Introduction to Aerospace Propulsion

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Module No. # 01

Lecture No. # 33

Ideal Cycles for variants of jet engines

Hello and welcome to lecture number 33 of this lecture series on introduction to aerospace propulsion.

We have been discussing over the last lecture about the ideal cycle analysis for gas turbine engines. So we started our discussion in the last lecture on trying to derive an equation for thrust and other performance parameters of a jet engine like the fuel consumption, the specific fuel consumption, the thrust specific fuel consumption and the different efficiencies like the thermal efficiency, the propulsion efficiency and the overall efficiency. These are some of the performance parameters that we can define for evaluating the performance of air breathing engines.

In the last lecture, we had our discussion on the ideal cycle analysis for turbojet engines. So, turbojet engines are one of the basic forms of jet engines and we have done the cycle analysis for that which primarily involved trying to determine the performance across each of the components in terms of the temperature and pressure, then subsequently for each of the components which constitute a turbojet engine.

Once we reach the nozzle of the turbojet engine, we can find out the exhaust velocity and from the exhaust velocity, we can find out the thrust that the engine is going to develop under those circumstances. Once we calculate the thrust, we can also determine other performance parameters like the fuel consumption as well as the efficiencies. So that was the basic cycle analysis procedure that we had followed and we had discussed in the last lecture.

So in today's lecture, we are going to continue with discussion on that but, we shall be taking up variants of turbojet engine. We shall be discussing about one of the most popularly used jet engines in current day civil aviation that is the turbofan engines. We shall be discussing in detail about turbofan engines and how we can carry out a cycle analysis for turbofan engines.

There are some different variants of turbofan engines as well that we shall be discussing about and some of those analysis, I shall probably be leaving it to you for carrying out an exercise on the cycle analysis of some of the variants of the turbofan engine. Then we shall also move on to discuss some of the other types of jet engines which are used like the turboprop engines, the turbo shaft engines and also in very brief about the ramjet engines which we shall take up towards the end of this lecture.

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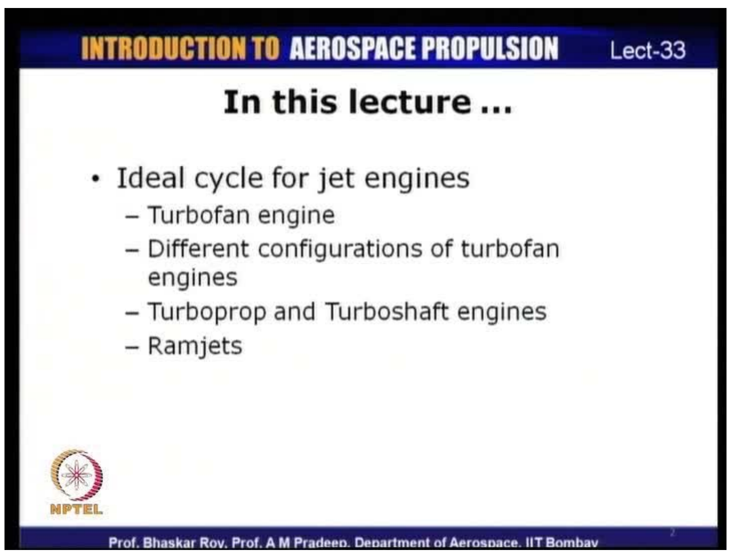

Let us take a look at what we are going to discuss in today's talk. We shall be discussing about ideal cycle again, we are not taking into account efficiencies of different components, we shall be discussing about the ideal cycles. We will begin with the turbofan engine, turbofan engine which constitutes of different components most of which are similar to what is there in a turbojet engine but, there are is an additional component in turbofan engine which is basically the fan. There are different configurations of turbofan engines which we shall be discussing in detail depending upon the particular configuration, that the turbofan engine is operating on the cycle analysis needs to be modified slightly depending upon what configuration it is.

We shall then be discussing about two other popular engines which are in use the turboprop and the turbo shaft engines. Turboprop and turbo shaft engines are also used primarily in of course, they are used in military as well as in civil aviation but, many of the civil aircraft which probably you might have seen are flown would be using the turboprop engines usually with those engines are used in smaller aircraft which have lesser seating capacity.

The high bypass turbofan engines what are used in most of the large class jet engines and aircraft like some of the larger aircraft which carry about 300 to 400 passengers or even more, all of them use the turbofan engines. Turbo shaft engines are used in helicopters and of course, they have both civil as well military applications. Then we shall also be discussing about ramjet engines which are very simple form of a jet engine. In fact it is even simpler than a turbojet engine but, it is not being used for any civil application its primarily for missiles and probably for some of the futuristic aircraft applications that ramjets might probably be used a little later on, but currently it is primarily used in missiles.

So, these are some of the topics we shall be discussing in today's lecture and so we will begin our discussion with discussion on the turbofan engines. Now let us understand why we need a turbofan engine in the first place. We have seen in one of the performance parameters that, we can use to evaluate the performance of a jet engine is the propulsion efficiency.

You already learnt in a great detail about the propeller based engines and we have also seen that the propeller the based engines have very high propulsion efficiency as compared to the pure jet based engines, let us say the turbojets. So, if you compare the propulsion efficiency of a jet engine a turbojet engine with that of a propeller based engine, the propulsion efficiency is much higher for a propeller based engine as compared to turbojet engines. So, if the propulsion efficiency is higher, this also contributes to the overall efficiency of the engine.

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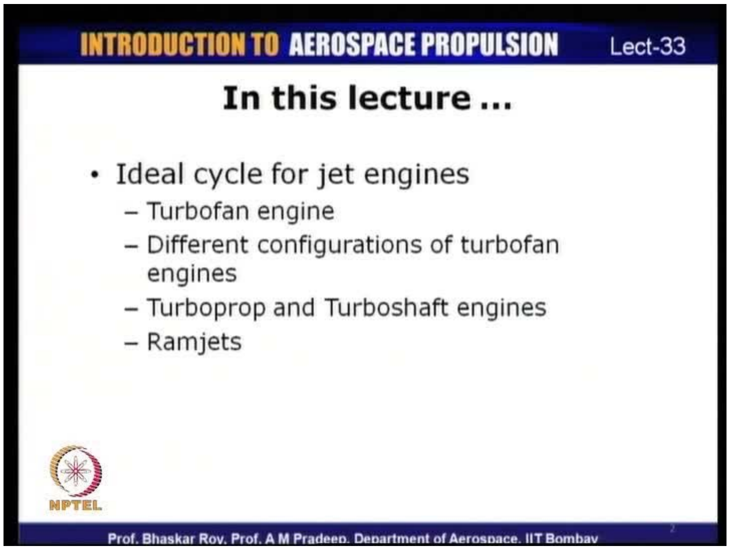

This is one of the parameters which we shall make use of in trying to modify the basic jet engine, so that we have a better overall efficiency as well. What we shall be doing is that if we can increase the propulsion efficiency of the jet engine in some way, then it means that we will also have a higher overall efficiency. So in order to do that, we need to increase the front stages of the compressor in terms of the diameter; we have a larger diameter and therefore, the mass flow rate associated with that fan will also be higher but, it will exhaust at a velocity which is lower than that of the core engine and therefore, the propulsion efficiency can be increased.

Turbo fan engines are characterized by the presence of huge fans which are placed ahead of the compressor. So, if you had a chance to take a closer look at the aircraft engine, which is used in most of the commercial civil aircraft, you might have seen that the first component that you see is this huge fan and that is the main difference between a turbofan engine and a turbojet engine.

This is something which you could see either if you are in an airport waiting for the plane or if you are boarding in aircraft then you probably will get a chance to see the engine in little bit detail or at least the next time you board an aircraft, make sure you can have a view of the engine, you will notice that there are these huge fans. The basic reason that these fans are present is that firstly they of course, give you a higher mass flow rate and we have seen that thrust is a direct function of mass flow rate and the other reason is that it will also have an effective lower exhaust velocity. Therefore, the propulsion efficiency can be higher, which means that turbofan engines in general can have higher overall efficiency.

But besides this, turbofan engines also have a higher thermal efficiency which we shall see a little later but, the only issue is that because they have larger diameters, the overall drag of the aircraft can be higher but, this can be compensated by the fact that turbofan engines can generate larger thrust because of the presence of the fan which generates a lot of mass flow rate through the engine which is higher than that of the core mass flow.

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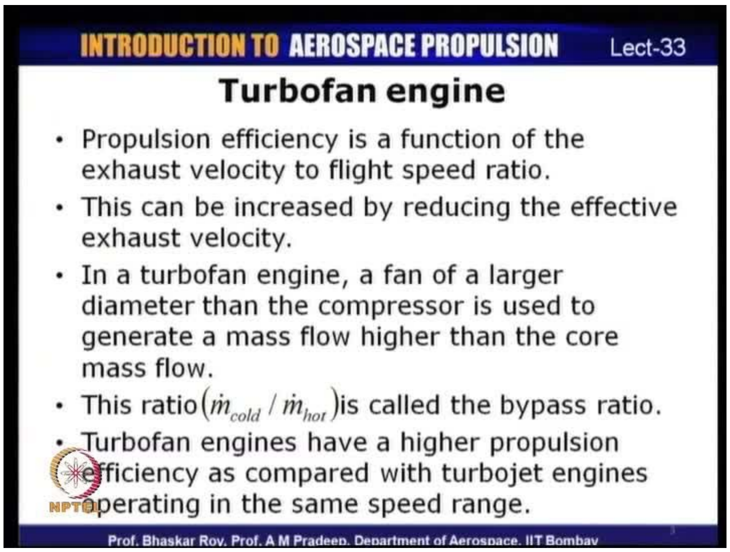

If you take a look at the turbofan engine characteristics, the first two points is what I was mentioning about that propulsion efficiency is one aspect, which turbofan engines will have higher than turbojet engines because the effective exhaust velocity is lower and we can do that by increasing the fan diameter. In a turbofan engine a large diameter fan is used ahead of the compressor, it generates a mass flow which is higher than that of the core mass flow. So, this ratio of the fan mass flow to the core mass flow is called the bypass ratio.

This bypass ratio for modern turbofan engines can be as high as 6 or even 7 which means that the mass flow which is being generated by the fan is six times greater than the mass flow which is passing through the core engine. So, six times the mass flow actually goes through the bypass duct and therefore, your overall thrust can be higher because the mass flow is much higher than what you get in the core which also contributes to thrust. At the same time, you also have a lower effective exhaust velocity and hence increased propulsion efficiency, so turbofan engines will in general have propulsion efficiencies which are higher than that of the conventional turbojet engines.

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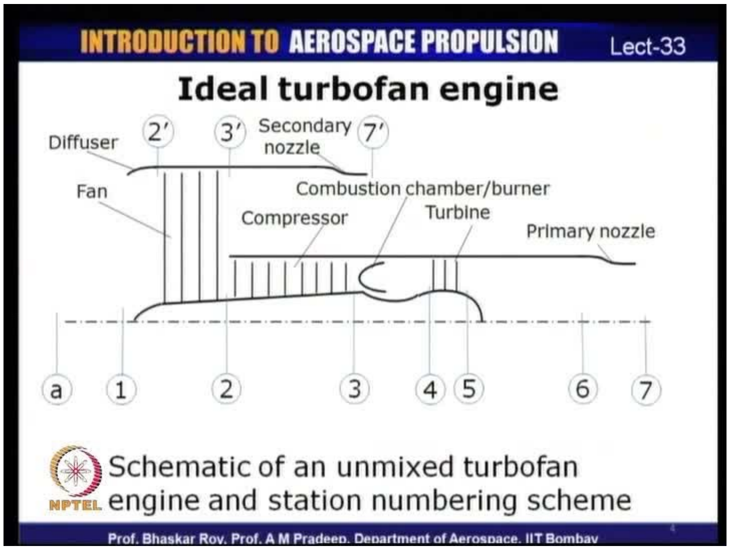

Now let us take a look at a schematic of a turbofan engine, we have already seen that for a turbojet engine. Let us now see, how we can analyze a turbofan engine and the different types of turbofan engines which are in existence. A schematic of turbofan engine is shown here and what is shown here is a schematic of an unmixed turbofan engine. Unmixed turbofan engine means that there are two separate exhausts, there is one exhaust from the fan and the other exhaust is the core engine that is the primary nozzle.

Let me explain, the different components of a turbofan engine. So turbofan engine like the turbojet has a diffuser and immediately following the diffuser is a fan; you can see that the fan diameter is much higher than that of the compressor. This is the compressor (Refer Slide Time: 11:34), fan diameter is much higher than that of the compressor. Then downstream of the compressor, we have the combustion chamber which is where the primary heat addition takes place. Then we have a turbine which could be in multiple stages, we could have different stages of turbines.

After the turbine, we have the primary nozzle and after the fan you might notice that there is a secondary nozzle. So, you could have exhaust velocities from the secondary nozzle as well as from the primary nozzle, both of them contribute to the thrust.

If we were to carry out a cycle analysis we have already seen, we normally follow a certain convention for station numbering. For the core engine it is pretty much the same as what we had done for the turbojet engine that we have stations a for the free stream, 1 for diffuser inlet, 2 for the compressor inlet, 3 for compressor outlet, 4 for the turbine inlet, 5 for turbine exit, 6 is the nozzle entry, 7 is nozzle exit.

For the bypass duct, we shall denote these numbers with a prime. So 2 prime refers to the fan inlet, 3 prime refers to the fan exhaust which means, 3 prime and 2 for the core stream are the same and the secondary nozzle exhaust is 7 prime. These are different components of a turbofan engine which is often unmixed configuration that is these 2 streams do not mix within the engine vaults. Now it is also possible to have a turbofan engine, where these 2 streams mix and that is known as a mixed turbofan engine, which is what I shall show in the next diagram.

This is a mixed turbofan engine, where the core mass flow mixes with the cold mass flow before exhausting through a single nozzle (Refer Slide Time: 13:33). So here, there is only a single nozzle and therefore, this is very similar to that of a turbojet engine and such engines usually have a lower bypass ratio as compared to the high bypass which I had shown earlier. So such engines are also sometimes referred to as low bypass turbojets because these bypass ratios are very small and they are mixed. The mixing is done for other reasons as well for military advantages to reduce the infrared signatures and so on.

This is a schematic of a mixed turbofan (Refer Slide Time: 14:14), here the analysis would be very similar to what we had seen for a turbojet engine, just that we have to calculate the properties in the mixture and which is basically done by an enthalpy balance of these two streams.

These are the different components of a turbofan engine in two of its configurations. Now, there are multiple ways of operating a turbofan engine, you could have a turbofan engine with a single spool that is the compressor, the fan and the turbines are mounted on the same shaft. But, that is a little unrealistic or an inefficient way of operating a turbofan because if you mount all of them on the same shaft, it means that all the stages have to run at the same speed; so there are operational issues with regard to running the fan and compressor at the same speed.

Normally it is practiced to split the different turbo machines on and mount them on separate spools or shafts. You could have a turbofan with two spools or a twin spool turbofan where usually we have the fan and the low pressure compressor; that is the initial stages of the compressor which is attached to later stages of the turbine and that is known as a low pressure turbine.

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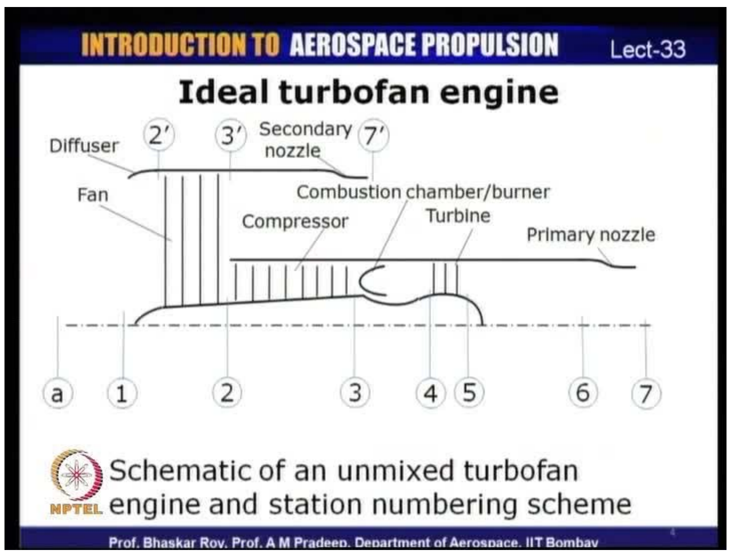

The later stages of compressor are known as high pressure compressor is driven by the initial stages of the turbine, which is the high pressure turbine. So, this is a twin spool configuration, you could also have a 3 spool configuration where the fan is driven by the LPT that is low pressure turbine, the LPC that is low pressure compressor is driven by an intermediate pressure turbine or IPT and the HPC that is high pressure compressor is driven by the high pressure turbine. These are different configurations of a turbofan and all these 3 configurations could either be operating in a mixed mode or an unmixed mode.

We can see that there are a different varieties of turbofan engines or configurations possible and cycle analysis for each of them though the basic philosophy is the same; they could be slightly different depending upon which configuration of the engine is being analyzed at the moment. So what we shall do is to analyze the cycle analysis for an ideal turbofan engine for one of these configurations and the others can be carried out in a very similar fashion. We shall only discuss that in a very short duration for that time.

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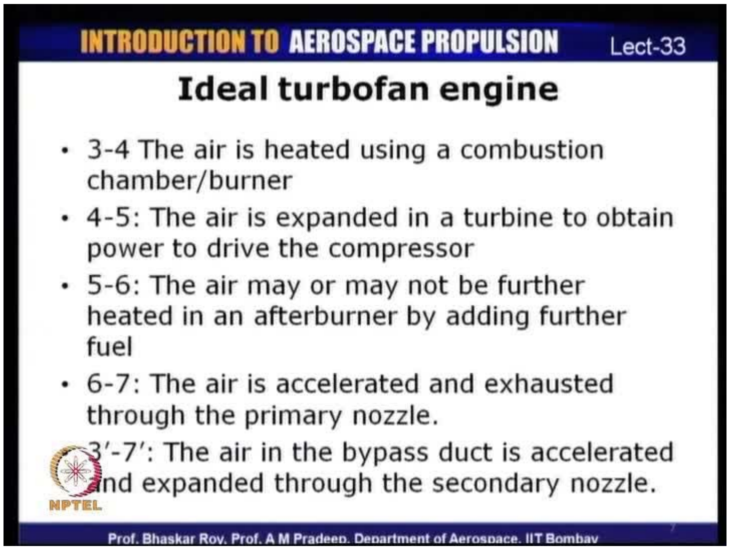

Let us take a look at one of the configurations of an ideal turbofan. Now the different processes which are involved in an unmixed turbofan cycle constitute the first process that is a to 1 which is air intake from the far upstream, which involves air from the far upstream brought to the air intake with some acceleration or deceleration. Well, you could also have intakes where there is either acceleration or deceleration depending upon the operating condition. We will not discuss that in detail here; it is out of the scope of the current syllabus.

The second process is 1 to 2 dash or 1 to 2 prime, where the air is decelerated as it passes through the diffuser. 2 prime to 3 prime is the compression process in the fan and 2 to 3 is the compression process in the compressor which could be either an axial compressor or centrifugal, most of the cases it is indeed an axial compressor which is used. 3 to 4 is the combustion process of the core engine; air is burnt or heated in a combustion chamber. 4 to 5 is air is expanded in a turbine to obtain power to drive the compressor, so this process that is 4 to 5 could happen in different stages depending upon the number of stages that are involved.

5 to 6 is there could be an afterburner or normally in a turbofan it is unusual to have an afterburner but, there have been engines which have low bypass ratios and still have afterburners. 6 to 7 is the nozzle, the primary nozzle where air is expanded through the primary nozzle. 3 prime to 7 prime is the air in the bypass duct is accelerated and expanded through a secondary nozzle. So, secondary nozzle is the nozzle which is present in the cold stream and does not take part in the combustion where as the primary nozzle is the one which passes the air or combustion products which is coming from the turbine after the combustion and then it gets expanded through the nozzle.

So there could be two distinct nozzles or you could have a single nozzle which is what would be in a mixed turbofan where both these streams are mixed. You can have turbofan engines which are operating in different modes and what we shall do is take up one of these for our cycle analysis. Let us say, we take up one case where we have the turbine there are 2 stages of turbine a twin spool turbofan, where the fan is driven by the one of the stages of the turbine and the compressor is driven by the another stage of a turbine. So let us say, the turbine consists of 2 stages; 1 stage drives the fan, other stage drives the compressor. We shall do a cycle analysis for this case and other cases we will discuss in a little bit detail.

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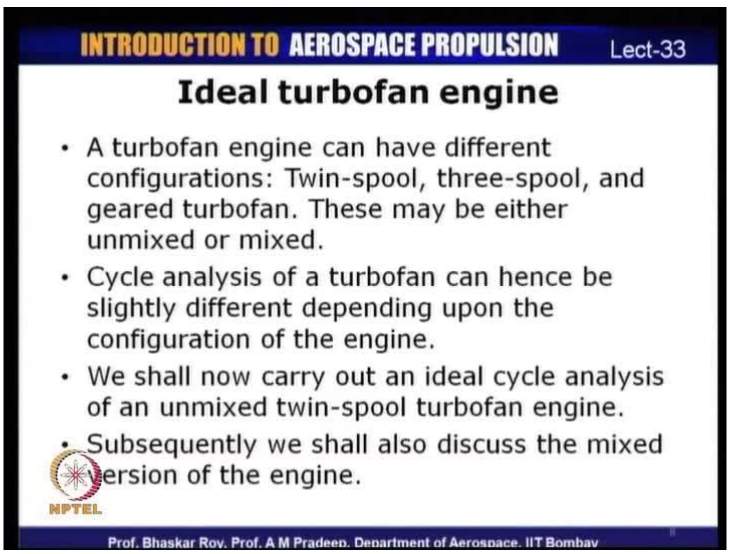

So, depending upon what configuration the turbofan is operating on the cycle analysis can be slightly different depending upon what configuration it is. We will carry out an ideal cycle analysis for an unmixed twin spool turbofan engine then of course, there are also mixed versions of the same engine.

So like we did for the turbojet engine, we shall be carrying out cycle analysis by considering the components one by one. Then based on some of those parameters which are known a priory like the ambient conditions and the Mach number are fixed, the compressor pressure ratio, the fan pressure ratio and the turbine inlet temperature are also designed, parameters which are fixed or known a priory; so based on these known parameters we can now carry out the cycle analysis.

Let us take up the first component that is the intake. For an intake we should know the ambient pressure, the temperature and the Mach number. Therefore, P a which is the ambient pressure, static pressure T a and the Mach number are fixed. Now based on this the intake exit conditions which is T 02 prime is equal to T a into 1 plus gamma minus 1 by 2 M square. So, this is following the isentropic relations because the compression in the intake is assumed to be isentropic for an ideal cycle.

P 02 prime is the stagnation pressure at the intake exit which is equal to P a into T 02 prime divided by T a raise to gamma by gamma minus 1, which is again as a consequence to the isentropic nature of this process.

The second process or the component which follows the intake is the fan and for the fan we know that, the fan pressure ratio is a design parameter which is known. Therefore, pi f which is the fan pressure ratio is equal to P 03 prime divided by P 02 prime ,where P 0 3 is the fan exit stagnation pressure. Therefore, P 03 prime that is fan exit stagnation pressure is equal to pi f fan pressure ratio into P 02 prime, P 02 prime has already been calculated.

The fan exit stagnation temperature is T 03 prime which is equal to T 02 prime into pi f raise to gamma minus 1 by gamma, where pi f as we know is the fan pressure ratio. So these are the first two components of a turbofan engine the intake and the fan. Both these processes are isentropic for an ideal cycle and in fact the next process which we shall see that is the compressor will also be an isentropic compression process and so for the compressor, the cycle analysis which involves isentropic relation is similar to what we did for the turbojet.

So for the compressor the known parameter is the compressor pressure ratio, which is fixed. The compressor inlet pressure is known stagnation pressure is known because the fan exit stagnation pressure should be equal to the compressor inlet stagnation pressure. So, P 03 prime should be equal to P 02 which is the inlet stagnation pressure of the compressor similarly, the stagnation temperatures. So, based on that since we know the compressor pressure ratio we can find out the compressor exit conditions the temperature and pressure and just the same way as we did for the turbojet engine.

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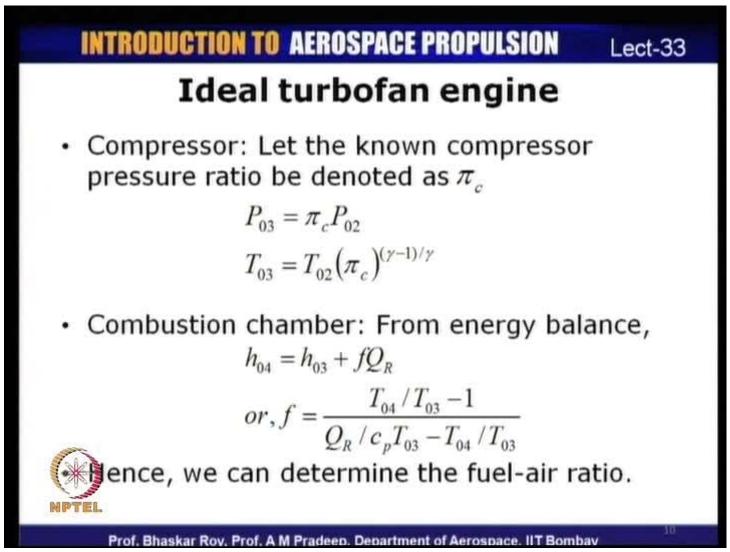

So for the compressor, we have P 03 which is the compressor exit pressure, stagnation pressure is equal to pi c into P 02 where P 02 should be equal to P 03 prime and P 03 prime is the fan exit stagnation pressure. Similarly, T 03 is equal to T 02 into pi c raise to gamma minus 1 by gamma, here T 02 that is the compressor inlet stagnation temperature should be equal to fan exit stagnation temperature that is T 03 prime.

These are the compressor exit conditions; the stagnation temperature and the pressure. Now we move on to the combustion chamber, combustion chamber analysis is something you are already familiar with we did that in the turbojet. What we do is to carry out an energy balance across the combustion chamber, so at the inlet we have conditions of pressure and temperature coming from the compressor then fuel is added in the combustion chamber and we find out the exit conditions.

So h 04 is the stagnation enthalpy at the combustion chamber exit, this should be equal to stagnation enthalpy at the inlet which is h 03 plus the fuel flow rate that is f into Q R which is the heat of reaction of that particular fuel.

From this by simplification because we are assuming it to be ideal gas here with constant specific heats, so h 04 should be equal to c p into T 04 which is equal to c p T 03 plus f into Q R. So, from this we can find out the fuel to air ratio that will on simplification we get the fuel to air ratio as T 04 by T 03 minus 1 divided by Q R divided by c p into T 03 minus T 04 by T 03.

So from this, we can find out the fuel to air ratio. The fuel to air ratio we can find because we have the conditions at the inlet and the conditions at the outlet of the combustion chamber because the turbine inlet temperature that is T 04 as I already mentioned is a design parameter. So that should be known a priory, once that is fixed and inlet conditions are obtained from the compressor analysis, we get the inlet stagnation pressure and temperature, so we can find the exit conditions. In an ideal cycle, we assume that there is no pressure loss occurring in the combustion chamber therefore, P 04 should be equal to P 03.

Now we have the properties up to the combustion chamber inlet or combustion chamber outlet or the turbine inlet. In the turbine the analysis is now going to be slightly different from what we did for the turbojet because here we have a twin spool engine, where there are two stages of turbines one driving the compressor and the other driving the fan.

Now the first stages of the turbine, first few stages or at least it could 1 or 2 stages is known as the high pressure turbine because that is the turbine stage which is operating at the highest temperature and that is therefore, known as the high pressure turbine. High pressure turbine is going to drive the compressor because compressor requires more work than a fan and the later stages of the turbine which is known as the low pressure turbine or LPT will be driving the fan because fan requires lesser work than the compressor as a whole.

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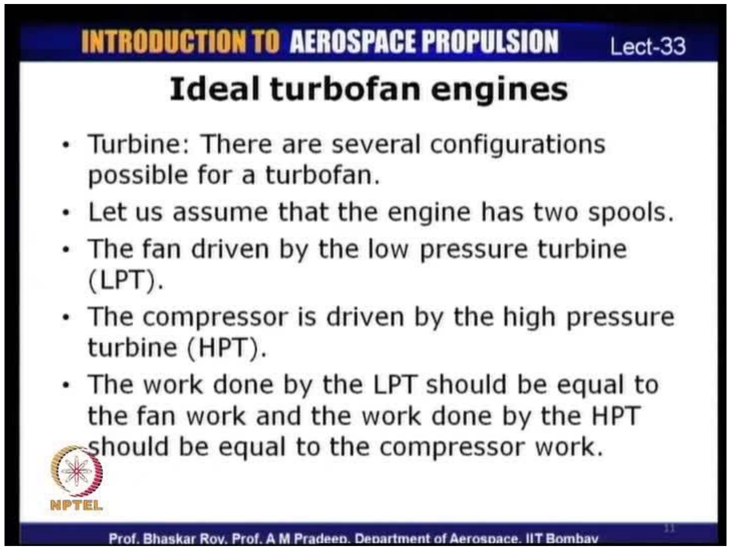

We have to now split the compressor well the turbine stages into two and so the high pressure turbine drives the compressor, low pressure turbine drives the fan. If you have to do that now depending upon the type of configuration we are going to use we have already assumed that the engine is going to have 2 spools, now if the engine has 2 spools the fan will be driven by the low pressure turbine and the compressor is driven by the high pressure turbine.

How do we calculate the properties across this? The work done by LPT that is low pressure turbine should be equal to the fan work and work done by the high pressure turbine which is HPT should be equal to the compressor work. So, we are going to carry out a work balance between the fan and the low pressure turbine and then the compressor and the high pressure turbine. Since, initial stages are the high pressure turbine and we know the turbine inlet temperature, which is the high pressure turbine inlet temperature we will use that for carrying out the work balance.

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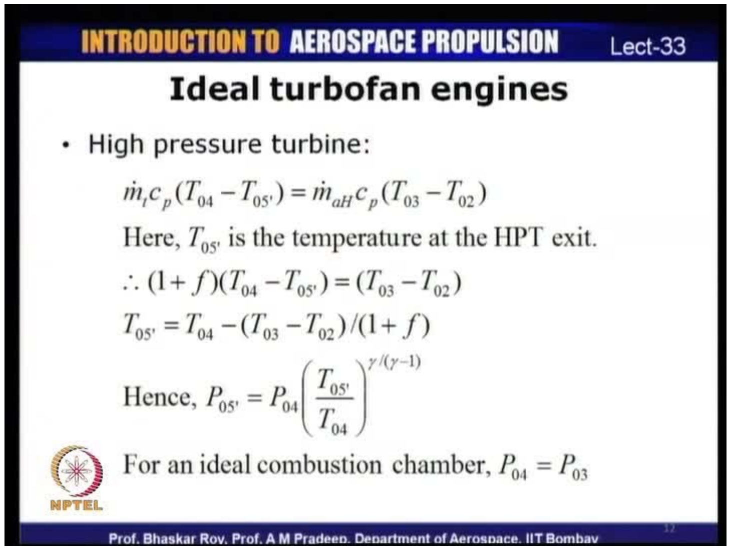

Now, for the high pressure turbine which is the first component after the combustion chamber, the work done by the high pressure turbine should be equal to the work required for the compressor. So if we equate the two, we have m dot t which is mass flow rate through the turbine, which is the mass flow rate coming in from the compressor plus the fuel flow rate multiplied by c p into T 04 minus T 05 prime. So here, T 05 prime is the temperature at the high pressure turbine exit - HPT exit; this should be equal to m dot which is the mass flow coming in from the compressor. The subscript h denotes hot exhaust or the hot core of the engine multiplied by c p into T 03 minus T 02.

Now from this, we can find out the h p turbine stagnation temperature at the exit of the h p turbine, so T 05 prime is equal to T 04 minus T 03 minus T 02 by 1 plus f. Similarly, P 05 prime is equal to P 04 into T 05 prime by T 04 raise to gamma by gamma minus 1, where P 04 is equal to P 03 for an ideal cycle; there is no pressure loss in the combustion chamber, so the stagnation pressures are the same.

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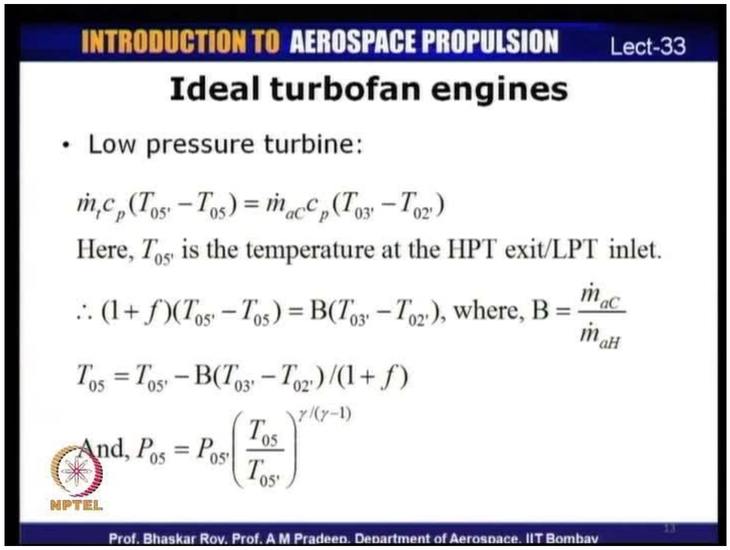

Now after the high pressure turbine, we move on to the low pressure turbine. Here, the low pressure turbine drives the fan and therefore, m dot t remains the same as that for the high pressure turbine m dot t into c p multiplied by T 05 prime which is the inlet stagnation temperature of LPT minus T 05 which is exit stagnation temperature of the LPT. This is equal to m dot aC which is mass flow rate required for the fan into c p into T 03 prime minus T 02 prime.

So here, we have the exit stagnation temperature which is T 05 that is what we need to find out. Therefore, if you simplify this we get since m dot t is equal to m dot aH plus m dot f so, if we divide throughout by m dot aH we get 1 plus f into T 05 prime minus T 05 is equal to B which is the bypass ratio into T 03 prime minus T 02, where B is equal to m dot aC by m dot aH that is the cold mass flow divided by the hot mass flow.

From this we can simplify and find out the exit stagnation temperature of the low pressure turbine which is T 05. T 05 should be equal to T 05 prime minus B into that is bypass ratio into T 03 prime minus T 02 prime divided by 1 plus f. Similarly, the stagnation pressure which is P 05 which is equal to P 05 prime into the temperature ratios T 05 divided by T 05 prime raise to gamma by gamma minus 1.

So, we have now carried out the analysis across the low pressure turbine, we already carried out that for the high pressure turbine. At the l p turbine exit, we now have properties which are basically corresponding to the turbine exit.

Now from the turbine exit, we will now move on to the nozzle and the nozzle exit conditions that is the exhaust velocity can be determined which in turn we can use to find out part of the thrust which is generated by the hot nozzle or the primary nozzle. Similarly, we will also find out the thrust which is contributed by the secondary nozzle that is the bypass duct and so the total thrust will be equal to the sum of these two for this case that is the unmixed turbofan case. In the mixed turbofan case of course, there will be only a single exhaust which would be a mixture of the bypass mass flow with the core mass flow.

So moving on to the primary nozzle, the analysis is identical to what we did for the turbojet. We have the stagnation temperature and pressure at the turbine exit and in an ideal cycle there are no loses occurring in that duct subsequently. Therefore, these temperatures and pressures will be the same as that of the nozzle entry.

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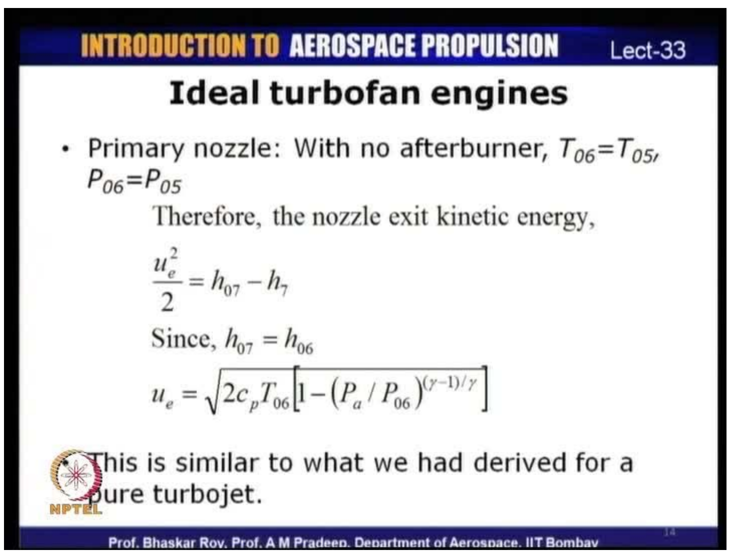

At the nozzle entry if we do not have any afterburner, we have T 06 is equal to T 05 and P 06 is equal to P 05. So, the nozzle exit kinetic energy will be equal to u e which is the same as we did for the turbojet is equal to square root of 2 c p T 06 into 1 minus P a by P 06 raise to gamma minus 1 by gamma, so this is the exhaust velocity from the primary nozzle.

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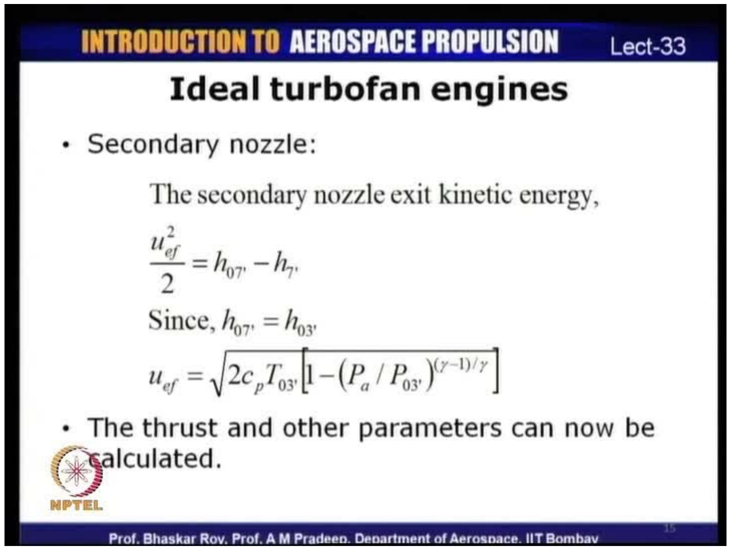

Now for the secondary nozzle, we have u ef, where f corresponds to that of fan. We can derive an equation for the exhaust velocity from the fan from the secondary nozzle in the same way as we did for the primary nozzle. So, u ef is equal to square root of 2 c p T 03 prime which is the nozzle inlet stagnation temperature into 1 minus P a by P 03 prime raise to gamma minus 1 by gamma.

Now we have the exhaust velocities from the nozzles, primary nozzle as well as the secondary nozzle. So how do we now calculate the thrust because mass flow rate through both these streams are different, they are governed by the bypass ratio. Now that we know the bypass ratio, we can calculate the thrust which is the total thrust which will have two components, one is from the core duct and the other is from the bypass duct.

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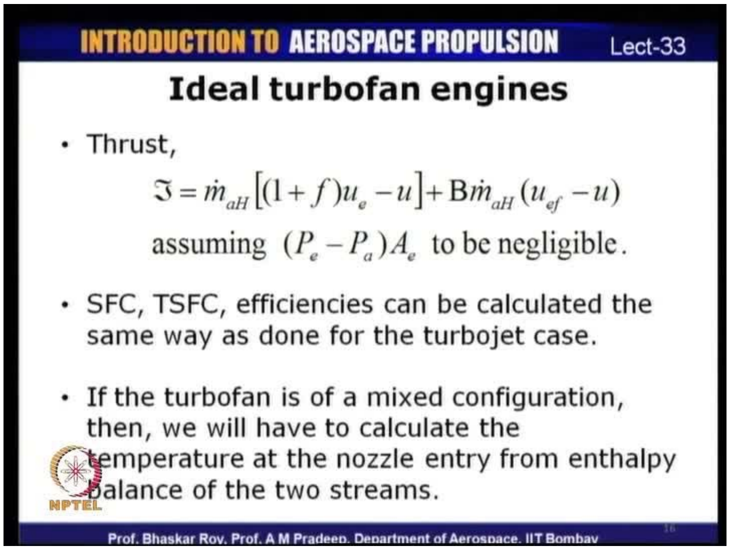

So the thrust that is generated by this unmixed turbofan engine is equal to the first part of it is the thrust by the core nozzle which is m dot aH which is mass flow rate through the core stream into 1 plus f into u e minus u. The second term that is the thrust generated by the bypass duct will be equal to the bypass ratio into m dot aH which is basically equal to m dot aC into u ef minus u which is equal to the velocity differences through the bypass duct.

Of course, there will also be pressure thrust term if it is to be assumed negligible then this is total thrust which is developed by this turbofan engine, the ideal turbofan engine where the two streams are unmixed. Now similarly, we can calculate the specific fuel consumption or the thrust specific fuel consumption and the efficiencies in the same way as we did for the turbojet case. Once we calculate thrust, the other parameters are straightforward.

Now if the turbofan consists of a mixed configuration that is the 2 nozzles mix and there is only a single exhaust nozzle if it is a mixed turbofan engine, then there is only 1 nozzle which generates the thrust. In this case, the difference in the cycle analysis comes only at the nozzle entry, how you find the temperature at the nozzle entry which is not equal to the turbine exit temperature because there is a bypass duct mass flow which mixes with the turbine exhaust mass flow. So what we need to do there is to carry out an energy balance between the 2 streams, which is the bypass stream and the turbine exhaust stream both of them mixed, then you have a final mixture enthalpy. So final mixture enthalpy that is m dot into H 06 should be equal to m dot ac into the temperature and that is enthalpy of the cold stream plus the mass flow rate of the hot stream multiplied by the enthalpy of the turbine exhaust.

So from that you can find out the nozzle entry stagnation temperature and therefore, thrust because the nozzle exhaust velocity is a function of the temperature and pressure ratios. If the configuration is a mixed turbofan, then we can find out these parameters by carrying out this energy balance.

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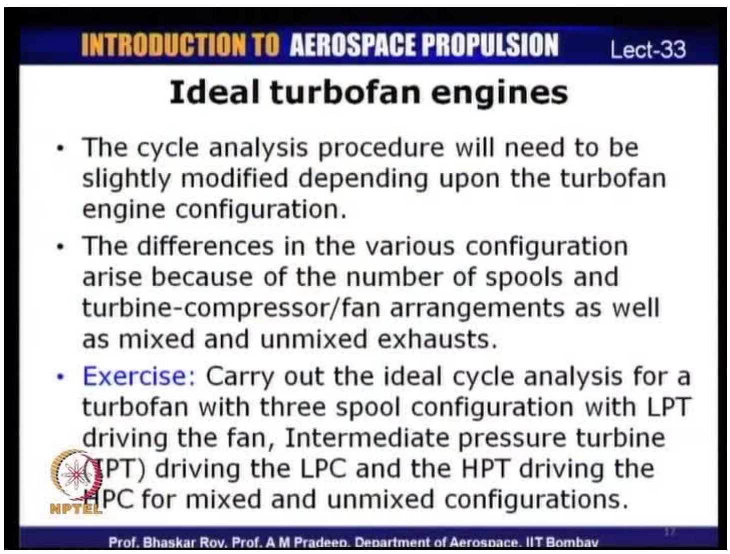

Now similarly, there could be other configurations of turbofan engines which are possible like you could have different number of spools. We have now carried out the analysis for a 2 spool configuration, you could have 3 spool configuration or you could have the same configuration with mixed or unmixed exhaust and so on.

So, the procedure for analysis is very much identical to what we have already discussed. I will leave it as an exercise for you to carry out an ideal cycle analysis for a turbofan with 3 spools. That is 3 spool configuration with the low pressure turbine driving the fan and intermediate pressure turbine driving the LPC and the high pressure turbine driving the HPC. You could have 2 types of configurations either mixed or unmixed configurations. I leave it as an exercise for you to carry out a cycle analysis; there are 2 cases here that is a 3 spool engine and 1 configuration is a mixed turbofan and the other is an unmixed turbofan. So, based on the discussion we had, you should be able to now carry out a cycle analysis for these two configurations of a turbofan engine.

So we have now discussed cycle analysis for turbofan engines, as I mentioned there are different types of turbofan engines that you could come up with and cycle analysis will be slightly different depending upon what type of configuration it is. The next type of engine that we shall be discussing there are two types of engines, together we shall discus; these are the turboprop engines and the turbo shaft engines.

Now these are 2 types of engines which are slightly different from the turbojet and turbofan in the sense that these engines also develop a certain shaft power to either drive a propeller, in the case of a turboprop or you could be driving a main rotor blade as in the case of a turbo shaft engine. But, the difference between a turboprop and a turbo shaft is that in a turboprop there is also thrust generated by the nozzle exhaust which is absent in the case of a turbo shaft. Turbo shaft necessarily generates only shaft power to drive the main rotor blade, there is hardly any nozzle exhaust thrust which is developed by the turbo shaft engine.

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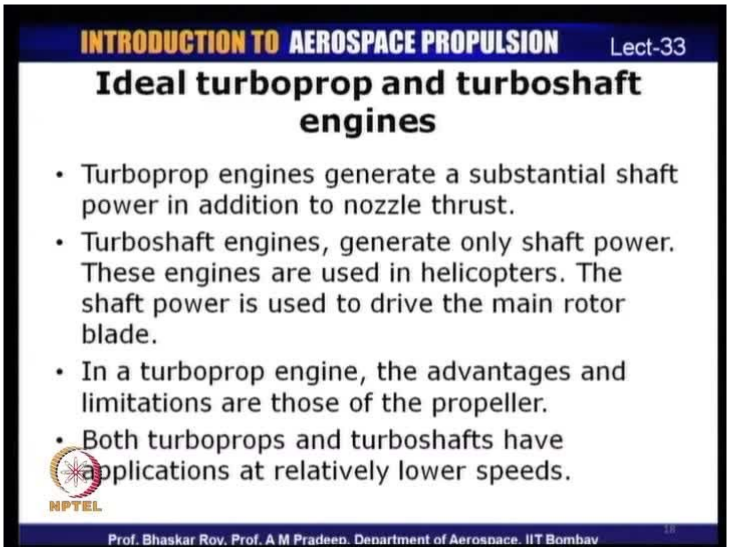

A turbo shaft prop engine generates a substantial shaft power in addition to the nozzle thrust and turbo shaft engines on the other hand, generates only shaft power. Turbo shaft as I mentioned in the beginning they are used in helicopters and the shaft power is used to drive the main rotor blade.

In a turboprop engines, the advantages and limitations are primarily to that of the propeller, in the sense that the advantage of a turboprop engine it is high propulsion efficiency. The limitation is that the presence of the propeller leads to limited speeds that the propeller based engine can operate and so the limitations as well as advantages are both on account of primarily the propeller.

Both these types of engines turboprops as well as turbo shaft engines are primarily limited to relatively lower speeds because at higher speeds, the compressibility effects come into picture and that lead to increase in loses because of compressibility effects and shocks which could occur at the tip of the propeller or the blades. So, their applications are limited to relatively lower speed but, they are still not very low speed but, relatively lower than a turbofan or a turbojet engine.

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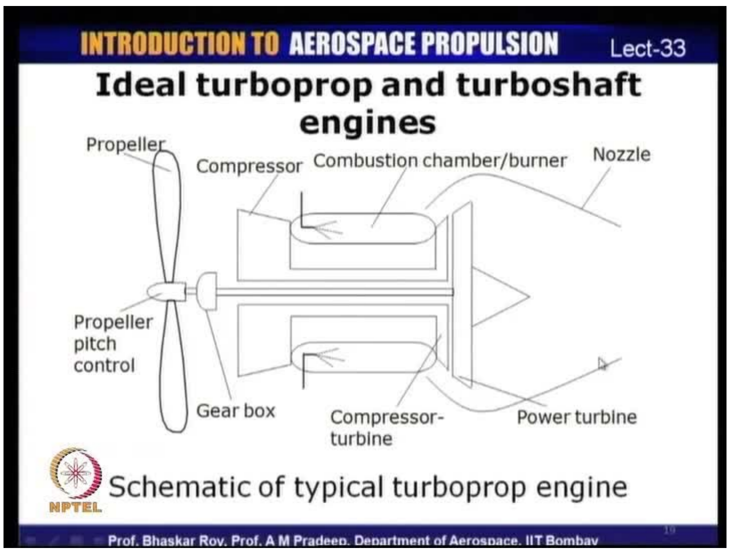

Let us take a look at a schematic of a typical turboprop engine. Now we have here is a turboprop a schematic of that, some of the components you are already familiar with which were discussed for the turbofan and turbojet engines, we have a compressor, then a combustion chamber and turbines. I have shown two types of turbines or stages of turbines; one is the compressor turbine which drives the compressor and we also have a power turbine which is meant to drive the propeller.

So this is the propeller here (Refer Slide Time: 42:15) and this is driven by the power turbine in turboprop. Since the propeller speeds are limited, the rotational speeds are limited invariably there is a gearbox which reduces the speed of the shaft from the turbine, so that the propeller can run at relatively lower speed. So, the gearbox is also a constituent of this arrangement and you may also have a propeller pitch control mechanism for changing the pitch which you had already seen in some of the earlier lectures.

There is also a nozzle at the exhaust that is generating some amount of thrust. So, the power turbine exhaust through a nozzle which also generates a certain amount of thrust. These are the different components of a turboprop engine and it is very similar for a turbo shaft engine also, instead of a propeller we have the main rotor blade. The nozzle component of the thrust is very limited is negligible in a turbo shaft engine, other components are more or less the same.

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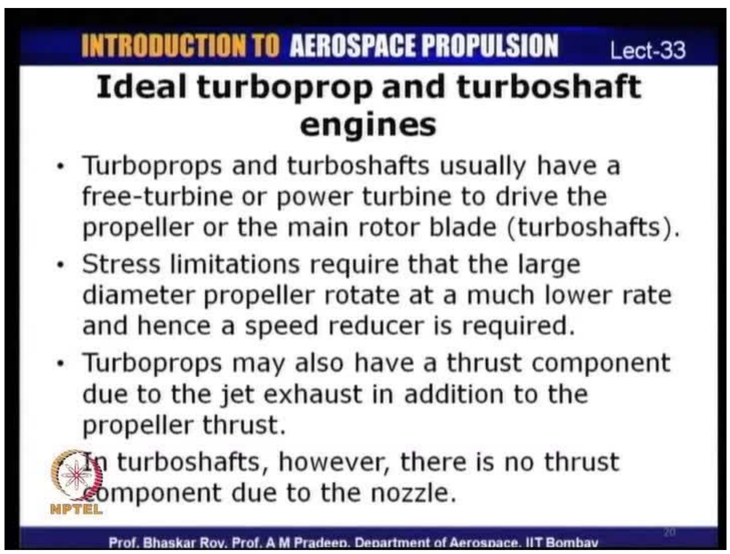

Now in both these engines, turboprops as well as turbo shaft engines they usually have a free turbine or a power turbine which is used to drive either the propeller in the case of turboprops or the main rotor blade in the case of turbo shafts. So the speeds at which the propeller can rotate are basically limited by as I mentioned, compressibility affects and stress limitations and so they have to have a speed reducer, so that the speed at which the propeller rotates can be limited.

In the case of turboprop I mentioned, there are two components of thrust; the thrust because of the propeller itself and the thrust on account of the nozzle exhaust. In the case of the turbo shaft, it is just the primary the thrust or the entire power of the engine is used for driving the main rotor blade.

The cycle analysis of both these engines are in most of the components being identical to that of the turbojets or the turbofan, cycle analysis remains more or less the same except for the free turbine or the power turbine which is used for driving the propeller or the rotor blade. So that is the only component where there could be a slight difference between the cycle analysis.

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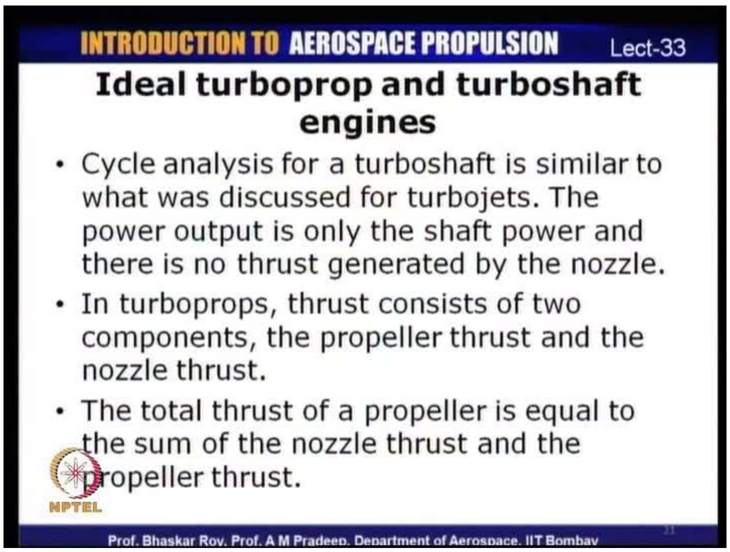

So cycle analysis for the turbo shaft is very identical to what we had discussed, only thing is here the power output is the shaft power and there is no thrust generated by the nozzle. In turboprops thrust comprises of two components, the propeller thrust and the nozzle thrust therefore, the total thrust will be equal to sum of the nozzle and the propeller thrust.

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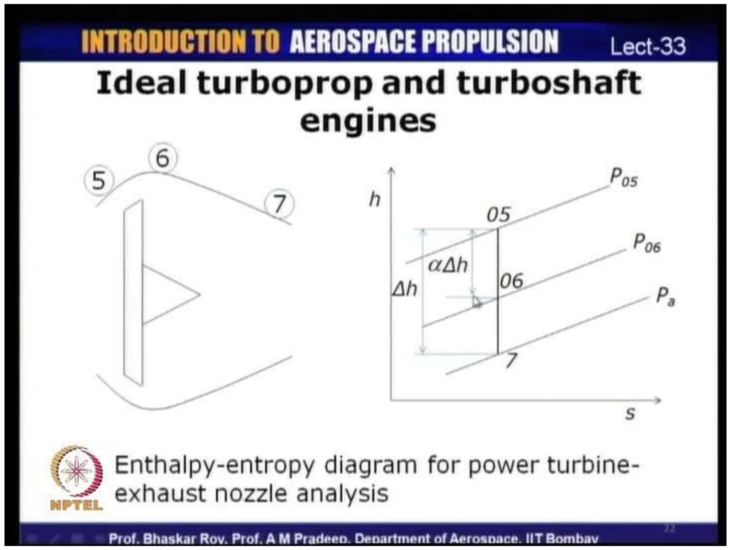

So if you look at the power turbine I mentioned, that is the major difference between a turboprop or a turbo shaft and other forms of engines. This is the power turbine that is shown here, so 5 is the main turbine or the compressor turbine exit, 6 is the power turbine and 7 is the nozzle exit. If you look at this process on an h s diagram, it is an expansion process, so an ideal cycle expansion process is isentropic so stagnation temperature at 5 is t 05 and pressure is P 05. So, it expands all the way to P 06 in the power turbine and then rest of the expansion takes place in the nozzle; so 06 to 7 which is the ambient pressure is the nozzle expansion.

Let us say this total enthalpy drop across the power turbine and the nozzle together is delta h, a fraction of that enthalpy drop occurs in the power turbine which is let us say alpha. So, alpha times delta h is the enthalpy drop which occurs in the power turbine; so 1 minus alpha into delta h is the power is the enthalpy drop in which takes place in the nozzle.

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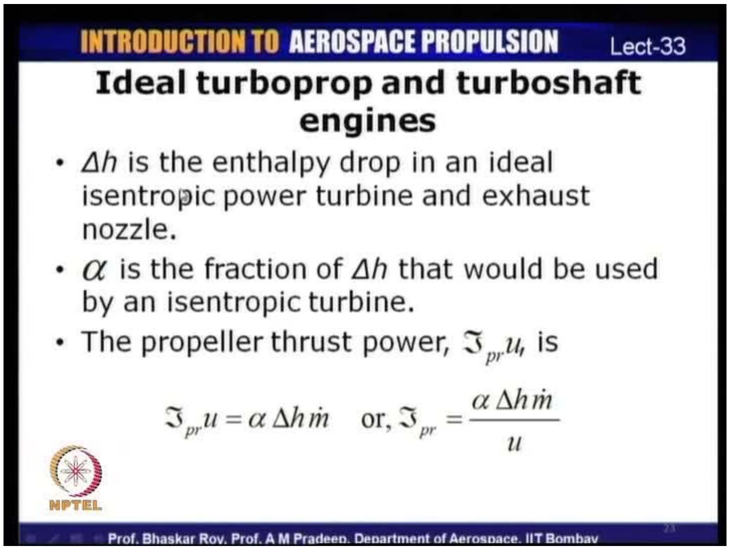

So delta h is basically the enthalpy drop in the both the power turbine as well as the exhaust nozzle put together. Fraction of that delta h which is alpha would be used by the turbine and remainder is used by the nozzle. The propeller thrust power which primarily comes from the power turbine, let us say is the thrust power, thrust by the propeller is tau to subscript pr which is the propeller, so thrust power is this multiplied by u. So thrust power is alpha delta h, which is fraction of the total delta h which is occurring across the turbine power turbine plus the nozzle multiplied by the mass flow rate. So propeller thrust will be equal to alpha delta h into m dot divided by u.

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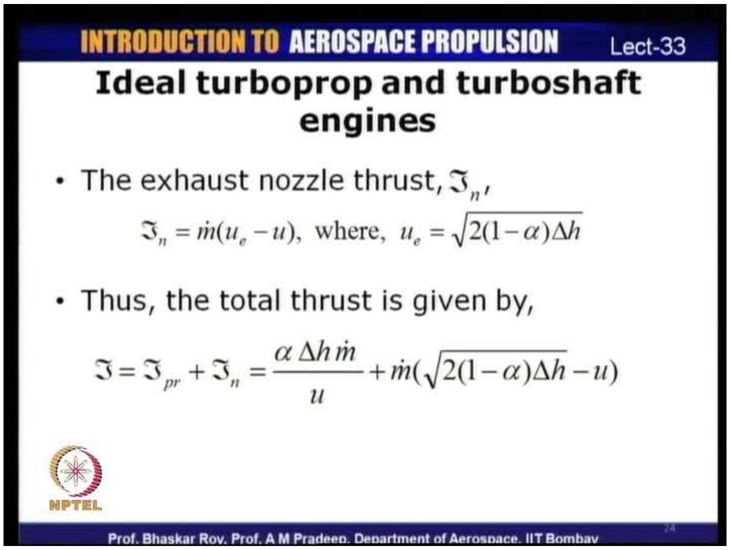

The next component of that is the nozzle thrust, so exhaust nozzle thrust is tau n, so tau n is mass flow rate times the velocity differences. Here velocity difference you can find by the same way as we did for the turbojet and turbofans, which is square root of 2 into the enthalpy drop multiplied by the fraction which is 1 minus alpha. So u e is equal to square root of 2 into 1 minus alpha into delta h so, 1 minus alpha into delta h is the fraction of enthalpy drop which occurs in the nozzle.

Therefore, the total thrust is equal to thrust generated by the propeller plus the thrust generated by the nozzle which is equal to alpha delta h into m dot divided by u. Thus m dot into square root of 2 into 1 minus alpha delta h minus u, so here I have not described the step by step cycle analysis because it is identical to what we have done for turbojets and turbofans. All you have to do is to find out the temperature at the power turbine inlet and therefore, across the power turbine you could determine the enthalpy drop and which in turn gives you the propeller thrust.

Once the power turbine exhaust conditions are known, you can also find out the nozzle exhaust conditions and therefore, the nozzle thrust can also be determined. So, the total thrust will be equal to some of these two thrust components part of which is coming from the turbine, part of it is coming from the propeller and rest of the thrust generation is taking place across the nozzle.

The delta h that we have talking about the enthalpy drop should be coming from the cycle analysis of the preceding components that is starting from the compressor, the combustion chamber and the compressor turbine. So, from there we can determine the enthalpy drop that will be required for these two components together and that in turn gives us the total thrust which is developed by the turboprop engines.

Obviously, once you calculate the thrust, we can also determine the fuel consumption and the efficiencies. You already discussed the efficiency definition for turboprops wherein, we also have the shaft power which needs to be taken into account while calculating the efficiencies.

So this is the general procedure for carrying out the cycle analysis for the turboprops. It is identical for a turbo shaft as well, just that in a turbojet no need to really calculate the nozzle thrust because there is hardly any nozzle thrust developed in a turbo shaft engine.

Now the last cycle analysis, which we shall discuss is that for a cycle which is simplest form of an air breathing engine, which is ramjet engine. We will again not go in to details of the cycle analysis because we have already discussed that in fact a ramjet cycle analysis should be much simpler than what we have discussed for all the other engines because ramjet is the simplest form of an air breathing engine. Some of the components we have discussed like compressor and turbine are actually absent in a ramjet engine.

So a ramjet engine consists of three basic components; it consists of a diffuser or an intake followed by a combustion chamber and a nozzle. So, there is no compressor, there is no turbine as well. You may wonder if there is no compressor and a turbine, how is it that this engine is going to operate?

In a ramjet engine, the basic idea is that if the engine itself is flying at very high speeds, then the compression across the intake itself leads to substantial increase in the stagnation pressure and temperature to the extent that you would not need to have a compressor anymore; because the intake or the diffuser itself is compressing the flow to such an extent that the pressures and temperatures are high enough that you can have combustion taking place at that kind of temperatures and pressures.

So once you do not have a compressor, you no longer need a turbine to drive the compressor. Once the compressor is not required, you would not need a turbine as well so exhaust of the intake goes into the combustion chamber and from the combustion chamber that combustion products are expanded in nozzle to generate thrust.

Now the only drawback that is there for a ramjet is that this can work only if the ramjet itself is operating at a certain speed. That is ramjet will start generating pressure ratios only if the ramjet is operating at a certain speed, which means that ramjet engines cannot really generate any static thrust. That is if a ramjet is stationary it is not going to start on its own ramjet has to be taken to a certain reasonably high Mach numbers or speeds before which ramjet engines can start developing or generating thrust. So once the ramjet reaches a certain power or certain Mach number then, the compression in the intake is high enough that you can have a stable combustion in the combustion chamber and so the ramjet can start operating.

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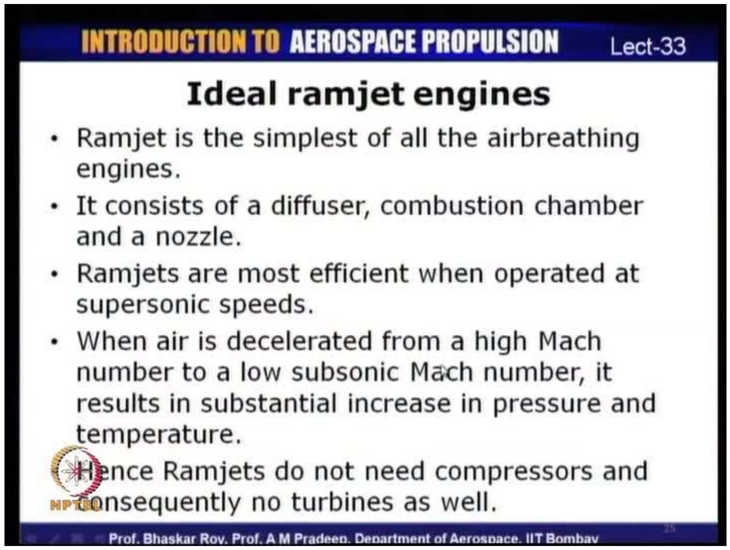

So let us take a look at some of the salient features of a ramjet. As I mentioned is one of the simplest forms of air breathing engines consists of a diffuser, combustion chamber and a nozzle only, there are no compressors or turbines. Obviously, ramjets are most efficient when they are operated at supersonic speeds and in fact the peak efficiency of a ramjet occurs around Mach number of 2 2.5 and again beyond that Mach number the ramjet efficiency also starts dropping.

When we have already seen that, when air is decelerated from a very high Mach number to very low subsonic Mach number this leads to a substantial increase in the pressure and temperature. Now, if you are already having such a high increase in pressure and temperature without the need of using a compressor, then you do not necessarily need a compressor and therefore, no turbines. That is why ramjet is considered the simplest form of air breathing engine because you do not have any turbo machinery present there, you do not have a compressor, and you do not have a turbine, so there are no rotating components there.

Since there are no rotating components in a ramjet, you can actually have very high temperatures in the cycle as compared to a turbojet where these temperatures are limited, the turbine inlet temperatures are limited because the turbine blades which are rotating cannot withstand very high temperatures. So, you have limited temperatures there; in a ramjet you do not have any such limitation there are no rotating components and so you can actually go for higher temperatures in a ramjet.

In some sense which means that thermodynamically ramjets may essentially have a higher efficiency because you are adding heat at a higher temperature. So, that is one of the advantages that ramjets have you can actually operate it at higher temperature.

Let us take a look at a schematic of a ramjet engine and look at what are the different components of a ramjet engine. Ramjet engines primarily consist of as I mentioned three components; the diffuser, the combustion chamber and the nozzle. So ramjet engine begins with a diffuser, it requires a very efficient diffuser because it is going to operate at supersonic speeds which means that deceleration in a ramjet occurs through shockwaves.

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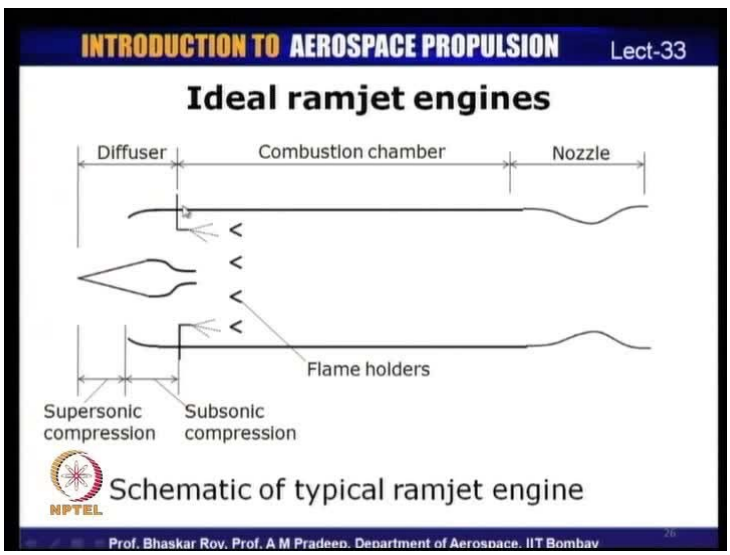

So if you look at the schematic that is shown here (Refer Slide Time: 55:44), we have the diffuser part of it then fuel is added in the combustion chamber and then at the exit of the combustion chamber we have a nozzle.

Now, I have indicated that the diffusion or diffuser consists of - or the compression process consists of - two distinct processes; the supersonic compression and the subsonic compression. This is the supersonic compression part of it where there could be shockwaves there would be shockwaves for decelerating it from supersonic speeds to subsonic speeds and at the end of supersonic compression, we have a normal shock which takes it to subsonic speeds. The subsonic flow enters the combustion chamber fuel is injected here in the combustion chamber and there are flame holders for ensuring that there is a stable flame in the combustion chamber and the combustion products are expanded in the nozzle.

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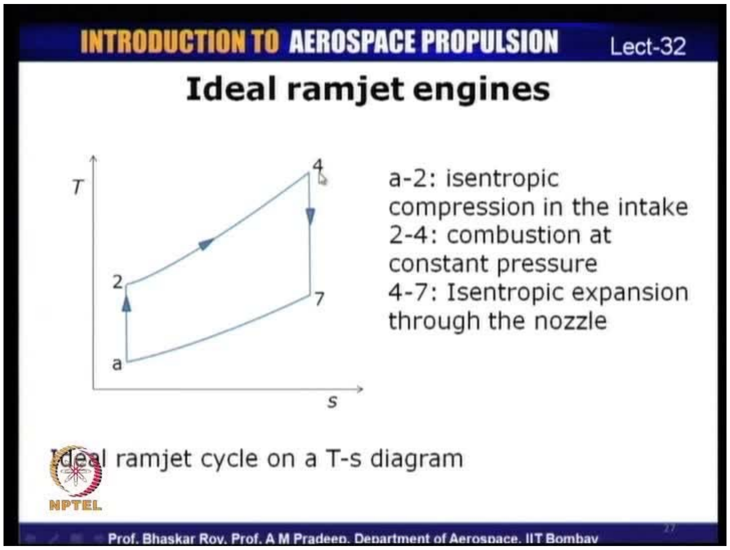

So these are the different components or that constitutes ramjet. If you look at the T s diagram of the same, it is the basic Brayton cycle which we have seen process a to 2 is the isentropic compression in the intake, 2 to 4 is the combustion process which is at constant pressure, 4 to 7 is the isentropic expansion through the nozzle. So, this is the basic Brayton cycle that is shown there.

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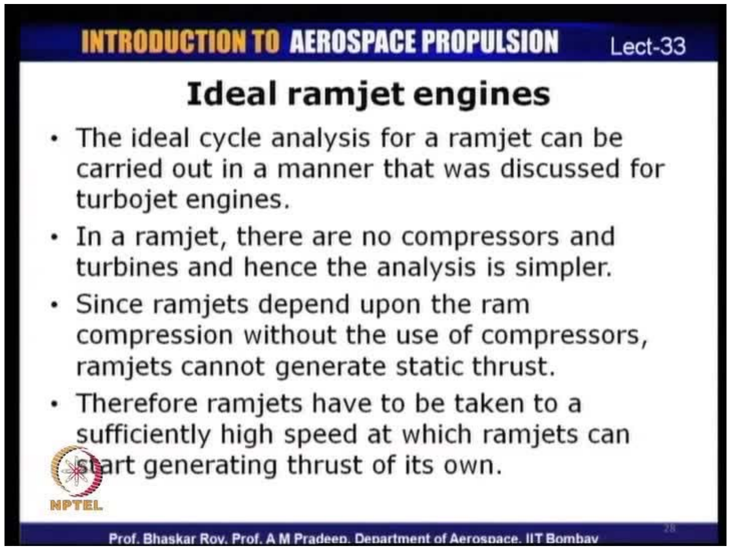

Ideal cycle of the ramjet obviously is a simpler version of what we have seen for turbojets and turbofans and since there are no compressors and turbines the analysis is a lot simpler. As I have already mentioned, since ramjets depend upon the ram compression and the intake without the use of compressors they cannot generate any static thrust. Ramjets have to be taken to a reasonably high Mach number before which ramjets begin to generate thrust and so they cannot really start from 0 Mach number and start operating they have to be flown to a certain Mach number before which ramjets begin to operate.

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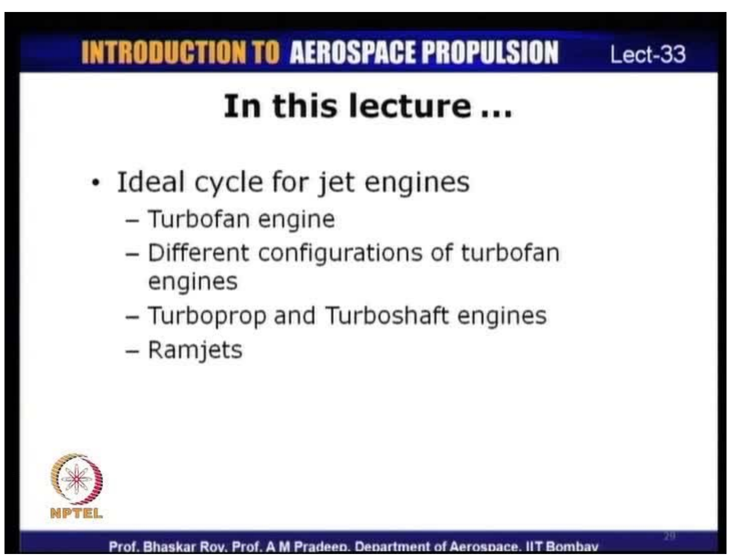

I will not discuss the ramjet cycle analysis in detail because it is a lot simpler and something we have already discussed for lot of other types of cycles. Let us take a relook at what we have discussed in today’s lecture. We were discussing about different forms of turbofan engines, how you carry out cycle analysis for these turbofan engines, the variations of the turbofan engines like different spool configurations, the mixed and the unmixed forms of turbofan engines.

We also discussed a little bit about turboprop and turbo shaft engines and what are the different forms of the thrust in the case of turboprop, it is the nozzle thrust plus the propeller thrust and so on. Towards the end, we also had a very quick discussion on ramjet engines and what makes ramjet engines different from other forms of engines.

This completes the cycle analysis discussion, which we have had over the last 2 lectures. In the next lecture, what we shall do is to try and solve a few problems pertaining to ideal cycles of air breathing engines; we will try and solve problems from turbofans, turbo jets and turboprop engines; this we shall take up during our next lecture.