Jet Aircraft Propulsion

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Module No. #01

Lecture No. # 07

Jet Engine Cycles For Aircraft propulsion

Hello and welcome to lecture number 7 of this lecture series on Jet Aircraft Propulsion. In the last lecture, I had given you some introduction to what is meant by the Joule Brayton cycle, which is basically the thermodynamic cycle, based on which all the jet aircraft engines operate, all the jet basically the jet aircraft engines operate on the Brayton cycle.

So, we were discussing about the ideal Brayton cycle and also towards the end of the previous lecture, we also had some discussion on what could be the deviations from the ideal cycle, because of irreversibility's occurring in the various processes for example, the compression process for an actual cycle is non isentropic.

So, is the expansion process which happens to be non isentropic, there also pressure losses, which occur in the heat addition and heat rejection processes, so, all these irreversibility's put together make the Brayton cycle non ideal for actual engines. And so, what we will be discussing today is application of the Brayton cycle for jet aircraft propulsion and how is it that the different forms of jet aircraft propulsion use the basic Brayton cycle for their operation.

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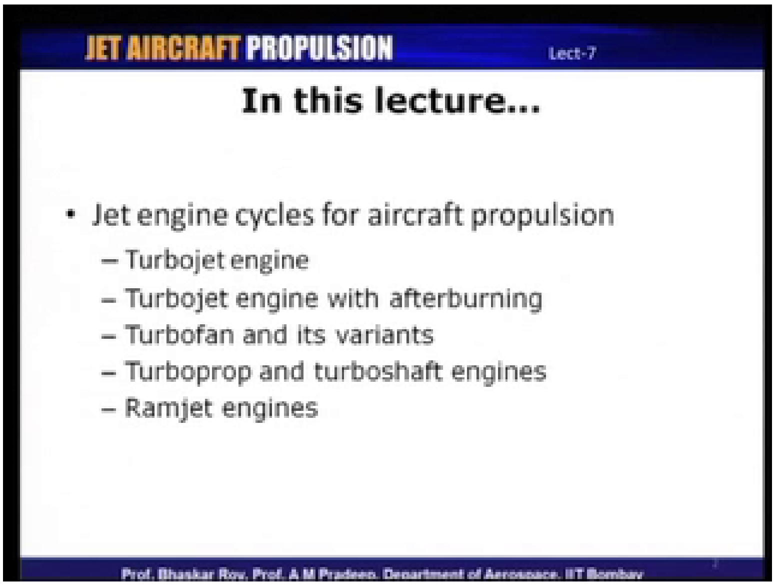

So, let us take a look at what we are going to discuss in today's lecture, we will be talking about, we will begin with basic thermo dynamic cycle which is used for jet aircraft engines, something we have discussed in the last lecture. Then, one of the most common or the basic fundamental forms of the jet engine is the turbojet engine, you would you already had some introduction to turbojet engines in some of the earlier lectures. Today, we will discuss about the cycle based on which the turbojet engines operate.

We will then discuss about, turbojet engine with after burning and then we will talk about turbofan engines and it's variance, the different types of turbofan engines, then turbo prop and turbo shaft engines and also very quick look at ram jet engines. We are going to discuss about ram jet engines, towards the later half of this lecture series but, we will just have spend a few minutes on discussing, what ram jet engines as well.

Now, as we have seen in the last lecture Brayton cycle involves, at least the ideal Brayton cycle involves four processes, the first process is the in the ideal cycle it is the compression process an isentropic compression, which raises the temperature and pressure of the Perkins fluid. At the end of the compression process, the heat addition process takes place, which occurs at a constant pressure for an ideal cycle. And then after the heat addition process, we have an expansion process and for an ideal cycle that is an isentropic expansion; and then there is a heat rejection process and so, all these four processes put together complete the Brayton cycle.

Now, Brayton cycle by it is very nature is a closed cycle, which means that it is the same working fluid that keep, that is used continuously in the operation of this cycle. But, aircraft engines, which operate based on the Brayton cycle operate in the open cycle mode, that is they do not use the same fluid all over again.

But, just that the for example, if an aircraft is cruising at a certain altitude, the temperature and pressure can be assumed to be more or less constant and so, we can assume that whatever fluid is coming in is it is the same fluid that keeps coming in all over again; and so, using air standard assumptions, we can kind of approximate the jet engines to which basically are open cycle engines towards a closed cycled Brayton cycle form.

So, gas turbine engines all jet engines operate on the Brayton cycle in in some fundamental sense but, of course, the actual form of these engines are much different in the sense, that none of the processes are isentropic or constant pressure and so and so. All the processes involve some form of irreversibility or the other. And therefore, these the actual engines are quite different from or the cycles are slightly different from the ideal Brayton cycle.

And so, in an ideal Brayton cycle that we have discussed in the last lecture where in the cycle will assume to have been operating in a closed cycle mode. For a jet engine, it can still be assumed but, with certain approximation with air standard assumption and so on.

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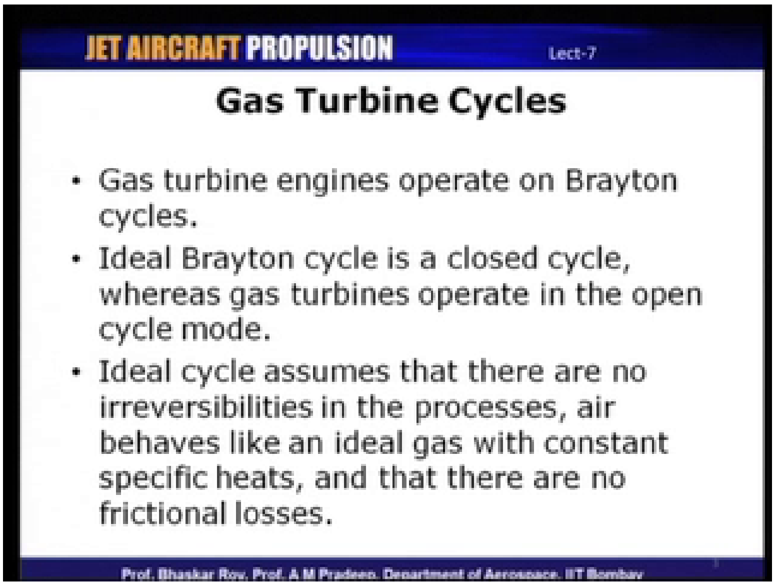

We can still assume that the jet engine in they jet engine also operates on the Brayton cycle mode.

Now, in a ideal cycle, we have seen that it does not assume any irreversibilities and that air behaves as an ideal gas with constant specific heats and no frictional losses, etcetera. This will still be true for ideal jet engine cycles but, when we discuss about the actual or real jet engines cycle, which we will discuss in later lecture.

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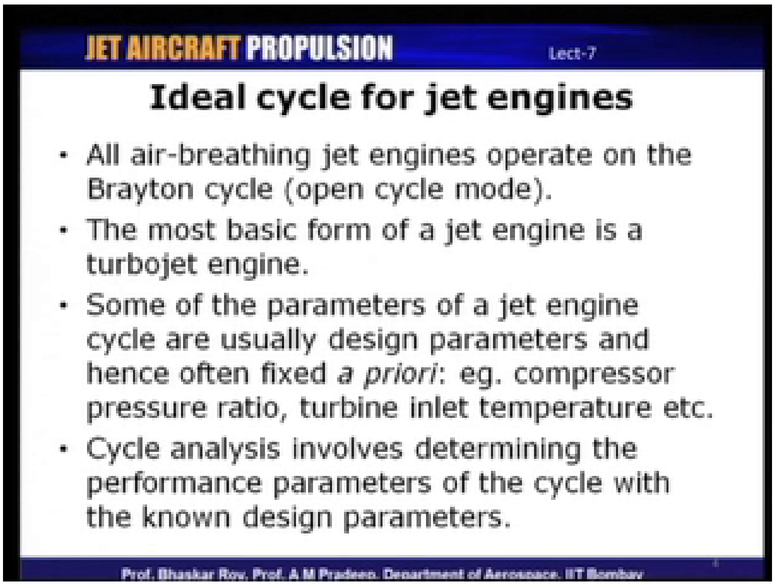

We will see that, we will have to account for all these variations. How we will do that is something we will discuss during that particular lecture. Now so, the most basic form of a jet engine is the turbojet engine. A turbojet engine is the fundamental form of a jet engine and there are many variance of turbojet engine, as we see it today depending upon the different applications for example, a civil aircraft, a passenger aircraft, the at least the larger sized ones like the air bus a 380 and many other which of course, the recent one; and the Boeing 737 and 7, 777's all of them operate using, what are known as the turbofan engines. And we will see why they these aircraft would use a turbofan engine, it is basically because of fuel efficiency and many other reasons.

Some of the smaller aircraft and helicopters use a different form of a turbojet engine, which is for a for a an aircraft these are known as turbo prop engines, that is there is a thrust component significant thrust component because of the propeller. And in the in the case of a helicopter, the jet engine just drives the main rotor blade and the thrust and of course, the lift is also generated both by the main rotor blade. So, we can see that the jet engines are used for variety of applications all of them happen to be some form or some variant of the turbojet engine.

Now, when we have to analyze a turbojet engine, if you would have something we were discussed in one of our earlier courses that is known as the cycle analysis. Where in we carry out some of the analysis parametric analysis of the jet engine, based on some of the design parameters that are known like compressor pressure ratio turbine inlet temperature etcetera. And then, we find out the performance of the cycle like the thrust and efficiencies, the fuel consumption, etcetera based on some of these known parameters.

So, we will take up these cycle analysis of real engines a little later in some in one of the later on lectures, today we will just look at the basic cycles of all these different forms of jet engines. So, one of the first cycles that, we shall be discussing today is the turbojet engine. As I mention turbojet is one of the most fundamental forms of a jet engine it involves few salient components, which we will discuss shortly. And so, the ideal turbojet engine cycle closely resembles, that of a Brayton cycle; and we will see, why it resembles, when we take a look at the cycle of a turbojet engine.

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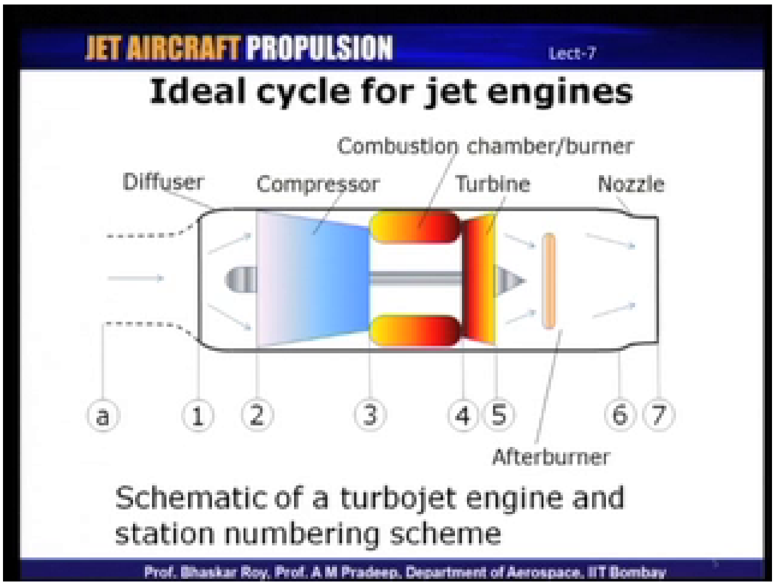

So, here is a schematic of a turbojet engine typical turbojet engine and the different components of a turbojet engines are also shown here. Now, the first component of a turbojet engine is known as a diffuser; diffuser is a component which decelerates the air to velocities, which are suitable for that operation of a compressor.

So, diffuser is followed by a compressor and then the compressor delivers compressed air into the combustion chamber, where ignition takes place fuel is added in the combustion chamber; and this is where head addition in this Brayton cycle takes place. And downstream of the combustion chamber, we have the turbine and turbine expands the air, which is at high pressure and temperature at the exit of the combustion chamber. And in that process it delivers work output and this work output is basically used to drive the compressor, so turbine in a turbojet is mainly used for driving the compressor.

At the exit of the turbine, there would be a component which is known as a after burner, so turbojet engine may operate in an non after burning mode or an after burning mode, will discuss about after burning in a little later; you already seen that in one of the early lectures. And then, the exhaust combustion products, then exhaust through a nozzle which also generates thrust.

So, these are the different components, which constitute a turbojet engine and there are some numbering schemes that, we you can see here, that each component is denoted by a certain number, which is just used in in the cycle analysis, that we will do for the actual turbojet engine in later lectures.

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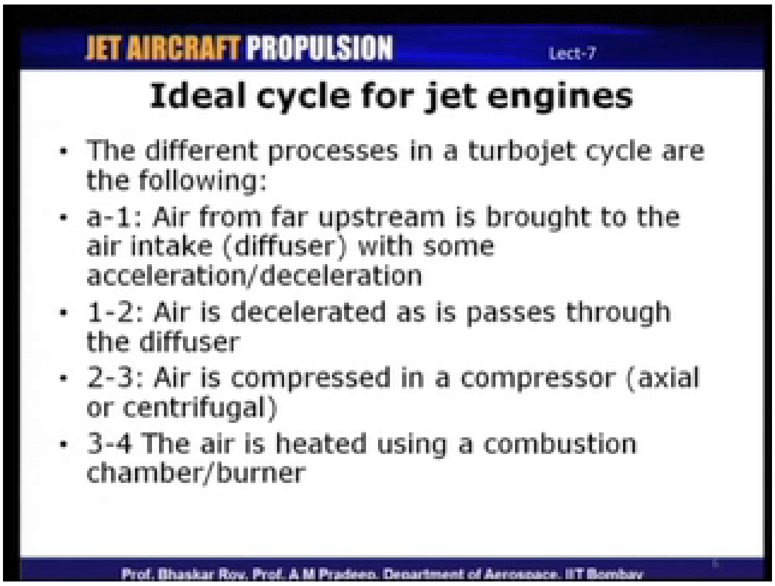

Now, how does this look like in T S diagram we will see that little later, basically the components each of these components have a certain role to play in the whole Brayton cycle. And for example, the diffuser is part of the compression process as we know in a Brayton cycle; there are four distinct processes, the compression process, a heat addition process at constant pressure, then expansion process and again a heat rejection process.

So, the compression process in a turbojet engine consists of two different components one is the diffuser. So, part of the compression occurs in the diffuser and then rest of the compression occurs in the compressor, well in the most of the compression. In fact, occurs in the compressor only a very small fraction of the compression occurs in the diffuser, now after the compressor we have the combustion chamber.

So, in a turbojet engine you can see it is not really a heat addition process but, say it is combustion that is taking place but of course, in the cycle analysis, we replace this combustion by a heat addition process. So, heat addition in this turbojet engine occurs through the combustion chamber and then after the combustion chamber is the expansion, expansion again is split into two in a turbojet engine. We have expansion partly taking place in the turbine and rest of the expansion taking place in the nozzle.

So, compression and expansion processes involve two a different components and in a Brayton cycle there is a last process, that is the heat rejection process, in a turbojet engine there is no heat rejection per say it is an exhaust process, that is combustion products are exhausted through the nozzle. And so, this process is this can be assume to be the heat rejection process of a Brayton cycle so, let us look at these different components and their functions in step by step.

The first process that is process between a to 1, a is the diffusion process in the air intake that is air from far upstream is brought to the air intake, with some acceleration or deceleration, that is the what is known as the pre compression. And when we discuss about diffusers, we will understand why there are two different steps in diffusion itself will discuss that later on.

And then the actual diffusion takes place there is internal diffusion or internal compression between stations 1 and 2 compression occurs between stations 2 and 3 and we could have either an axial compressor or a centrifugal compressor. We will be discussing about these types of compressors in detail later on, we then have the combustion process between stations 3 and 4.

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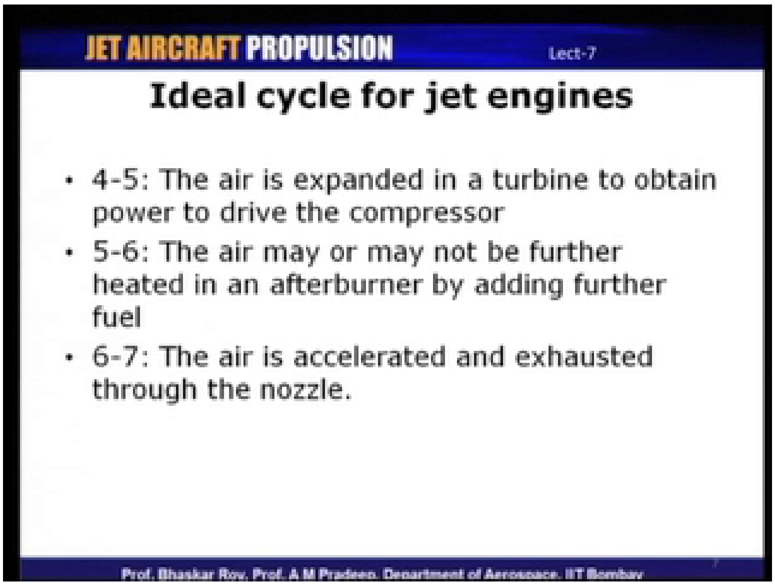

And 4 to 5 is the expansion in the turbine, so the turbine is primarily meant here, in a turbojet engine to drive the compressor; and then, there would be after burning taking place between stations 5 and 6 and 6 to 7 is acceleration and exhaust of the products through in nozzle, so 6 to 7 is in nozzle process in the Brayton cycle or the turbojet cycle.

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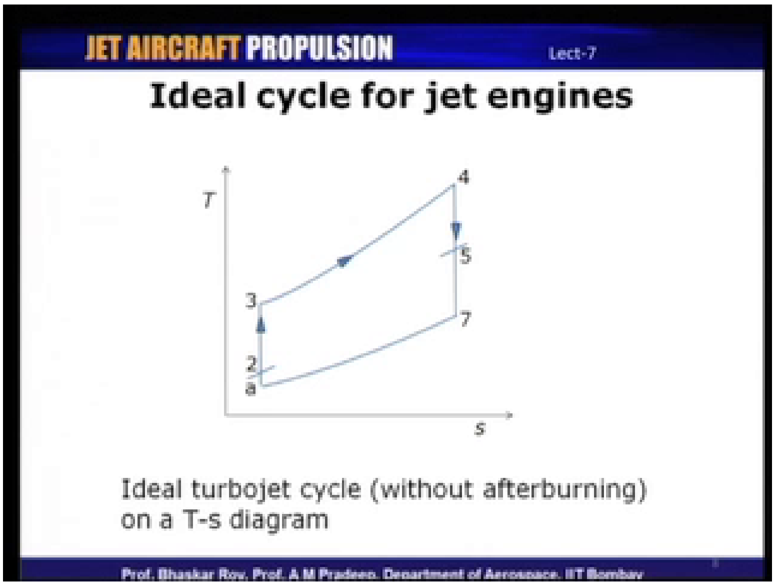

Now, on a T s diagram, this is how an ideal turbojet cycle would look like, it looks very similar to that of an ideal Brayton cycle just that the compression process is a split into two processes here and so, is the expansion process, there are two processes you can see here. So, process a to 2 is compression in the air intake and from 2 to 3 is compression taking place in the compressor, so process between a and 3 is the compression process in an ideal turbojet engine, this is an isentropic process.

So, isentropic compression from station a to station 3 and then, between stations 3 and 4 we have the heat addition of the combustion process. And so, that is in a turbojet ideal turbojet cycle it is a constant pressure process, between 4 and 7 is the expansion process part of it is, in the turbine that is between 4 and 5 and between 5 and 7 is the nozzle exhaust occurring through the nozzle.

So, process between 4 to 7 is the expansion process in the nozzle, so these are the different processes, which constitutes an ideal turbojet cycle. And we will discuss about real turbojet cycles in the in couple of lectures from now, where we will see what are the deviations that that can occur in a real turbojet. And why is it that it is different from an ideal cycle and what difference does it make to the performance of jet engine.

So, we will discuss about some of these aspects in our later lecture, now as we have seen turbojet, can operate in two different modes that is without afterburning and with afterburning. We have discussed about afterburning in some detail in one of the earlier lectures, afterburning is basically a process, where in you can add additional heat or fuel in as the case of turbojet to increase the temperature of the combustion products to much higher temperatures.

And therefore, one can gain additional thrust by adding additional fuel as we know that the air to fuel ratio in jet engines is substantially higher than this stoichiometri ratio. Which means that there is much more air that is available after combustion, which is which can still take part in combustion. Therefore, after the turbine exit, there is substantial amount of air or oxygen, which is still present and therefore, there it is possible for us to add additional fuel there, without having to actually ignite, because the temperatures are substantially high.

So, simply by injecting additional fuel, we can further raise the temperature at the nozzle entry and therefore, the pressure as well and this much pressure is available for expansion through the nozzle and that for, one can achieve additional thrust. Which could be used for which so, afterburning turbojet engines are basically used in aircraft in military aircraft. Especially when they need to accelerate to supersonic speed and cruise at supersonic speed and also carry out certain maneuvers.

So, after burning is not something, that is used in civil aircraft in turbofans and so on, it is usually used in a turbojet engine, so with afterburning there is a cycle, which resembles a Brayton cycle with reheating. So, we have already discussed about Brayton cycle with reheating in the last lecture; reheating is a process, where we add additional heat after the first expansion process. Which is exactly what happens in the case of an after burning turbojet engine that is we add additional fuel and raise the temperature to a much higher level and expand all over again.

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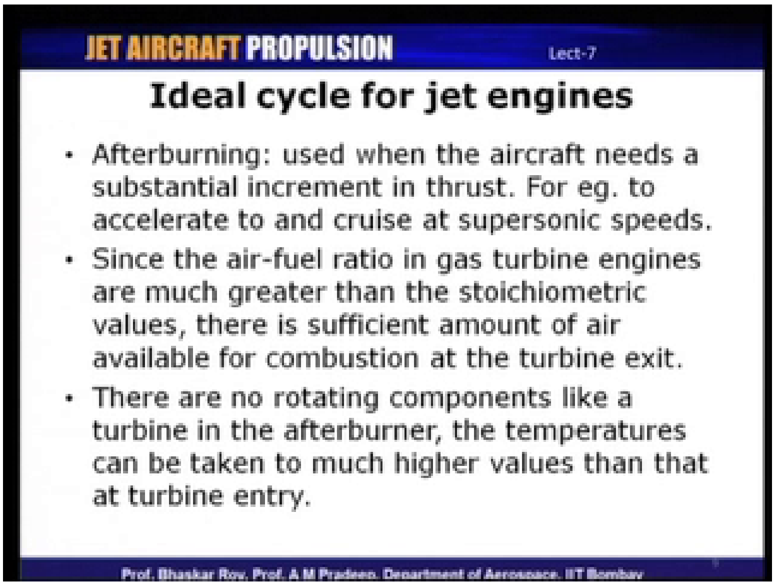

So, turbojet engine with afterburning closely resembles a Brayton cycle with reheat, will take a look at the turbojet with afterburning or reheat as well. And so, basically afterburning is something, which is used when they in an aircraft needs substantial increment in thrust for example, when it has to accelerate and cruise at a supersonic speeds.

And this is possible, because the air to fuel ratio in gas turbine engines are much higher than this stoichiometri values, leaving sufficient amount of air which is available for combustion. And the other aspect is that, after the turbine there are no more rotating components and there is no more temperature restriction as such and therefore, it is possible for us to have much higher temperatures than the turbine inlet temperature.

The turbine inlet the temperatures are limited, because turbine blades have certain temperature restrictions, because it is also rotating at very high speeds and so, it cannot have it cannot have temperatures which exceed a certain limit, which is not a restriction. In the case of an afterburner, so it is possible to have higher temperatures, than turbine inlet temperature.

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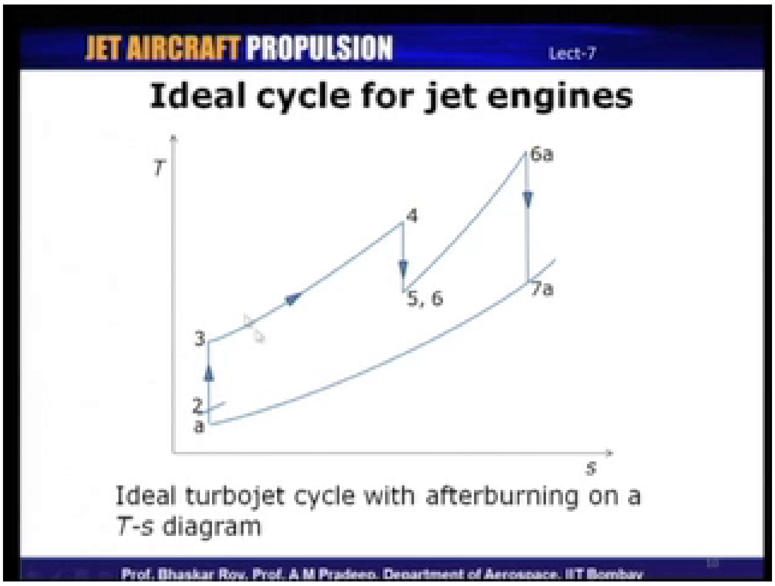

So, an ideal turbojet with after burning would look something like what is shown here, so the first process the compression process is the same as that of non afterburning turbojet it consists of two distinct processes or compressions, one is the intake or the diffuser. And the second process between 2 and 3 is the compressor, 3 to 4 is the combustion process, which is the heat addition 4 to 5 is the expansion in turbine and after the turbine exit is the reheating process or the after burning process additional fuel is added.

And so, we have a process which resembles the heat addition here, between 3 and 4, so 6 to 6 a is the after burning process, 6 a to 7 a is expansion in the nozzle. So, here you can see that, because the temperature at the turbine inlet or turbine exit is now, been raised to much higher level there is additional amount of energy or enthalpy drop. Which is available for expansion through the nozzle; and this is what results in additional thrust which one can achieve during afterburning process.

So, if afterburning was not to be there the nozzle would have only this much enthalpy drop for expansion and now there is an additional enthalpy drop, because of heat addition which has taken place during after burning process. So, an ideal turbojet engine with afterburning is basically, the Brayton cycle with reheat, so Brayton cycle with reheat will have a cycle, which is very similar to what we have just discussed about, turbojet engine with afterburning.

So, what we have discussed now is one of the most basic forms of the jet engines and that is the turbojet engine. And we also discussed about the ideal cycle of a turbojet engine which very closely resembles a Brayton cycle and ideal Brayton cycle it has all the four processes has, what a Brayton cycle would have but, the difference is of course in the last process, which is a heat rejection process. Which is not really existing in in a jet engine because it is an open cycle process but, the exhaust through the nozzle can be approximated to that of a heat rejection process.

Now, one of the issues with turbojet engine is the high exhaust velocity and resultant high exhaust velocity is something, which will affect one of the efficiency parameters, which we have discussed that is the propulsion efficiency. So, propulsion efficiency is is directly related to the velocity ratios exhaust velocity to the flight speed ratio.

And so, if we have to increase the propulsion efficiency, it is necessary that we have an effective exhaust velocity, which is not very high and so, in the case of a turbojet a pure jet engine; the exhaust velocities can be quite high and therefore, that affects the propulsion efficiency substantially. So, one of the ways of improving the propulsion efficiencies is to try and reduce the effective jet exhaust velocity.

And so, one way of doing that is to add another component to the basic turbojet engine, which will result in some reduction in the effective jet exhaust velocity and one of the ways of doing that is to add a fan. So, I had of a compressor, we now put a fan which will generate greater mass flow and this mass flow, will be directed around the basic turbojet core and this then later on mixes with the nozzle exhaust.

And so, this form or variant of a turbojet engine is known as a turbofan engine you already seen this is some of the earlier lectures and so, turbofan engine again can operate in different modes. We will see at least two different modes of operation of a turbojet turbofan engine the unmixed form and the mixed turbofan modes. And so, turbofan engines have what is known as a bypass, ratio that is a mass flow passing, through the bypass duct divided by the core mass flow is known as the bypass ratio.

So, some of the modern jet engines, which are used in turbofan engine, which are used in transport aircraft typically have bypass ratio of the order of 5 or 6, which means that the bypass mass flow, the cold mass flow. Relatively cold mass flow is five times the mass flow of the core engine. And so, there are two advantages to this, one is of course is that the effective jet exhaust velocities will be lower, which means propulsion efficiencies can be higher. The other advantage is that this additional mass itself can generate a thrust and therefore, you get an additional thrust and also a slightly better propulsion efficiency, which means that the overall efficiency can also be better, than that of a pure turbojet engine.

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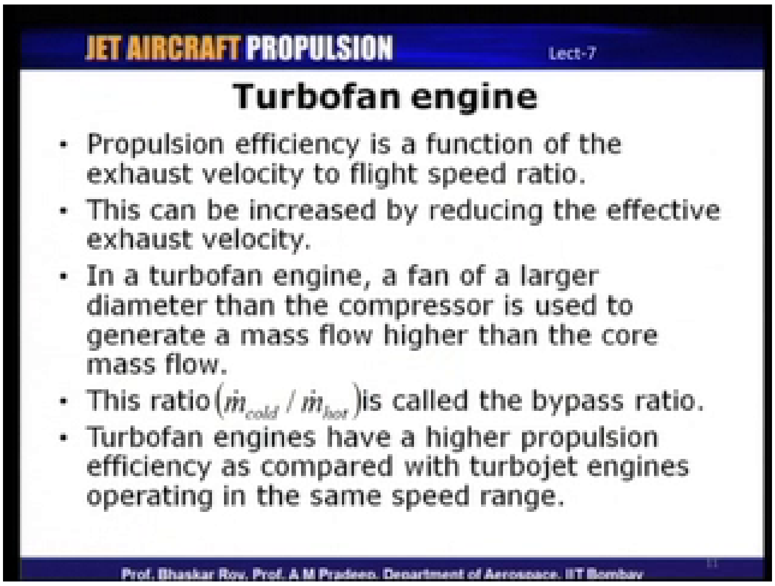

So, the need for a turbofan engine is basically to reduce the effective exhaust velocity and therefore, we add a fan, which has a larger diameter than the compressor and therefore, that generates higher mass flow, than the core mass flow. So, this ratio basically, the mass cold mass flow to be hot mass flow is known as the bypass ratio and so, for the same speed range turbojet turbofan engines will have a higher propulsion efficiency than turbojet engines. Basically, because the exhaust velocities are lower and therefore obviously, means that we get a better propulsion efficiency than a turbojet a pure turbojet engine.

Of course, there is an another advantage of turbofan engines in the sense that, turbofan engine generate lesser noise, jet noise of a turbofan engine is lower than a turbojet engine. This is again related to the jet exhaust velocities, because the very high speed jet, when it expands into cold ambient leads to a lot of noise. Whereas in the case of a turbofan engine, the speed of the jet effective speed of the jet is lower and therefore, the noise of the jet noise of such engines are lower than, that of a pure jet engines, that is another advantage of a turbofan engines, because in these in current scenario the noise restriction are also getting string and very year.

And so, aircraft engine manufacturer, need to stick to certain noise norms in the sense that noise levels of jet engines need to be lower than certain levels, which have been which have been stipulated and so, every few years, these norms are revised and it gets stricter, every time it is revised. So, it is necessary for engine manufactures to idea to all these norms and so, turbofan engines have that additional advantage as well. Because these aircraft have to take off and land in airports, which may be close to civilian regions and so, it is necessary, that the noise levels are under control.

So, let us now, look at a schematic of a turbofan engine one of the forms of a turbofan engine and we will immediately see, what makes it different from a turbojet engine.

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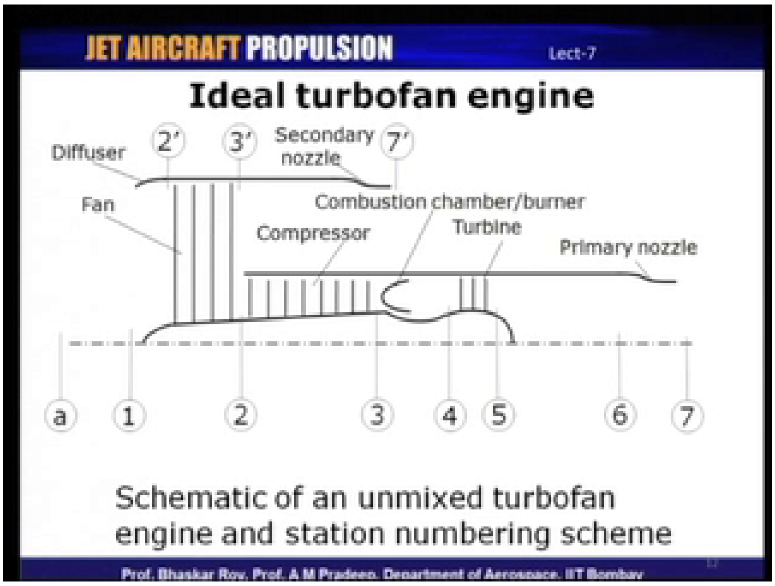

So, this is one schematic, that I have of a turbofan engine this is basically an unmixed turbofan engine, I will explain what is unmixed shortly. And you can see that the fundamental difference between this engine, which is shown unmixed turbofan and pure turbojet is the first component that you can see here, well rather the second component that is a fan.

In a Turbojet this fan was nonexistent and therefore, after the diffuser, we had a compressor the combustion chamber the turbine and the nozzle in a turbofan, we have this additional component. And so, this fan diameter as you can see is much larger than that of the compressor and so, this will be able to generate a greater mass flow, which will pass through this bypass duct.

So, there is a bypass duct which surrounds the core engine and then this bypass duct, will exhaust through a secondary nozzle in the case of an unmixed turbofan. And so, after the diffuser we have a fan, part of the fan mass flow goes through the compressor, but a larger mass goes through the bypass duct, which gets exhausted through the secondary nozzle.

Then we have the usual turbofan here for the Turbojet for the core engine that is a compressor than a combustion chamber then expansion in the turbine followed by the primary nozzle. So, these are the various components of turbofan and unmixed turbofan and at least the core engine here, closely resembles at pure turbojet engine. Now what about the second variant of this engine, we have a mixed turbofan here.

In a mixed turbofan you can see that, the there is only a single exhaust from such an engine that is the bypass mass flow mixes with the turbine exhaust, before it exhaust through a common nozzle. Whereas in the unmixed turbofan, we had two separate nozzles one was bypass nozzle or a secondary nozzle and the primary nozzle, which was from the core engine the hot nozzle.

In a mixed turbofan there is a single nozzle and the bypass mass flow mixes with the turbine exit mass flow, before it gets exhausted through a common nozzle, so these are two variants or two different types of turbofan engines. So, turbofan engines can operate can exist in these two different modes or forms, for transport aircraft it is the first form that is the unmixed turbofan, which is more commonly used. And in some of the recent military aircraft, we have the mixed turbofan with a very low bypass, which is something we have seen in some of the earlier lectures, that very low bypass turbofan of course it very difficult to say whether it is a turbofan engine but it has of small bypass with a very small mass flow.

And therefore, it gets classified as a turbofan engine which is mixed and a single nozzle exhausting and what are the different processes, which are involved in a turbofan engine well it is very similar to that of a turbojet most of the processes are common except for the first few processes which involve the fan and the bypass nozzle and so, on.

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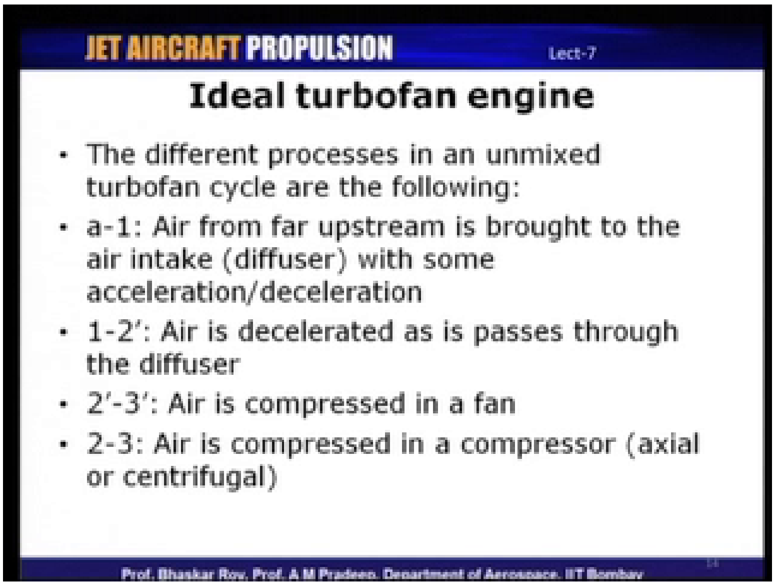

So, the different processes, let us say in an unmixed turbofan will be the following, we have the diffusion taking place between stations a and 2 prime. And then we have compression in the fan between 2 prime to 3 prime compression in the nozzle well compression in the compressor which could be axial or centrifugal is between stations 2 and 3, so 2 to 3 is compression in the compressor.

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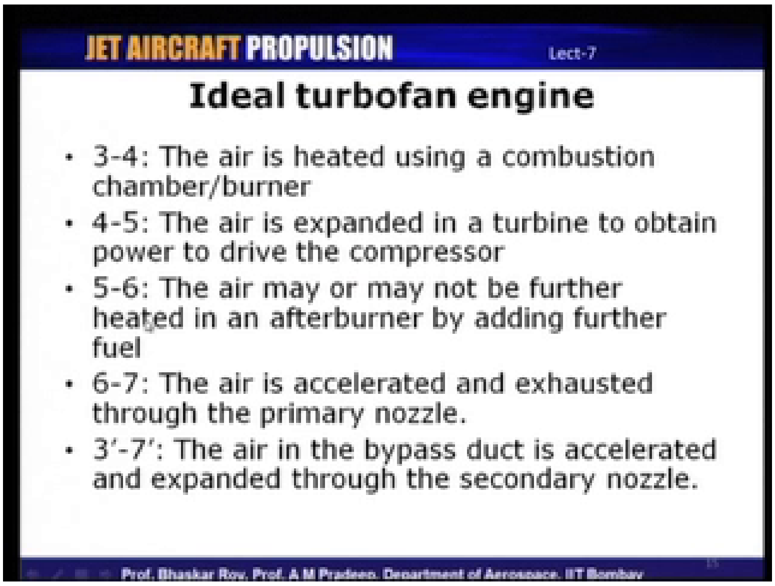

Then, there is a combustion chamber between 3 and 4 and between 4 and 5 is a turbine and 5 to 6 of course, there could there is if it is unmixed, there is very little chance that there is any afterburning here but in a mixed turbofan, there could be an afterburner as well and between 6 and 7 is the primary nozzle and the bypass duct also has a nozzle. Which is the secondary nozzle noise and that also generates a substantial amount of thrust, basically because of the mass flow that the fan generates.

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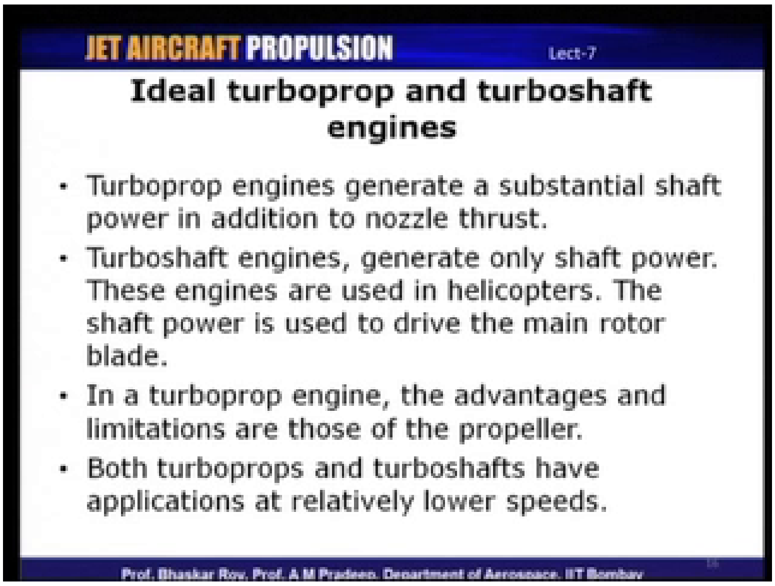

So, the different processes in a turbofan engine as compared to that of a turbojet engine is the differences are basically, because of the presence of the fan and the bypass duct. And in the case of let say an unmixed turbofan or even a mixed turbofan, sometimes it is also possible, that we have we may have to split the turbine into different stages to enable us to drive these, the fan. And the compressor at different speeds; because the fan has a much larger diameter, than that of a compressor therefore, an unmixed turbofan, it is necessary for us to drive the fan and compressors at different speeds.

And so, one of the ways of doing that is to use a multi spool engine, you have already seen what is multi spool engine, what are the different forms of those could be twin spool or a three spool turbofan. Which means that the fan is driven by one of the stages of the turbine, usually the last stages of a turbine, that is the low pressure turbine and the compressor is driven by the high pressure turbine. And you could if it is a three spool turbofan, when you the compressor itself is split into two the low pressure compressor the l p c and the high pressure compressor the h p c which are driven by again two different stages of the turbine; and one of the stages of the turbine driving the fan.

So, these are basically meant to drive the different components at different speeds because; obviously, it is not possible for us to drive all of them at the same speed because, the diameters are quite different. And so, if we were to drive for example, the fan at the same speed as that of the compressor, then the tip speed of the fan, obviously, would be much higher than that of the compressor. And so, the other issues like shock loses and so, on which will come into picture, we may discussing this when we discuss about compressors in detail later on.

So, it is for this that we have to split and drive these components at different speeds and so, in unmixed turbofan this is one of the issues that these may have to be driven at a different speeds. Now if you look at the thermodynamic cycle of a turbofan as compared to a turbojet they, will look more or less very similar except, that we would have one more cycle for present for the bypass stream. Because for unmixed turbofan the core stream and the bypass streams are entirely different or separate and therefore, the bypass process itself is entirely different.

So, and so, we could have another cycle which is meant for the bypass stream, there is no heat adhesion occurring there and so, it is basically not part of the core bypass, the core Brayton cycle mode. Whereas, the core engine is very similar to that of a turbojet and so, the cycle is very much the same as what we have discussed. And what we will also be discussing may be in one of the later lectures is about the how, how is it that we can analyze a real turbofan engine.

That is a turbofan engine, which has all those loses and irreversibility's accounted for and how can we carry out a cycle analysis of such engines and get estimates, about their performance in terms of thrust and efficiencies and fuel consumptions and so on; we will discuss that in one of our later lectures.

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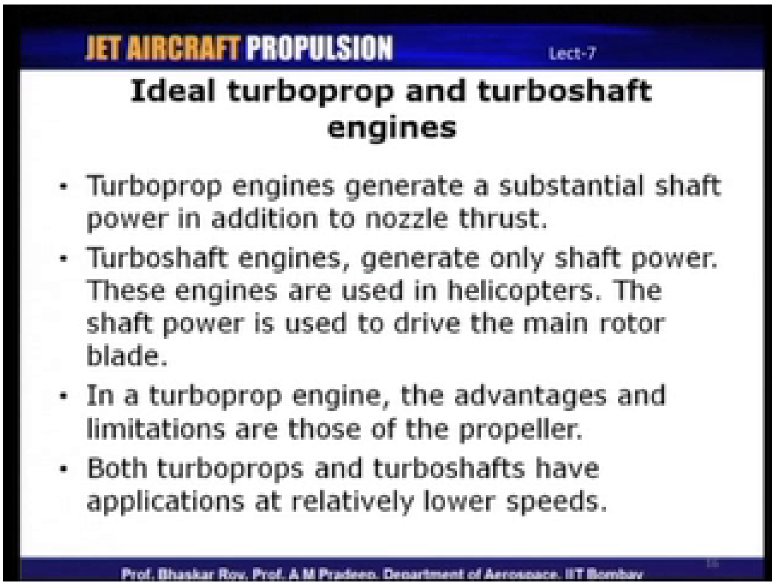

And so, the next set of engines that we will be talking about are the turboprop and the turbo shaft engines, turboprop engines as you know is a class of engines, which generate substantial shaft power. And there could be of course, turboprops which also generate nozzle thrust, besides the majority through the shaft power itself. Turbo shaft engines on the other hand it generate only shaft power and these are used in helicopters and the shaft power which these engines generate is used to drive the main rotor blade and in a turboprop engine the, what we aim to do is to incorporate.

The advantages of a propeller based engine into a jet engine as we know the propeller based engines have a very high propeller efficiencies and propeller efficiencies of pure jet engines and much lower than as compare to propeller based engines. So, if we want to combine the both these engines together and see we can get a better propeller efficiencies by combining these two. So, turboprop engines is one way of trying to use the advantage of the propeller type of engines and jet engines and therefore turboprop engines have higher professional efficiencies compared to pure jet engines.

And turbo shaft engines on the other hand of course are do not generate any nozzle thrust the primarily generate a shaft power but, both turboprop as well as turbo shaft engines are meant to operate the lower speeds as compared to pure jet engines. And both they have a applications at relatively lower speeds and lower altitudes as compared to pure jet engines

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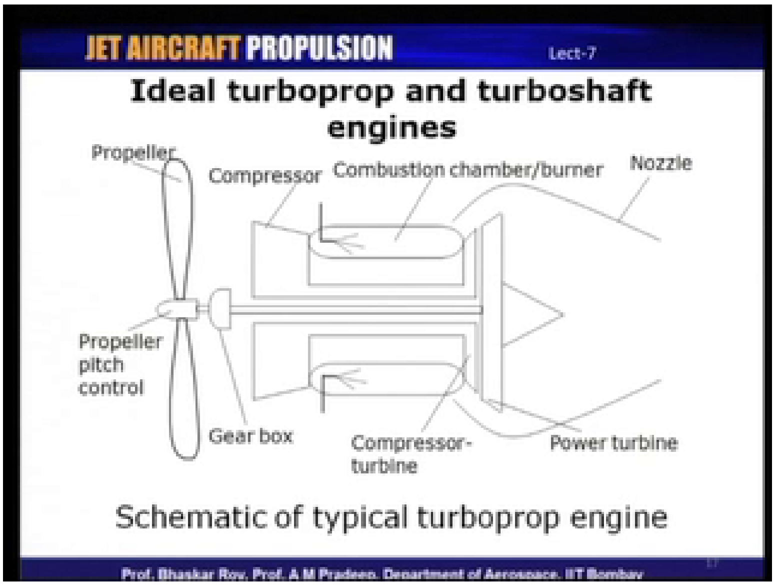

Now this is a schematic of a typical turboprop engine and let us takes a look at what are the different features or components of a turboprop engine, so one of the most prominent components of a turboprop engine is the propeller.

So, this as you see here, is the propeller and propeller is driven by a turbine, which is usually referred to as power turbine or sometimes also refers to as a free turbine. And the shaft power from the turbine is transmitted to the propeller, usually through a gear box, because it may have be necessary to reduce the speed of the turbine exit shaft, because propellers may not be running at very high speeds. And propellers may also have certain pitch control mechanisms, if they have to be altered during flight, during the different changes in altitudes and flight conditions.

And then the other components, which constitute this engine are similar to that of a jet engine, there is a compressor and then a combustion chamber and then from the at the exit of the combustion chamber there is a nozzle well, there is a turbine. And this turbine is usually referred to as the compressor turbine, because it drives the compressor and from the exhaust of this turbine the there is a power turbine. This power turbine is meant to drive the propeller and then exhaust of this power turbine goes through a nozzle, which may generate some amount of thrust.

And so, if the difference between a turboprop and a turboshaft is basically, that in a turbo shaft engine this the thrust develop by the nozzle is negligible and so, a propeller is replaced by the main rotor blade. And so, the power turbine drives the main rotor blade and there is negligible nozzle thrust generated by turbo shaft engines but, the rest of the cycle and the components remain the same.

So, here again you can see that many of the components are common to that of the turbojet engine like compressor, combustion chamber turbine. So, these components are present even in a turbojet it is also present in a turboshaft, turbofan engine and obviously, it is also there in these engines that is turboprop and the turbo shaft engines.

So, many of these components are common and the difference between these variants of the basic turbojet is in the presence of certain additional components like the fan and the bypass duct and the secondary nozzle. In the case of the turbofan engines and the presence of propeller or the main rotor blade, in the case of turboprop or turbo shaft engines. So, these components basically, make the these variants of a pure turbojet engine, now both turboprops and turbo shafts have as we have seen a separate turbine, which is known as a free turbine or a power turbine. Which drives the propeller in the case of turboprop or the main rotor blade in the case of a turbo shaft engine.

And so, this particular turbine is known as a free turbine or a power turbine, because it is not driving any of the compressor stages it is driving just the propeller or the main rotor blade. And because of limitations in the maximum speed, that these propellers or the rotor blades can rotate it would be normally required to reduce the turbine shafts speeds too lower values. And that is why we normally use gear boxes in turboprops and in turbo shaft engines and in the case of turboprops in sometimes there could also be certain amount of thrust which is developed by the nozzle.

And so, there could be nozzle thrust developed in turboprop, which is not really present in turbo shaft engines because turbo shaft engines, primarily developed they the thrust because of the presence of the main rotor blade.

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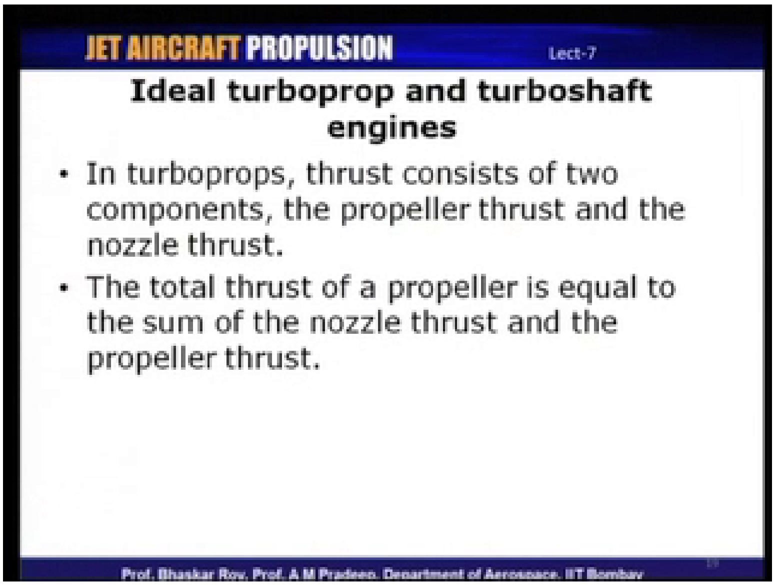

Now, in the case of turboprop engines, basically the thrust may consists of two components, one because of the propeller thrust and the other is the nozzle thrust and therefore, the total thrust is the sum of these two the nozzle and the propeller thrust. And in the case of turbofan engines, again the unmixed turbofans very similar thing happens that is the thrust component, because of the bypass duct and there is also a thrust component, because of the core mass flow, total thrust will be the sum of the bypass has and the core thrusts.

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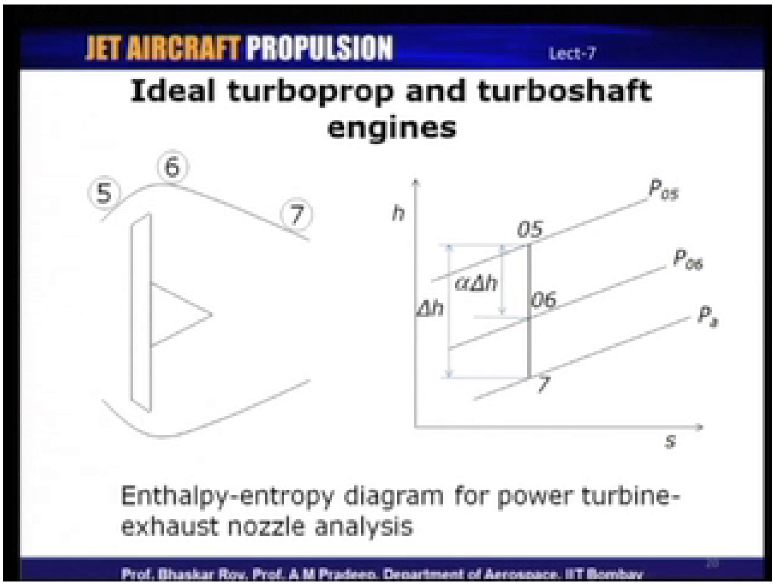

Now in the case of a turboprop or a turbo shaft engine, one of the differences between this and the basic turbojet engine is the free turbine, that is free turbine is one of the components which distinguishes turboprop and turbo shaft engine from a turbojet engine. And so if you look at the free turbine here, this is the free turbine that is shown which is present between stations 5 and 6; and so, there is an enthalpy drop, which is occurring in the free turbine and that is between the stations 5 and 6.

So, the total enthalpy between stations 5 and 6 drops and you can see there is a pressure drop total pressure drop as well between 5 and 6 and the rest of the expansion occurring between station 6 and 7, which is the nozzle. In the case of turbo shaft of course 6 and 7 are the same points and therefore, the expansion is entirely between 5 and 6 and which is what it would be in the case of a turbo shaft engine. And so, that is one of the differences between the turboprop and the turbo shaft, in the sense that in in turboprops it is possible to have certain amount of thrust, so in expansion which continues after the free turbine in the nozzle.

So, certain amount of thrust is still developed by the nozzle whereas, in the case of turbo shaft the entire enthalpy drop occurring during the expansion process occurs just across the turbine stages, which is the compressor turbine as well as the free turbine stages. So, that is once, the expansion is no longer split into the compressor and the nozzle here, in the case of turbo shaft it is entirely through the turbine exhaust. And so, that is what it makes difference between pure turbojet and these propellers or turbo shaft engines the presence of the free turbine.

So, far we have been discussing about jet engines, which involve rotating components like in the case of. In fact, all these engines, we have been discussing have compressors and turbines, which are rotating in nature. So, all these components all these forms of engines have turbo machines.

And so so, these are one class of engines jet engines, which use turbo machines for their operation and there is another simple form of a jet engine, which we will discuss, now which are known as Ramjet and Ramjet do not have any of these rotating components. So, without the presence of any of these rotating components it is still possible to develop thrust with certain conditions, we will discuss and so, you may wonder how is it that it is possible to have a jet engine, which can develop thrust without having any of these rotating components.

Where it sounds very simple and schematically also it looks very simple but it is operation is not as simple as what we would expected to be.

And so, Ramjet are the simplest form of jet engines, in the sense that they do not have any rotating components, they do not have compressors and therefore, they do not have any turbines but, they do have air intakes combustion chambers and nozzles. So, using these three components simple components it is possible to generate thrust and we will see why is it that, it is in spite of being, so simple it is not commonly used, we will discuss that little later.

So, Ramjet are the simplest form of jet engines and they basically have just three processes occurring a compression process occurring in the intake of the diffuser. A combustion process occurring in the combustion chamber and at the expansion process through the nozzle; so using three different thermodynamic processes, it is still possible to develop thrust where Ramjet operate based on this.

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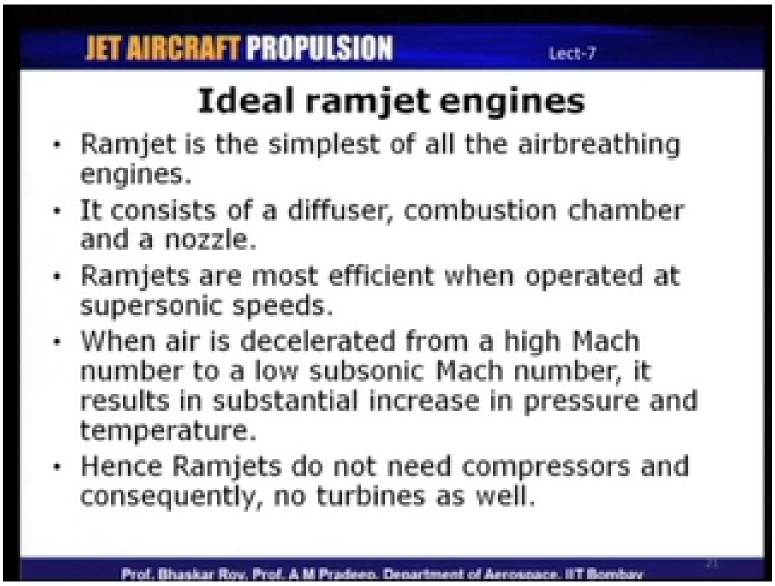

So, Ramjet are suppose to be most efficient only when they are operated supersonic speeds and the basic principle behind the ramjet is that, when air is decelerated from a very high Mach number to very low subsonic Mach numbers, it results in substantial increase in pressure and temperature.

We must we have discussed this earlier, in the earlier course and if we have gone through gas dynamics course you would know by now that if air is decelerated from very high Mach number to very low Mach number this requires of course the use of shocks and so, on. There is a substantial increase in the pressure and temperature, and if that is a case you do not really need a compressor, because the air is getting decelerated any way without using compressors and there is an increase in pressure and temperature.

So, with this I n mind you do not really need a compressor, because pressure and temperature has already been raised and since you do not need any compressor, you do not really need a turbine as well, because turbine is basically meant to drive a compressor if you do not need a compressor you do not need a turbine as well now.

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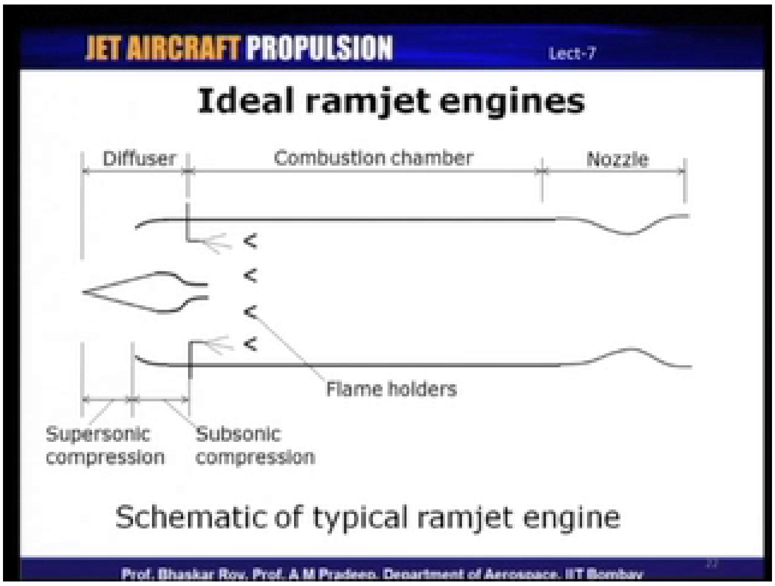

So, let us look at a schematic of a Ramjet I mentioned that it is very simple and it is indeed simple to look at the schematic that, it consists of a diffuser, a combustion chamber and a nozzle.

Because, the diffuser is slightly complicated it it is a supersonic diffuser it has one component which is known as a supersonic compression and then followed by a subsonic compression, at the inlet of the combustion chamber there are injectors fuel injectors. Which initiate combustion and there are flame holders to ensure that the combustion is stable and then at the exit of the combustion chamber we have a nozzle.

So, this type of diffuser geometry, which consists of supersonic compression, subsonic compression will we will discuss this later on when we take up diffuser analysis in detail. So, this is a schematic of a Ramjet and since it consist of only three processes and now turbo machines at makes it design of ramjet very simple at least theoretically. And so, even on a cycle if you look at ramjet cycle it is very similar to that of pure Turbojet cycle or a Brayton cycle consisting of a compression process a heat addition process for a Ideal ramjet it is at constant pressure and an Isentropic expansion.

So, with these three different components it is possible to achieve thrust using Ramjet, but the precondition for operation of a ramjet is that it has to operate at a certain speed before Ramjet can themselves be operational. Because Ramjet do not have compressors and turbines a stationary ramjet cannot generate any thrust it cannot operate at all, so for a ramjet to begin its operation it must be taken to a certain speed. Because it Ramjet require that the incoming air can get compressed on its own, by virtue of the diffuser geometry.

So, if that has to happen, Ramjet themselves have to be taken to a certain speed, before which they can start operation and Ramjet have may generate maximum thrust at very high supersonic speeds of around Mach three. So, at around Mach number of three is when Ramjet operates most efficiently and generate the maximum thrust.

And so, below mach three the performance is sub optimal and at very low mach numbers Ramjet can hardly operate on it is own, so Ramjet needs to be taken to a substantially high mach number before which they can begin to operate.

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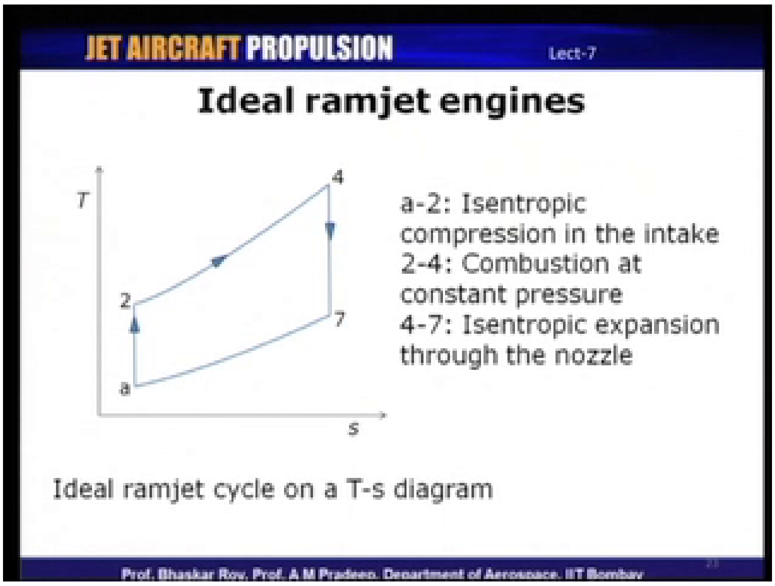

So, T s diagram of ramjet cycle and ideal ramjet cycle would look like this is an isentropic compression taking place in the intake, followed by combustion at constant pressure and then there is an isentropic expansion through the nozzle between stations 4 and 7. So, this is how an ideal ramjet cycle would be very simple cycle and resembles a Brayton cycle very closely.

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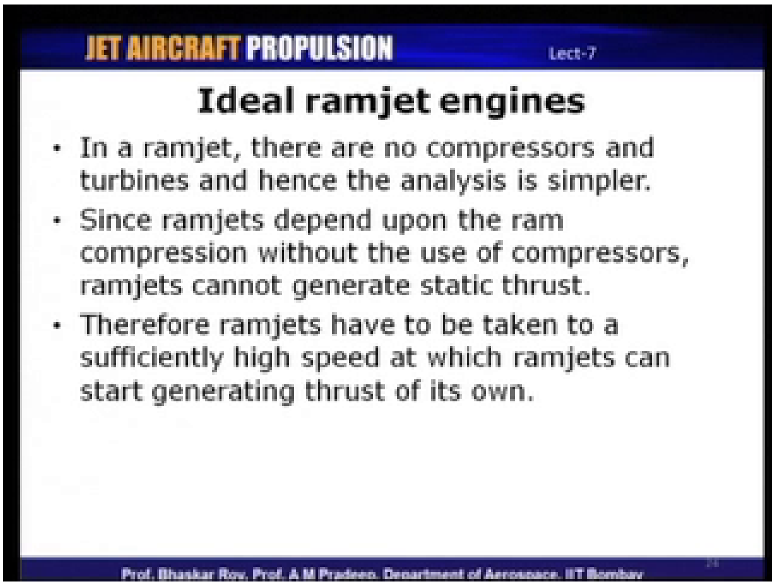

Now, in a Ramjet engine there are no compressors and turbines and therefore, it is analysis is quite simple, because you do not have too many complex geometries present in ramjet and so, Ramjet cannot generate any static thrust basically because Ramjet depend upon ram compression, without the use of compressors.

And therefore, they cannot generate any static thrust Ramjet have to be taken to sufficiently high speed there's a certain speed beyond, which only then Ramjet can begin to generate thrust of it is own. So, Ramjet have to be taken to a certain speed before which they can start generating thrust.

So, that is the basic limitation of a ramjet that it cannot generate thrust, static thrust on it is own, so what we have discussed today is the different type or the different types of jet engines.

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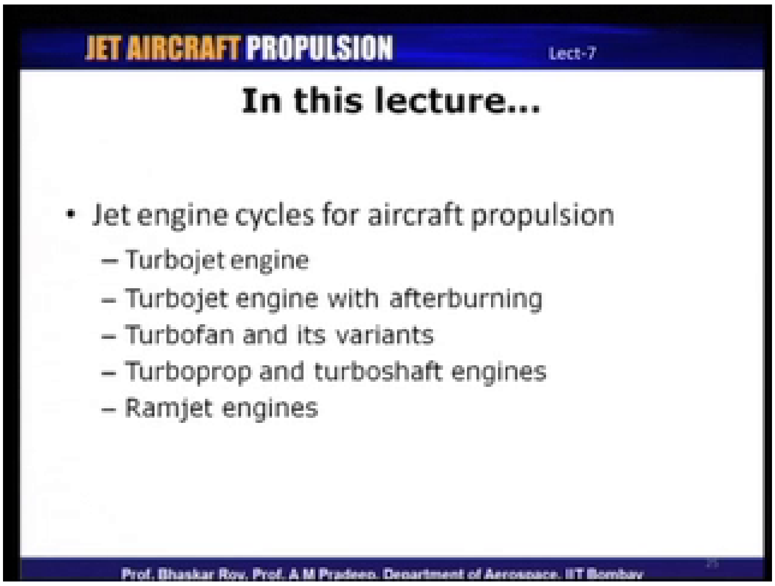

We started our discussion with the basic type of a jet engine, the turbojet engine and different forms of the turbojet engine, then we have also discussed about turbojet engine with afterburning and then the variants of a turbojet engine. We started with turbofan and different forms of the turbofan engine the mixed and unmixed turbofan engines, we also discussed about turboprop engines and the turbo shaft engines and then of course, we also discussed about Ramjet engines, which are the simplest form of a jet engines.

So, these are some the topics, we have discussed in today's lecture and we will continue with our discussion on jet engines in the next lecture as well.

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In next lecture, we will be discussing about the different components which constitute a jet engine and how can we account for the performance of these components, we will discuss about the air intake or the diffuser, the compressor or the fan, combustion chamber turbine and the nozzles. So, these are the different salient components of a jet engine, we will discuss about the performance of a performance parameters, which need to be considered for cycle analysis of an actual jet engine.

And So, we will discuss about these in our next lecture and subsequently, we will take up the cycle analysis of actual jet engines, we will be carrying out cycle analysis or of all these jet engines. What we have discussed and we will also account for the component performance variation occurring across all these different components, so we will take up discussion of these topics during the next lecture.