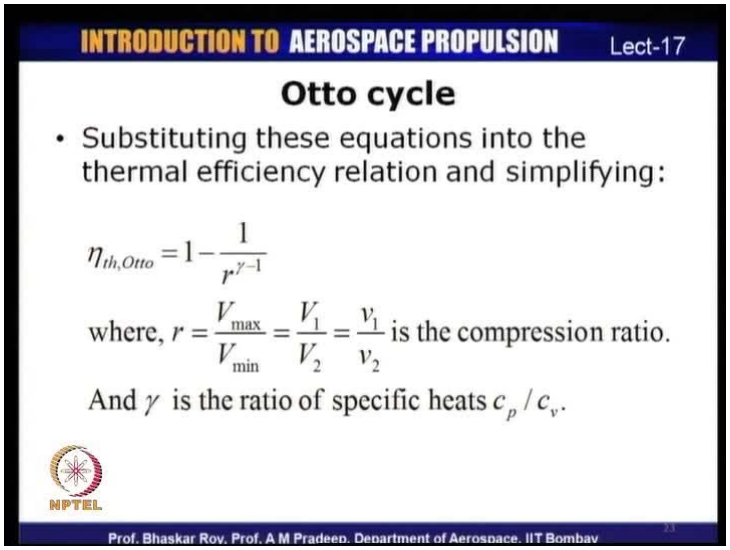

So with these substitutions in the thermal efficiency, that is if you substitute for this temperature ratios there the efficiency of the ideal Otto cycle is 1 minus 1 by r raise to gamma minus 1, where r we have already defined as the compression ratio which is equal to V max by V min which is V 1 by V 2 and gamma here is the ratio of the specific heats which is c p divided by c v.

We can see clearly that the Otto cycle is basically a function of two parameters, primarily the compression ratio which is V 1 by V 2 and it also depends upon the ratio of the specific heats. So Otto cycle efficiency is primarily ideal Otto cycle efficiency is basically a function of the compression ratio and it is also in some sense a function of the ratio of specific heats. As you change the compression ratio, you can also change the efficiency of the ideal Otto cycle.

So for an Otto cycle, we have seen it constitutes of four processes. The first process being an isentropic process followed which is basically a compression process, followed by a constant volume heat addition process, then an isentropic expansion and finally, a constant volume heat rejection process. Efficiency of an Otto cycle basically is a function of the compression ratio and the ratio of specific heats.

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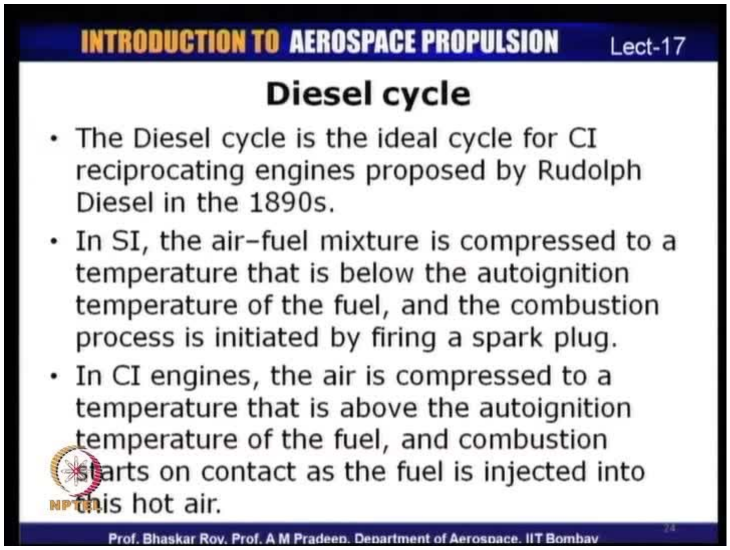

Now, the next cycle which we shall be taking up for analysis is the diesel cycle. Diesel cycle forms the basic thermodynamic cycle for compression ignition engines or diesel engines as we know today. We shall start discussions on how to analyze a diesel cycle very similar to that of the Otto cycle. Diesel cycle is basically an ideal cycle of the reciprocating compression ignition engine, it was proposed way back in 1890s by Rudolph Diesel.

In SI engine as we have seen basically, the air fuel mixture is compressed to a temperature that is still below the Otto ignition temperature and therefore, the combustion is initiated by using a spark plug where as in compression ignition engines, air and fuel mixture is compressed to a temperature which is above the Otto ignition temperature and the combustion basically starts as you inject the fuel into this hot air.

It is basically compression is taken to a temperature which is beyond the Otto ignition temperature and so you do not need a spark plug to initiate combustion in a diesel engine or in a diesel cycle. Let us now look at what are the different processes which constitute a diesel cycle.

What we shall see is that diesel cycle differs from the Otto cycle in only the heat addition process; the other processes remain at least thermodynamically the same. So, diesel cycle basically consists of four processes like in an Otto cycle.

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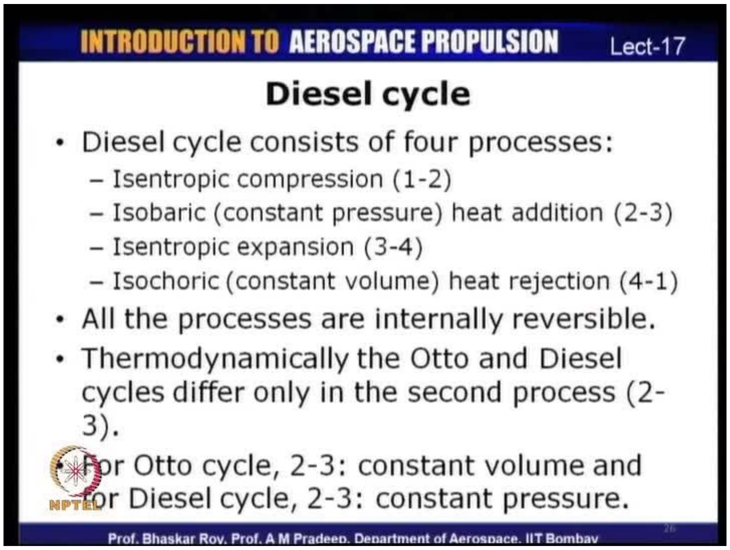

It begins with isentropic compression, process 1-2 is isentropic compression, and then we have constant pressure heat addition unlike an Otto cycle which was constant volume heat addition. So in a diesel cycle, we have constant pressure heat addition which is process 2-3, then an isentropic expansion process 3-4 and the last process is a constant volume heat rejection process.

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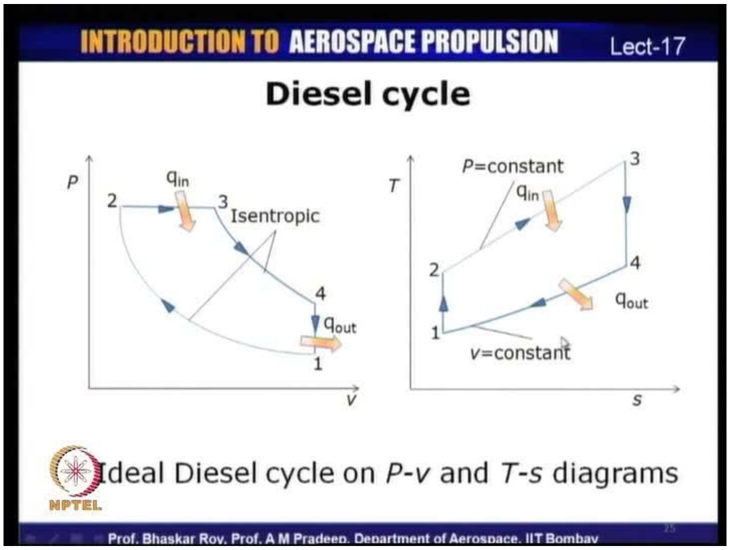

Again, all the processes here are internally reversible and thermodynamically the Otto and diesel cycle differ only in the second process. In the Otto cycle, it is constant volume heat addition, diesel cycle it is constant pressure heat addition. This is the ideal diesel cycle on P-v and T-s diagrams; so the process begins or the cycle begins at state 1, there is an isentropic compression which takes the cycle to state 2.

Basically, from state 2 to state 3 it is constant pressure process during which heat is added or q in takes place during process 2-3 which is constant pressure heat addition. Process 3-4 is again isentropic expansion and there is expansion from state 3 to state 4 which means there is a drop in pressure and increase in the volume.

At the end of third process, there is a constant volume heat reduction q out takes place during process 4-1. On the T-s diagram process, 1 to 2 is isentropic therefore, it is a vertical line, process 2-3 is p is equal to constant - it is a constant pressure process during which heat is added to the cycle, q in takes place during this process, process 3-4 is isentropic expansion and process 4-1 is constant volume heat rejection, q out takes place during the process 4-1.

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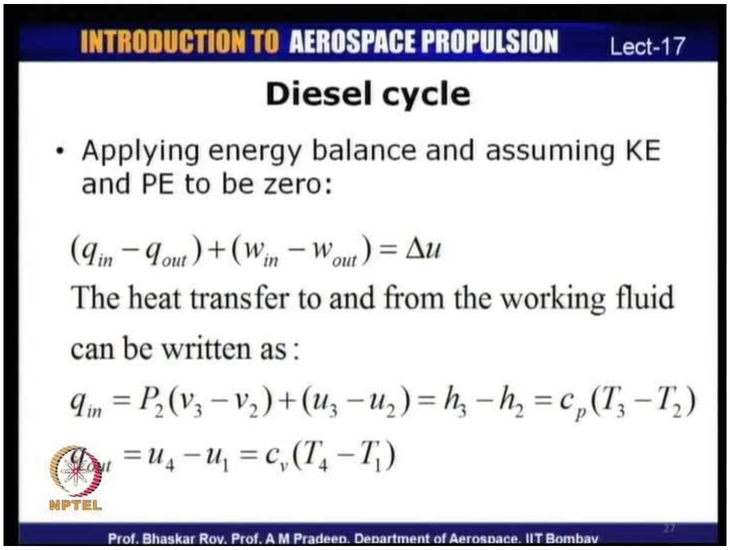

These are four different processes which constitute the diesel cycle and as I mentioned it differs from the Otto cycle only in the second process which is the heat addition process, other processes remain the same. We will now derive the expression for the thermal efficiency of a diesel cycle in a manner which is similar to that of the Otto cycle.

Basically, we will be carrying out an energy balance across the cycle and account for the different work and heat interactions. So, if you apply the energy balance, assuming kinetic and potential energy to be 0 as we did in Otto cycle, so we have delta q plus delta w is equal to delta u. So, q in minus q out plus w in minus w out is delta u, q in is equal to P 2 times v 3 minus v 2 plus u 3 minus u 2, which is h 3 minus h 2 that is basically change in enthalpy here, because it is a constant pressure process and therefore, it is c p times T 3 minus T 2, q out on the other hand is c v times T 4 minus T 1.

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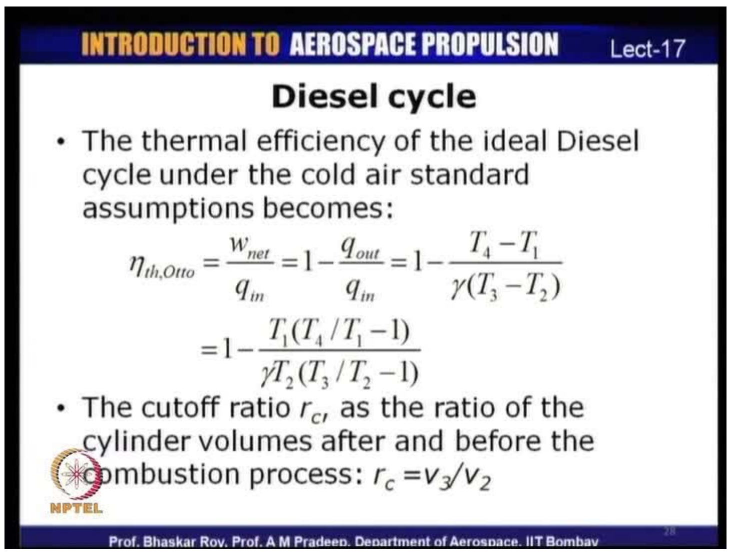

So thermal efficiency of an ideal diesel cycle is basically w net by q in which is 1 minus q out by q in which is equal to 1 minus T 4 minus T 1 by gamma times T 3 minus T 2. This gamma has come because we have ratios c v on the numerator and c p on the denominator, so it is c p by c v which is gamma. We can simplify this as 1 minus T 1 times T 4 by T 1 minus 1 divided by gamma times T 2 multiplied by T 3 by T 2 minus 1. So we will now define a ratio which is known as the cut off ratio, which is represented by r c.

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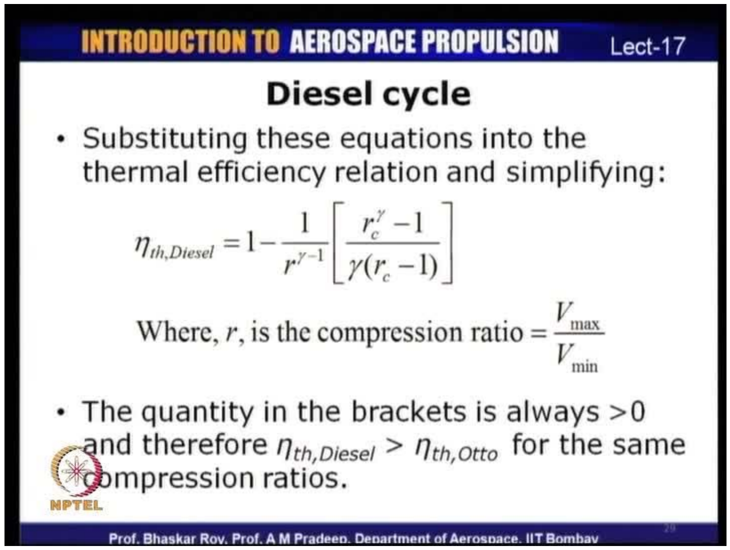

Cut off ratio is the ratio of the cylinder volumes after and before the combustion process. So, r c equal is to v 3 divided by v 2, so if we were to assume this ratio which is the cut off ratio then, we have the ideal efficiency or efficiency of the ideal diesel cycle as 1 minus 1 by r raise to gamma minus 1 multiplied by r c raise to gamma minus 1 divided by gamma times r c minus 1, where r is the compression ratio which we have defined even in the Otto cycle, v max by v min.

Now, what we see is that one part of this efficiency definition is very identical to that of the Otto cycle and the term in the bracket is different for the diesel and the Otto cycle. This quantity in the bracket is always greater than 0, as we can see r c is parameter greater than 1.

So, it will always be greater than 0 which means that efficiency of the diesel cycle will always be greater than efficiency of an Otto cycle for the same compression ratio. That is as long as you keep the compression ratios same, then diesel cycle will have an efficiency which is always greater than that of an Otto cycle. It is basically because in an ideal cycle the efficiency term also has a parameter in the bracket which always greater than 0.

So, efficiency of a diesel cycle and an Otto cycle if you were to compare, diesel cycle will usually have higher efficiency because of the fact that the term in the brackets is always greater than 0. In an actual engines, if you were to compare the compression ratios of diesel engines and SI engines or sparking ignition engines, diesel engines usually have much higher compression ratios than sparking ignition engines which means that if you were to have a diesel engine which is operating at compression ratios low as low as that of Otto cycle or sparking ignition engines obviously, the efficiencies will be different.

In actual practice, the compression ratios of diesel cycles or diesel engines are usually much higher than the compression ratios of Otto cycles or sparking ignition engines. It is basically because, as you increase the compression ratio the temperature at the end of the compression process will be higher, which means that you might reach temperatures which are very close to that of the Otto ignition temperature, which is not something that is desirable for a spark ignition engine because in a spark ignition engine, you would like to initiate combustion when you have the spark plug which is switched on, you do not want the fuel air mixture to be self-ignited which is not the case for compression ignition engines.

In the case of compression ignition engines, you would want the fuel air mixture to self-ignite, there is no spark plug there and you require a self-ignition to be taking place there. Therefore, there is a difference in the efficiencies of these two different cycles.

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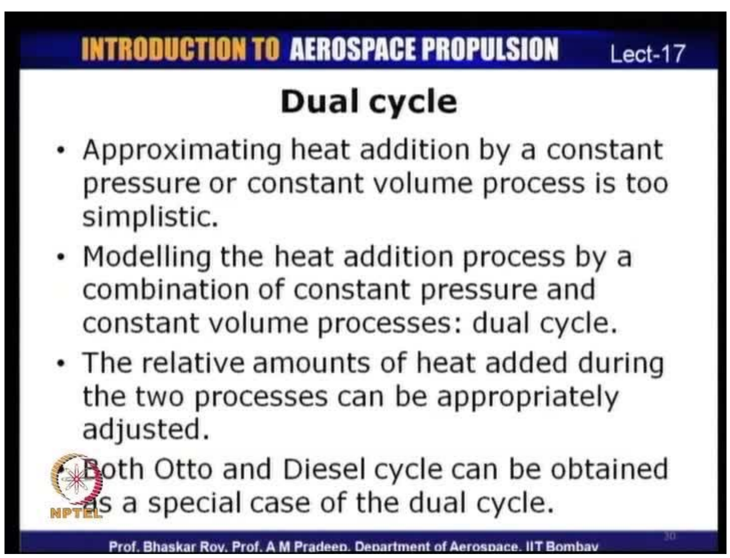

So what we have discussed are two different cycles. One is the Otto cycle and the diesel cycle and as we have seen there is a difference between the Otto and the diesel cycle primarily because of the heat addition process. In one case, the heat addition was at constant volume and in the other case heat addition was at constant pressure which was in the diesel cycle.

Now in an actual practice if we look at an actual cycle, the heat addition process is if you were to approximate it either as constant volume or simply as constant pressure that is too much of a simplification. So, actual process or actual cycles will not have heat addition taking place either at constant pressure or at constant volume alone. Therefore, it makes sense to model the heat addition process by a combination of constant pressure and constant volume processes.

That is we will have the second process which is the heat addition process comprising of both a constant pressure process as well as the constant volume process. You can actually adjust the relative amounts of heat added during these two processes depending upon the cycle itself.

So depending upon how much is the contribution of the constant pressure process or how much the contribution of the constant volume process, you can adjust the ratio of the heat addition during these two processes. A cycle which consist of heat addition process which has both these constituents; that is it has a constant volume process as well as a constant pressure process that is known as a dual cycle.

We can clearly see that both Otto cycle as well as diesel cycle can be obtained as a special case of the dual cycle. That is you can always infer or you can always approximate or derive the Otto or diesel cycles from the dual cycle because dual cycle has the second process which is common to both Otto as well as diesel cycle. That is in the case of dual cycle, you have a constant volume heat addition as well as constant pressure heat addition. In the case of an Otto cycle, you have only the constant volume heat addition part and in the case of diesel cycle, you just have constant pressure heat addition.

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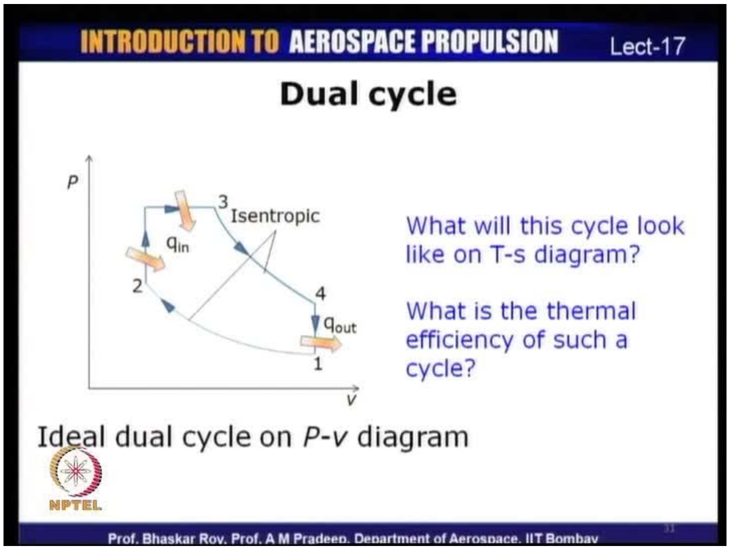

So let us look at the P-v diagram of a dual cycle. So, on a P-v diagram basically a dual cycle would look like this. The first process is the same that is you have process 1 to 2 which is an isentropic process. The second process which may have which is between states 2 and 3 would have both components; that is a constant volume process as well as a constant pressure process.

How much of constant volume and how much of constant pressure is something that can be adjusted depending upon the cycle itself. So heat addition takes place during both these processes. Process 3 to 4 is isentropic expansion process; 4 to 1 is constant volume heat rejection that is isochoric heat rejection. I have shown a dual cycle only on a P-v diagram here.

So I will leave it as an exercise for you to see how this diagram would look like on a T-s scale. That is if you were to plot the dual cycle on a T-s diagram on how would it look like, basically the three of the processes remain the same like diesel and Otto cycle; difference is only in the second processes where you have both components that is you have a constant volume part as well as a constant pressure part. You can also derive the thermal efficiency for such a cycle because we have already derived thermal efficiency for Otto cycle and diesel cycle separately and the difference was only in the second part.

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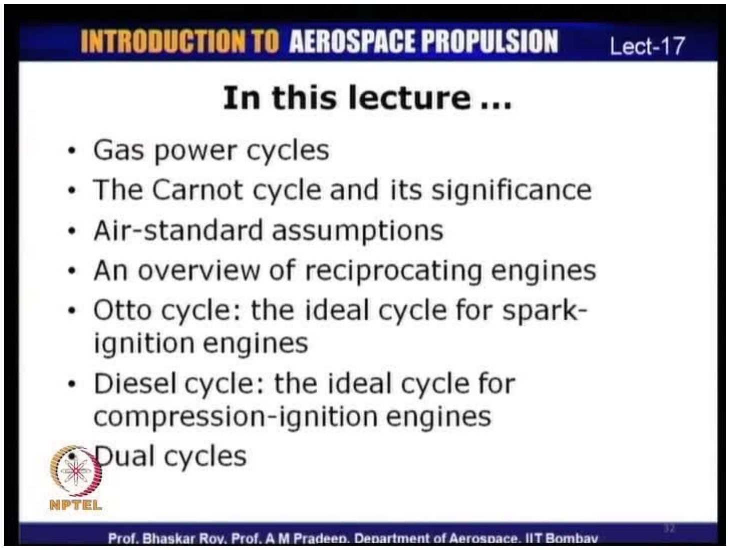

You can actually derive the thermal efficiency for a dual cycle and see how it compares with Otto cycle as well as diesel cycle. You can also actually see if you can derive the expression for efficiency of an Otto cycle and diesel cycle, if you were to assume that in one case the constant pressure processes is absent and the other case the constant volume process is absent. So, you can actually derive the efficiency for both these cases as a subset of the dual cycle. So that brings us to towards the end of this lecture.

Let us take a quick look at what we have discussed in today's lecture. We started our discussion today with discussions on the gas power cycle, the importance of analysis of gas power cycles. Then we also discussed about the Carnot cycle, we revisited the Carnot cycle and had some discussion on what is the significance of the Carnot cycle. Then we discussed about the assumptions that we make for analyzing ideal Otto and diesel cycles which are known as the air standard assumptions.

We had a very quick, very brief overview of reciprocating engines and the different terminologies used for reciprocating engines and then we started off with the discussion on the Otto cycle which is the basic thermodynamic cycle for spark ignition engines.

We then discussed about diesel cycles, which is the basic thermodynamic cycle for compression ignition engines process. Then we discussed about the dual cycle which constitutes of the heat addition process, which has both constant volume as well as constant pressure components of heat addition.

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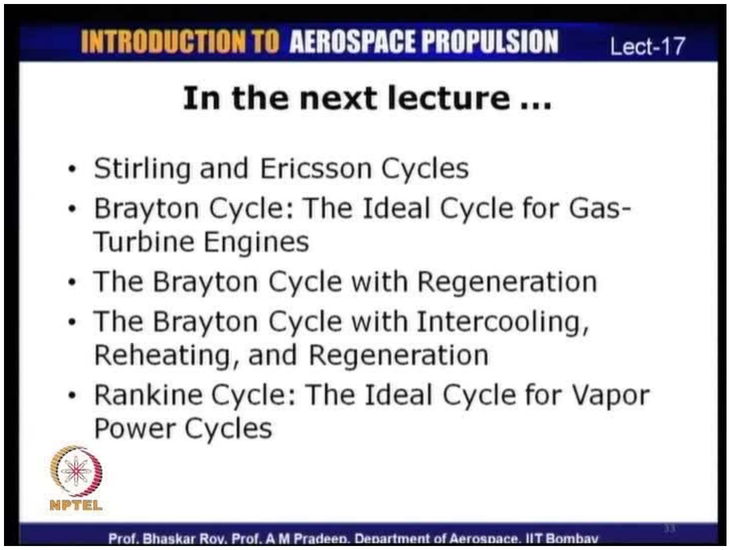

So this is what we had discussed in today's lecture and in the next lecture, we shall be taking up the following topics. During the next lecture, we shall be discussing about these: we will have quick discussion on Sterling and Ericsson cycles. Then we will talk about the Brayton cycle which forms the ideal cycle for gas turbine engines.

We will then talk about Brayton cycle with regeneration, Brayton cycle with inter cooling, reheating and regeneration. Then we will take up one vapor cycle which is the Rankine cycle, we will have some discussion on the ideal cycle for vapor power cycles which is the Rankine cycle, basically the power cycle for steam turbines or steam engines. So, this is what we shall be discussing during the next lecture that will be lecture 18.