Gas Dynamics and Propulsion

Dr. Babu Viswanathan
Department of Mechanical Engineering
Indian Institute of Technology – Madras

Lecture - 26
Propulsion - an Induction

Today, we are beginning our discussion on air breathing engines and in the beginning of the course we actually looked at air craft engines and we saw why studying gas dynamics was important for this application because we showed that the flow is predominantly compressible in most of the aircraft engine. We said that you know compressibility effects are significant in the intake, in the compressor, in the turbine and in the nozzle.

The only component in which compressibility effect was not significant was the combustor. So we have gone through a discussion of gas dynamics including all aspects of gas dynamics that are relevant to this application. See gas dynamics is a vast field by itself. What we have discussed are concepts and ideas relevant to application and proposition in air breathing engines.

So with that knowledge, today we begin our lecture on air breathing engines and what we will go through in this lecture is to first look at various issues and design considerations. There are many design considerations, practical considerations and decisions about the engines and other things are made based on these considerations.

Although it is important to have a knowledge of gas dynamics and so on, many times in a practical situation, decisions are made which are completely opposite to what you would have decided based on a gas dynamic analysis. Because it is simply not feasible to produce something. It may be more feasible to produce a slightly less efficient device than to produce a more efficient device. So those are practical aspects and there is also some of the things that we will look at today.

Design decisions and what drives these design decisions is something that we will look at. We will also look at basic operation of an aircraft engine, look at analysis of different components, how do we design the different components from a fluid mechanics perspective, thermo dynamics perspective, gas dynamics perspective and from a materials and manufacturing perspective.

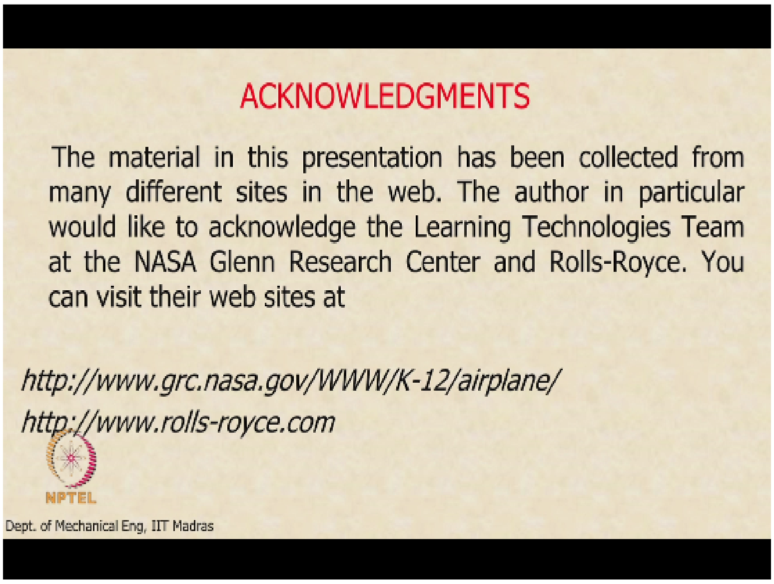
So we will take a look at all these things plus we will also start looking at thrust produced by engine. Ultimately, thrust and thrust specific fuel consumption are 2 are the quantities that we wish to calculate based on the discussion that we have. So we will develop expressions for both and we will show how to actually do thrust calculation and thrust specific fuel consumption calculations for practical engines that are in service today.

So we will look at aircraft engines that are being used today and then do thrust calculations for these types of engines through worked examples. Demonstrate how these can be calculated and not only that, we will do the calculations and compare the numbers that we are getting for thrust and TSFC with what the manufacture quotes to see how realistic our calculations are.

It is one thing to develop a procedure and do something but we must also make sure that we are getting numbers which are reasonable with what the manufacturer thinks they are to be. So we will do that comparison also and after finishing gas turbine engines, which are commercial aircraft engines, we will look at ramjets and we will also look at scramjets. We will try to do thrust calculations for ramjet engines.

But for scramjet engines we will look at the concepts and the challenges that are involved in manufacturing scram jet engine. Even today, there are lots of challenges that remain even today, we will take a look at some of those things okay. So that is the general outline for the rest of the course.

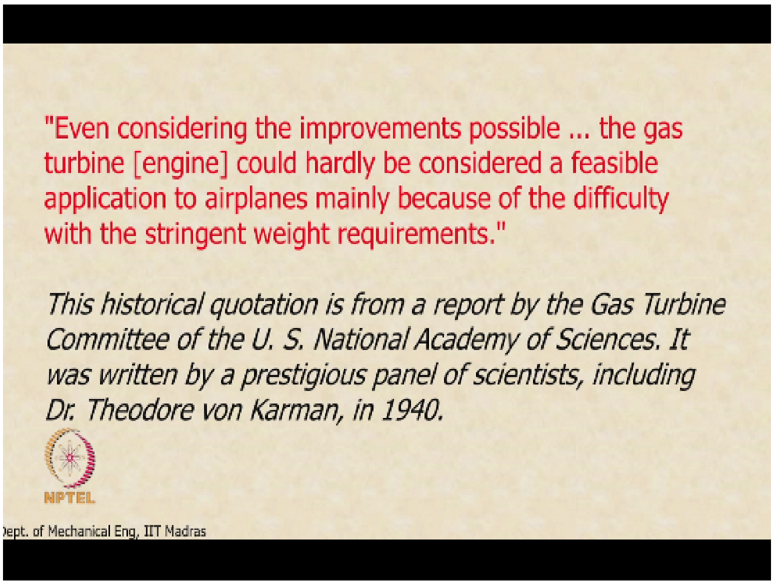
(Refer Slide Time: 03:35)



Much of the material that I am going to present from here onwards is actually taken from sources in the web, is an extremely good source in particular I have liked these 2 sources, one is the NASA Glen Research Center, the other one is the website for Rolls-Royce, they are very nice material and if you have time, I suggest that you go and take a look. Many of the diagrams and other things in the presentation are also generated by me.

So, wherever possible, I have acknowledged material which I have been taken from sources besides this. I do not claim any ownership to anything that has been taken from the websites.

(Refer Slide Time: 04:13)



So we start this lecture with a very interesting quotation. This is a quotation which is tribute to an expert committee of the U.S National Academy of Sciences and the report was written in 1940. In the committee concluded based on technology that was available at that time.

Even considering the improvements possible, the gas turbine engine can hardly be considered feasible alternative to airplane application mainly because of the difficulty with the stringent weight requirements okay.

One of the most important metric for an engine to be used as a propulsion device in an aircraft is not the thrust that it can produce or the thrust specific fuel consumption. I talked about thrust and TSFC, these are very important metrics, no doubt. But the most important metric which decides whether the engine makes the cut or not is thrust produced per unit weight of the engine. Because anything that is carried board the aircraft has to be lifted.

So which means you know heavier engine may generate more lift, but the lift that the engine produces will be largely consumed just for keeping the engine aloft. Which is of no use. You know what we want to maximize is the number of passengers or the payload that can be carried aloft, not the engine weight okay. So thrust produce for engine unit engine weight is the most important metric in an aircraft application.

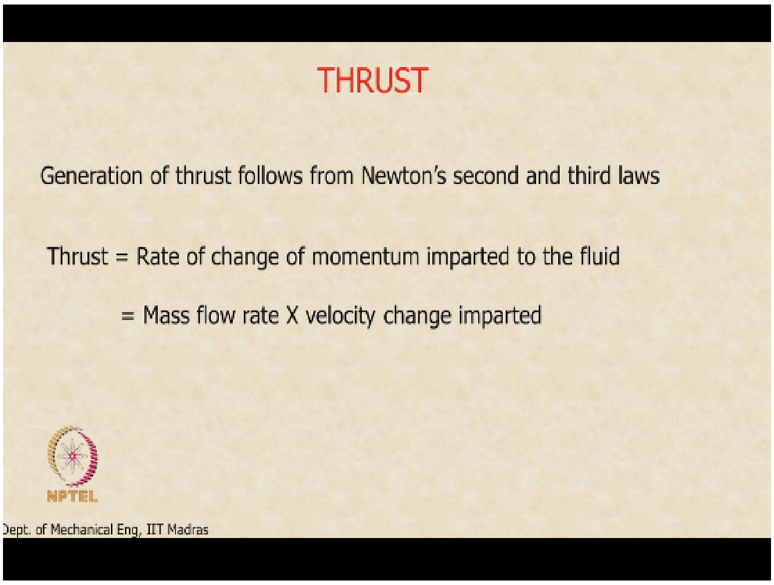
Unlike a terrestrial or LAN based application or even marine application where the weight, there are basically no constraints on weight. But the operating environment of aircraft is such that thrust per unit weight of the engine is very important and what this committee was saying in 1940 was that, precisely for the thrust per unit weight metric that the gas turbine engine will not make the cut was what they felt at that time.

But within about a decade of this report coming out, gas turbine engines had largely replaced piston engines for aviation application okay. That was driven by number one World War II and number 2 the booming of economy around the world after World War II. See it was basically the demand that drove the technology not vice versa and that was something that these scientists could not have foreseen. They were scientists after all not economists.

And so that was something they could not have foreseen so I give this quotation not to cast aspersions on the committee but to say what is possible when engineers set out to achieve something. That especially I am proud of saying that never challenge a mechanical engineer. You do not know what they are capable of okay. Because these engines are not made by aerospace engineers but by mechanical engineers.

People who are experts in turbo machines, turbines and high temperature materials, mechanical engineers and metallurgists okay.

(Refer Slide Time: 07:15)



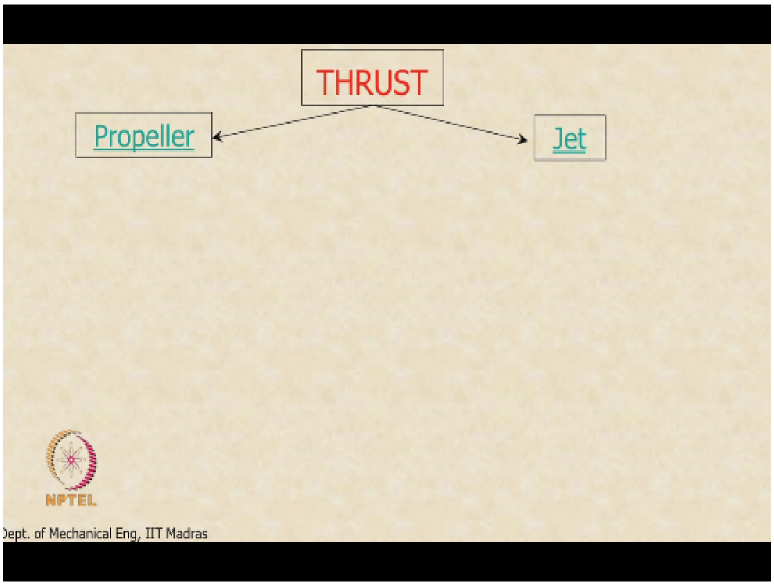
So, we start with the most fundamental thing as we said thrust. So any engine that is going to be used in an aircraft, the idea is for the engine to produce thrust and generation of thrust follows from Newton's first, second and third laws okay. So, basically we can show that thrust is nothing but rate of change of momentum imparted to the fluid as it flows through the engine right. So, this part of it is the second law right.

We impart rate of change of momentum to the fluid and the third law aspect comes when the fluid exerts and equal and opposite force on the engine frame. So that is the third law aspect of a thrust generation. And this rate of change of momentum is nothing but, the product of mass flow rate times velocity change imparted. Under study state operating conditions, this is nothing but, product of mass flow rate and velocity change.

Now because the thrust is the product of 2 terms. This offers the scope for us to develop engines which can develop thrust in 2 different methods. One is keep mass flow rate very large and try to impart a small velocity change. The other strategy is to keep this reasonably smaller but keep the second term quiet large, impart a large velocity change to a small mass of air okay.

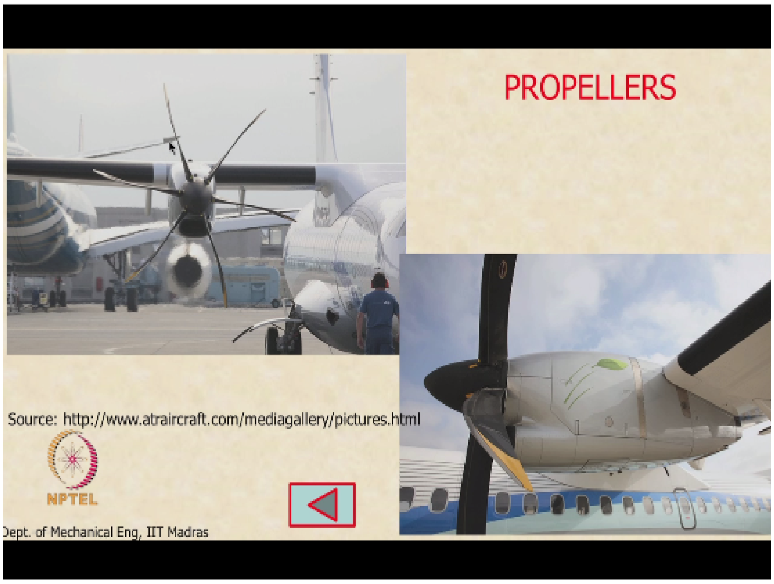
So these are the 2 strategies that are possible and if you take a look at how historically how the engines were developed, you will see that these are the 2 branches along which propulsion technology developed historically.

(Refer Slide Time: 08:54)



So we start with the requirement of generation of thrust and historically thrust in aircraft engine application has been generated by 2 devices. One is the Propeller, other one is the Jet okay.

(Refer Slide Time: 09:07)



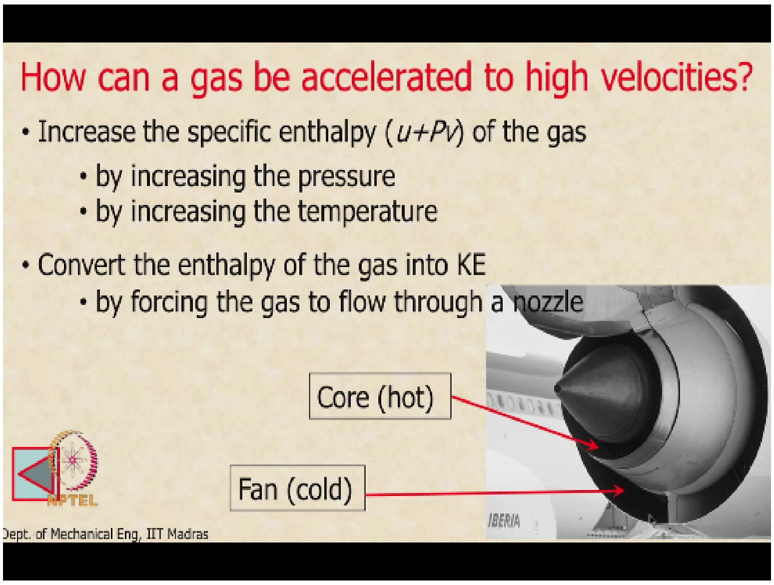
Now the propeller, here is a view of a modern turbo prop engine. So, you can see the Propeller here. The Propeller is very large, there is no duct surrounding the Propeller. It operates in the open atmosphere because the cross sectional area at the tip diameter is so high. We can see that the Propeller will suck in a large amount of air. So the Propeller works on the first idea. Impart a small velocity change to a large amount of air.

So it takes in a large amount of air and it generates thrust by imparting a small velocity change to it okay. Notice that as we can see from here, the modern turbo prop engine uses a gas turbine engine to run the propeller. It does not use a piston engine; this is actually a small gas turbine engine. So the Propeller is directly coupled to the shaft of the gas turbine engine and the engine runs the Propeller okay. So, this is the Propeller engine.

So, you can see there are large cross sectional area means M dot is very large, delta v is very small. So, you can see that in this case M dot is a large number I have indicated that with a capital M, but delta v is a small number, I have shown that with the small value. And I have also indicated that, I have indicated cold here, meaning the temperature on the air on a working flow it does not change as it passes through the Propeller right.

The temperature remains the same. That is why I have said that this is cold and this has very significant implications later on okay. We will now turn to this and then see what this does okay. Now as you can see from here, the jet engine uses the opposite strategy. Here, m dot is small and delta V is large. So, it imparts a large velocity change to a small mass of fluid okay. That is what a jet engine does.

(Refer Slide Time: 10:56)



How do we do that? So, how do we accelerate a gas to high velocities? Right, this is simple thermo dynamic problem right. So, we increase the specific enthalpy of the gas. As you know, as we discussed earlier, the specific enthalpy of a gas is nothing but u + Pv, where u is the internal energy, P is the pressure, v is the specific volume. There are 2 terms in this expression.

So we can increase the specific enthalpy by exploiting or increasing these 2 terms. So once I increase the specific enthalpy, how do I do? I convert the enthalpy of the gas into kinetic energy. That is how I accelerate a gas to high velocities. How do I convert, how do I do these 2 things? That is what we are going to look at next. So how do I increase the specific enthalpy of the gas.

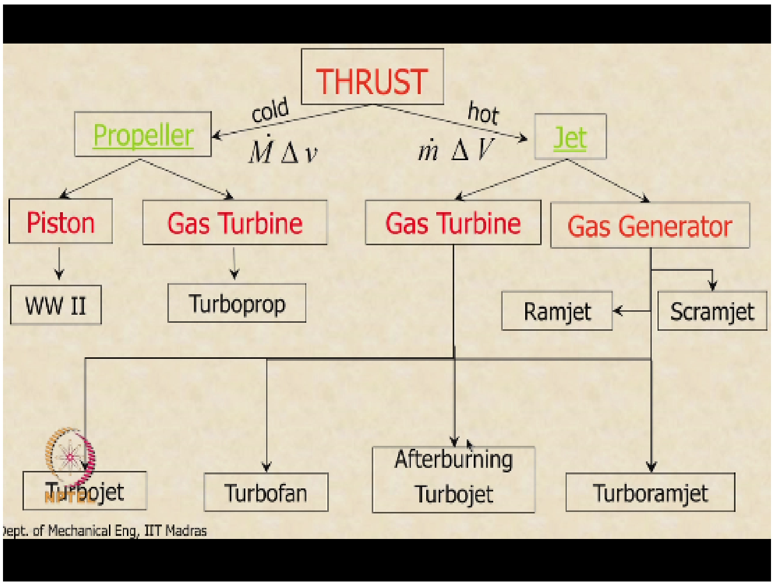
If I look at the second term, I can increase the pressure and increase the specific enthalpy right, or I can increase the internal energy. How do I increase the internal energy of an ideal gas? As you know, these are almost thermally perfect gases, so the internal energy depends only on the temperature. So I increase the temperature, I increase the specific internal energy.

So basically the gas turbine engine does 2 things. It increases the pressure, it increases the temperature thereby increasing enthalpy and then converts the enthalpy into kinetic energy in a nozzle right. How do we do this? We are forced the gas to flow through a nozzle and the conversion of the enthalpy into kinetic energy takes place right. So, here is a look at propulsion nozzle, these are the nozzles of a turbo fan engine, you see 2 nozzles here, one is on the outside, which is the nozzle for the fan, which handles cold here.

Another one is the nozzle at the core engine, which is the core nozzle and it handles hot gases. So by forcing the air to flow through this nozzles, we have already seen nozzle flows and we have applied impulse function to evaluate the thrust, you know that. The enthalpy is converted into kinetic energy and as the air leaves, the momentum that is imparted to the air is felt as thrust and we also said that I can calculate the thrust by looking at change in momentum or by integrating the pressure on the metal surfaces of the engine.

Both are, it is nothing but Newton's third law correct. So, that is how gas can be accelerated to high velocities and a small mass of gas when accelerated to large changes in velocity can also produce thrust. This is how a jet engine produces thrust okay.

(Refer Slide Time: 13:22)



So this is the difference between these 2. So jet engine has a smaller m dot larger delta V. Propeller engine large M dot smaller delta v okay. Now, historically Propeller engines have been driven by either piston engine that is around World War II or as I showed now in the modern times, the Propellers are driven by a gas turbine engine okay. So this was before World War II and the gas turbine engine which is what is used today, these are turboprop engine right, this is what I showed.

These are driven by small gas turbine engines; these are very efficient. Now, jet engines for example as we said, for the jet engine to operate, it needs a stream of high enthalpy gas, it needs a stream of high enthalpy gas which it will then force through a nozzle convert the enthalpy to velocity. So this requires an engine to supply high enthalpy gas and that engine can be the gas turbine engine.

In this case, the gas turbine engine produces the shaft power required to drive the Propeller. Whereas here, the gas turbine engine gives or produces the high enthalpy gas stream that is required to generate thrust. That is the difference between these 2. Here the gas turbine engine provides the shaft power or mechanical power to turn the Propeller. Here it provides high enthalpy gas stream that is required to generate thrust using the nozzle.

That is the difference. Now, the gas turbine engine itself has several variations, turbo jet is the simplest possible okay. Turbo fan is the modern engine; we will look at this also. The afterburning turbojet is a variation of a turbo jet engine where after going through the nozzle, the nozzle itself is slightly more complicated, we have additional functionalities for the nozzle.

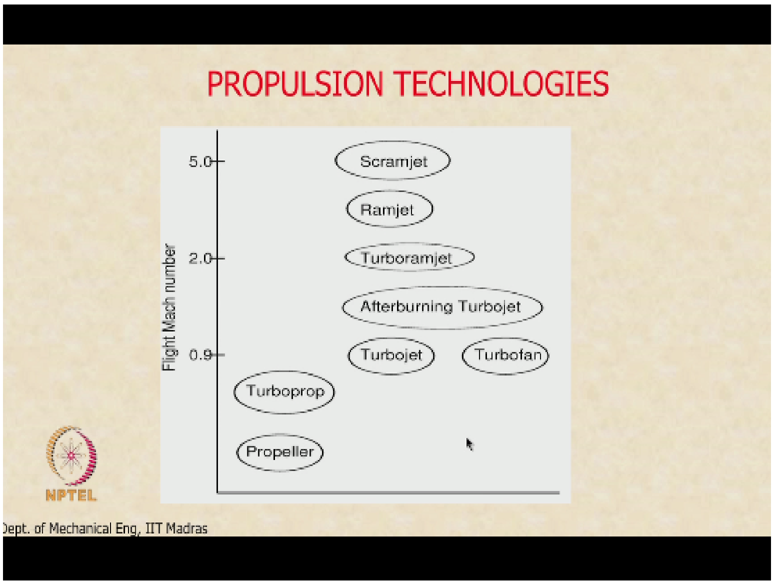
We will look at that also and then there is also a derivative of the gas turbine engine called the turbo ramjet, which is a derivative between a turbojet and a ramjet engine okay. We will look at this technology also as we go along. Now, there are engines which actually operate, we referred to this earlier, both the ramjet and the scramjet engine, because their flight mach numbers are higher.

They can actually use supersonic intakes properly designed intakes to decelerate the air and compress them. Remember we said 2 things had to be done to the air to increase the specific enthalpy. One was increasing the pressure right. So, increasing the pressure is done in these engines by decelerating the air itself. So, the momentum of the incoming high speed air is converted to pressure, that is what these 2 do.

So, they do not need a compressor consequently they do not need a turbine also. So they do not have any moving parts right. So, the turbo ramjet is actually a derivative between the gas turbine and the ramjet engine okay. This is also widely used in military applications and we will look at this concept also as we go along okay.

We will look at each one of this engines and have qualitative discussions in the beginning and then towards the end, we will try to do thrust calculations for a turbo jet engine, for a turbo fan engine, for an afterburning turbo jet engine and a ram jet engine. So we will do thrust calculations for all these engines.

(Refer Slide Time: 16:43)



Now here is a slightly different taxonomy of propulsion technology based on flight mach number. What we looked at earlier was a taxonomy based on chronology, how the technology developed over the years. Here we are looking at slightly different taxonomy using flight mach number. So, propellers to quickly or constraint to flight mach numbers about .5 or so.

See even if you look at the turboprop planes today, they usually fired altitudes only on 15,000 feet no more than that. Because their flight mach numbers are restricted to about .5 or so. Now, turbo propeller or turboprop is in that range. A turbo jet and a turbo fan typically operate in the high subsonic mach number range .95 or so 9 to 95 okay. These typically fly at altitudes of about 35 to 40,000 feet or may be slightly more than that okay.

Because their flight mach numbers can be high subsonic, this is operated at a higher altitude okay. Now the afterburning turbo jet can actually accelerate to supersonic speeds whenever required. It may not cruise consistently at supersonic speeds but, for short duration, by turning on the after burner, you produce extra thrust and we can actually breach the sound barrier and attain supersonic speeds but not sustain supersonic speeds.

This is not the way to go if you want to do sustained supersonic speeds okay. Now, the turbo ramjet is, as I said a derivative of the turbo jet and a ramjet. Ramjet as you can see operates at much higher mach numbers. But because the ramjet engine does not have a compressor, it cannot take off for land, like an ordinary aircraft. It needs to attain that flight speed before the intake will start working.

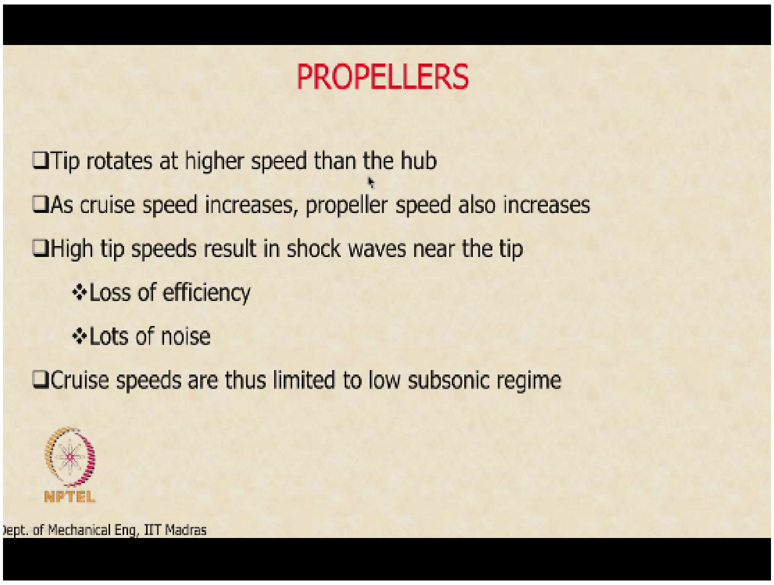
Remember supersonic diffuser can decelerate and convert the momentum to pressure only when it is already moving at a supersonic speed. So, to get into a supersonic speed, you need some other engine. That is why the turbo ramjet engine is a combination of this and that. So when it takes off for lands, this operates like a turbojet engine and when it cruises in a sustained fashion at supersonic mach numbers, it operates like a ramjet.

So for sustained supersonic operation, we use a ramjet part of the engine and for takeoff, landing and reaching cruising altitudes we use the turbo jet part of the engine. So in contrast to the afterburning turbojet, the turbo ramjet can actually cruise at supersonic mach numbers for a sustained period of time. Whereas the after burner can only attain supersonic speeds for short durations of time. Now the scramjet operates at even higher mach number.

So here we are talking about ramjet, we are talking about flight mach numbers about 3 or so. Now, scramjet usually operates at flight mach numbers 5 or even above. I have just qualitatively indicated 5 but we are talking about 5, 6 or even 7.5 and so on. That is the mach number for this and this is the very difficult technology to accomplish. Even to this date proves to be a challenge.

The longest sustained scramjet operation is reported to be about 2 minutes so far. That is the record right now. That is where the strait for the art is for this. Ramjet technology has been used mostly in missiles, we have both liquid fuel ramjet engines and also solid fuel ramjet engines. Turbo ramjet is a proven technology, very costly but proven technology. Others are, these are all commercial technology which are very, very viable okay.

(Refer Slide Time: 20:05)



Now, what are the disadvantages of propellers? Before we start looking at, our interest lies mainly in as I said turbo jet, turbo fan, afterburning turbo jet and ramjets. But it is in a good idea to look at the other technologies to see the short comings and to see how these can be addressed in the new technology. So it is always better to learn from others mistakes and also learn from others strengths.

Propeller has advantages, it is very efficient, but it also has disadvantages right. So, the tip rotates at higher speed than the hub, you could see that the propeller has very large diameter. So the tip moves much faster than the hub and if you want to increase the cruise speed, the propeller speed also has to increase understandably.

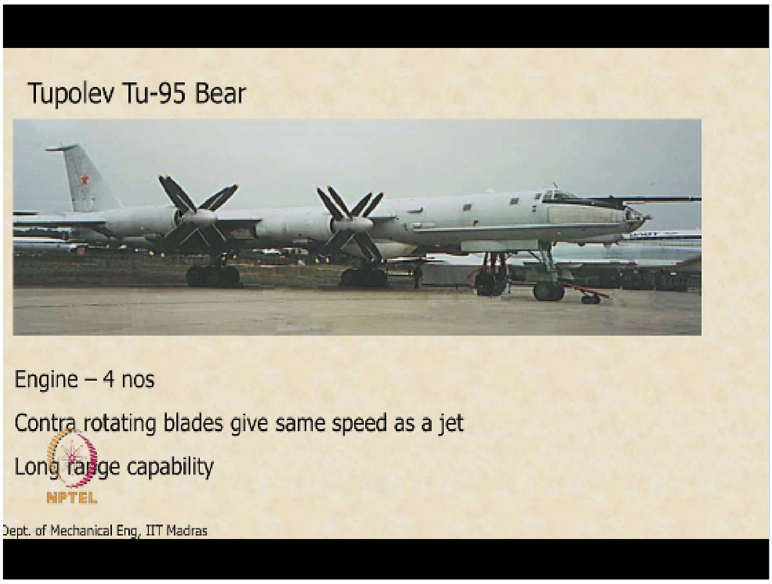
And when you keep increasing the propeller speed, eventually the tip will begin to move with speed which is more than the speed of sound and that starts resulting in shock waves near the tip. And once you start producing shock waves, then the efficiency goes down tremendously. So the propeller efficiency increases up to a certain point and once the tip speed exceeds a speed of sound, then the propeller efficiency falls off okay.

So the other disadvantage with the propeller engine is that you know it is very noisy from a mechanical perspective. Because the propeller is directly coupled or mechanically coupled to the gas turbine engine shaft, it produces a lot of noise. That you can see even today, if you fly in a turboprop engine, you know it is extremely noisy even inside the cabin right.

So for these reasons, cruise speeds of propeller engine, turbo prop are limited to about mach .5 or so and mach .5 is simply not a viable option both commercially and also from a military perspective. From a commercial perspective, trans Atlantic flight, you know lasts about 7 hours cruising at mach .9 or .95. if you reduce it to .5, that means 14 to 16 hours or more, which is simply to long you know for a single flight.

So there is always a push to increase the flight mach number to make the journey time shorter and shorter from a commercial perspective. From a military perspective, of course faster means more maneuverable, more agile, less susceptible to attack from enemy missiles and so on. So, there is always been a push to go to increase the mach number to higher subsonic in the commercial aviation industry and higher supersonic in military applications.

(Refer Slide Time: 22:51)



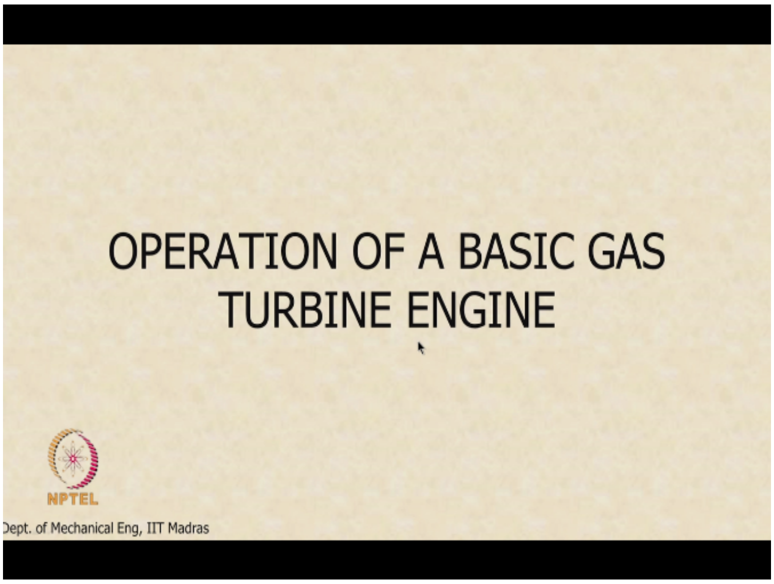
So, here is an example of what people try to do. So engineers did try to improve the cruise mach number of propeller engines to high subsonic mach numbers and this was the result. This is a Russian Tupolev Bear engine as you can see it has 2 propellers, so they said we will add one more propeller to each engine and increase the cruise mach number to high subsonic. It does have speeds comparable to a turbo jet.

There is no doubt about it. And it can fly long range but it is extremely noisy. It is said that you do not need a radar to detect this plane, you can use your ears to detect this plane, that is how noisy this plane is okay. So, this technology, you know never really kind of die, you know some time ago, probably about 30, 40 years ago, this was tried and abandon but interestingly now, it is making a comeback today.

So today, GE has been experimenting with something called an un-ducted fan. So, you can see the contra rotating propellers and one of the biggest advantage of this contra rotating propeller technology is that it is extremely efficient. Even more efficient or comparable in efficiency to ultra high bypass turbo fan engine. So this is a very promising technology from an efficiency perspective and GE has been trying to develop this technology into commercial engines.

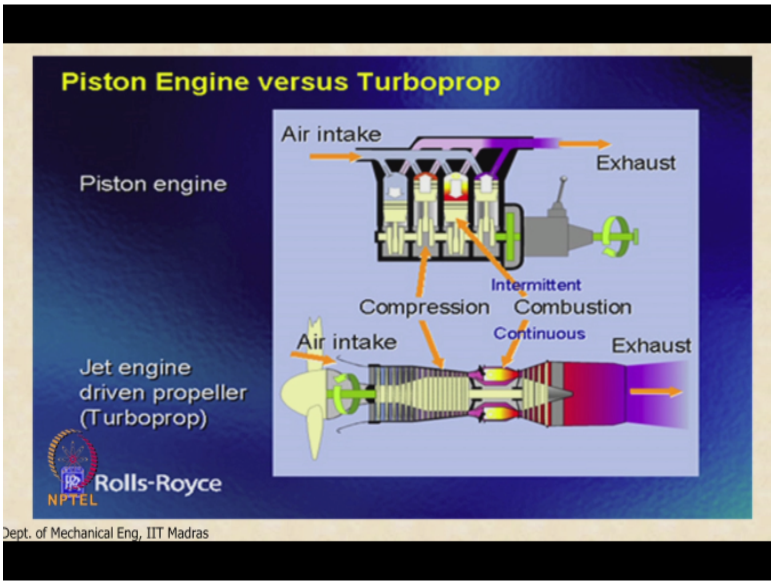
They have not been successful but they are really making a big push to developing this into a commercial technology. Much of the industry is going towards high bypass turbo fan and ultra high bypass turbo fan engines, whereas GE is trying to see whether the un-ducted fan is much more viable technology. We will look at these types of emerging technologies after we complete our discussion on the basic operation of the engine okay. We will look at emerging frontier in aircraft propulsion technologies.

(Refer Slide Time: 24:29)



So, now we will take a look at the operation of a basic gas turbine engine okay.

(Refer Slide Time: 24:38)



So here we are showing comparison between a piston engine, multi cylinder piston engine and a gas turbine engine here. So the gas turbine engine, remember both the engines have to do pretty much the same thing. From the thermo dynamic perspective, both the engines try to do the same thing. You have to increase the enthalpy of a gas, so you increase the pressure and you increase the temperature.

You increase the pressure by compressing the air, and you increase the temperature by injecting a fuel and burning the fuel in the air stream. Both do the same operation, but in a different manner. So you can see that in the piston engine, the air is taken in and then compressed by reciprocator motion of the piston and then you inject the fuel, then you ignite the fuel and it goes through.

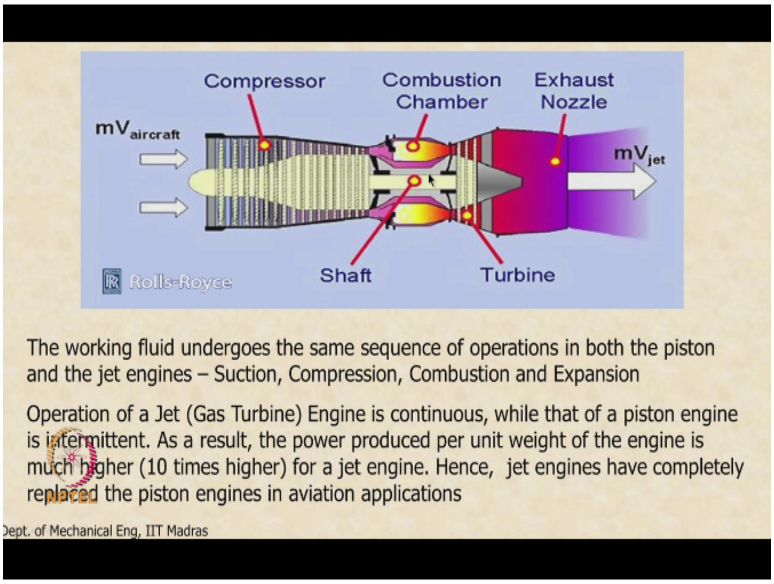
Because the engine or the cylinder can do only one thermo dynamic operation at a time. So, each cylinder can either do suction or compression or combustion or exhaust. The power produced by the IC engine is intermitted. Although the thermodynamic processes are the same, the power produced is intermitted and we deal with the, we tried to overcome the intermittency of this power production by doing what, by actually adding more cylinders.

You add more cylinders so what happens is at any given time, you hope that one of the cylinder will be in suction, one will be in compression, one will be in combustion another one will be in exhaust. So that you get power continuously. That is the strategy that is normally used. But one downside to this strategy is that as you keep adding more cylinders, you are also increasing the weight and remember thrust produced per unit weight is the most crucial metric for an aircraft engine application.

In contrast, the gas turbine engine goes through the fluid in a gas turbine engine goes through the same processes. There is an intake here, there is a compressor, combustion chamber, turbine and then exhaust okay. But here, as you can see, at any given instant of time, the fluid in different parts of the engine are continuously under going all the 4 processors. So this is continuous as oppose to this being intermitted right.

For example, if it is a 4 stroke engine, you get power only once every 4 strokes or once every 2 revolutions of the shaft. Whereas here, you get power during every revolution of the shaft, not once every 2, but every revolution of the shaft. So the power production is continuous here as oppose to intermittent being here.

(Refer Slide Time: 27:11)



Now, interestingly now because this can generate power continuously, it turns out that in total contrast to what that committee had said, the power to weight ratio of a gas turbine engine is about 10 times higher than a piston engine. So, what they thought was a distinct handicapped. Actually it was proven wrong and it is exactly this reason why gas turbine engines have replaced piston engines or any other form of engine completely in aircraft application.

Because the continuous operation gives them a superior advantage of power produced per unit weight of the engine. Because this being a very important metric, later on when we discuss new frontiers and new technologies, we will see the industry is still trying to reduce this. The industry is (()) (28:00) trying to make the engine lighter for the same power, how do you make the engine lighter? They are looking at many, many different technologies.

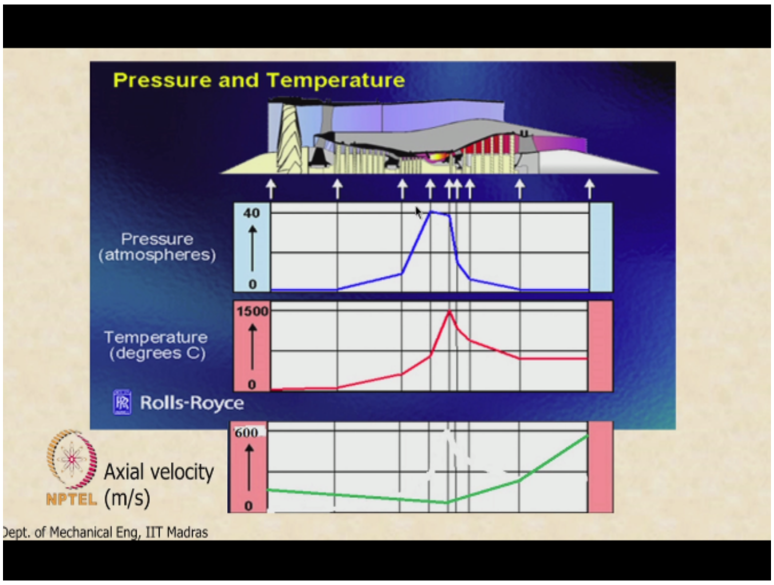
Not just when I say making the engine lighter, does not mean here to fabricate each component, you keep all the components and make them lighter, that is only one way. Reducing the components will also make the engine lighter right. So when I say lighter, that means it is not just making each component lighter, let us say reduce the number of fan blades or reduce the number of compressor blades.

That will also make the engine lighter right. So, we will look at what the industry is doing to make this even better. So today's aircraft engines are actually even they will have a better margin than the 10 that this given here. And the push is continuously to reducing the weight of the engines further.

So the basic parts of the gas turbine engine is as you can see or there is usually an intake which for a engine operating in subsonic mach numbers is not very important and then we have a compressor, then we have a combustion chamber, a turbine and a nozzle okay. So, as you can see the gas turbine engine part is just this part, up to the nozzle. So in this case, the gas turbine engine provides the nozzle with the stream of high enthalpy gas that is required by the nozzle to produce thrust.

So notice that the engine can be divided into 2 parts, the nozzle is the thrust generating part, which is where the enthalpy is converted to momentum. The rest of the engine provides the high enthalpy gas that is required for thrust production, which means if I want to use a propeller as the means of producing thrust, I can remove the nozzle, connect the propeller shaft to this and generate thrust that way okay. So the basic engine can be used either ways.

(Refer Slide Time: 29:47)



Now, let us look at we said that the fluid has to undergo 2 major processes right, increase in enthalpy is accomplished by increasing in the pressure and increase in the temperature. So what kind of pressures and temperatures are we talking about here? So, if you look at, so, this is the variation of pressure along the length of the engine for a turbo fan engine, and you can see that the pressure ratio is about 40 for a modern gas turbine engine, commercial engine, pressure ratios are about 40 or so okay.

So, we can see the pressure increasing here, reaching the maximum value at the end of the compressor right. So, you can see that the pressure increases at different rates in different parts of the compressor, this is the fan, we will look at the fan later on. Reaches a maximum value and then in the combustion chamber, you can see that the pressure more or less remains constant right and then the turbine is required to run the compressor.

The compressor needs power, if you want to compress the gas. So the turbine produces the power that is required to run the compressor. So, the energy, the enthalpy of the air, so here we can see there is increase in pressure, increase in temperature. So the fluid has maximum enthalpy when it comes out of the combustor. Part of that enthalpy is extracted in the turbine and converted to work to run the compressor.

The remaining enthalpy is then converted in the nozzle to produce kinetic energy okay. And you see variation of temperature here as you can see here the peak temperature at the end of the combustor is about 1500 degree Celsius. That is about as we will show later 400 degree

Celsius more than the melting point or the turbine blade metal okay. But still the turbine blade does not melt okay. So, that is the kind of thing that we are going to look at.

What kind of technologies are being used today? So the higher the temperature, the more efficient the engine, propulsion perspective. But there are other downsides to increase in the temperature especially from an emission perspective. So we need to deal with that separately. So you can see reduction in temperature as the enthalpy is converted to work in the turbine and then again temperature decreases in this scale.

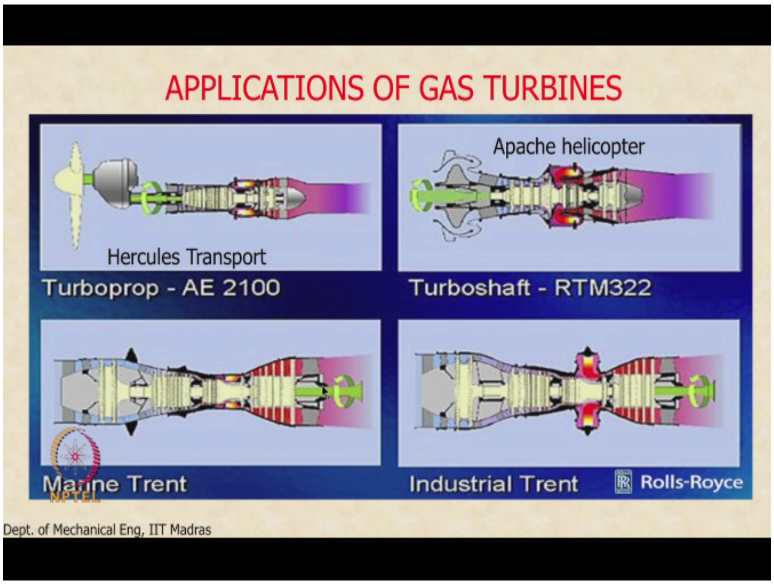
It is very difficult to see the variation in the nozzle, but if you look at the axial velocity scale, you can see that the axial velocity more or less remains constant up to the end of the combustor, then it begins to increase in the turbine as it undergoes expansion, then in the nozzle we can see that the velocity increases to nearly 500 to 600 meter per second okay. But remember the temperature of the air here is higher, so even 500 meter per second will still be only subsonic not supersonic.

Speed of sound is much higher bit here because the temperature is also higher okay. So this gives an idea of the kind of things that we are talking about, in the kind of values, numbers that we are talking about. So what are the pressures and temperatures and velocities for which we should design this equipment. One thing that is not visible or clear from this is, this axial velocity as I said earlier in my initial lecture, axial velocity is not the only velocity that is present in this engines.

Because the compressors and turbines rotate, there is a rotational component of velocity, which in most of these case can be comparable to or in this cases more than the axial velocity okay. So when we talk about designing a component we are talking about the pressure that it is going to be operating at, temperature that it is going to be operating at and velocity with which it is going to spin.

Those are the 3 most important things from the perspective of a design engineer or a mechanical engineer who is trying to design these components, the blades and other equipment okay.

(Refer Slide Time: 33:35)



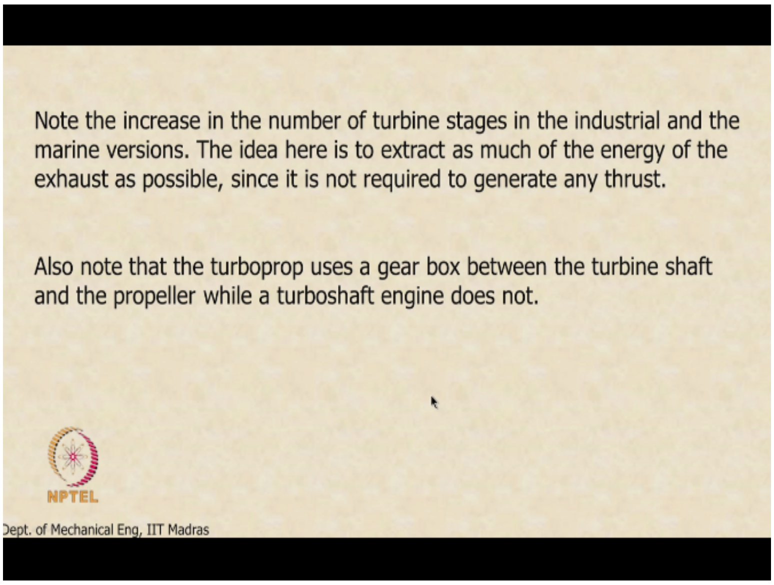
In addition to being used for aviation application gas turbines are also widely used in other applications. Of course one of these is as we saw the turboprop engine which uses the gear box in between these 2 to drive the propeller that we can see from here. The engine is directly connected to the propeller from the engine is directly connected to the gear box, then the propeller is run from there.

Helicopter also uses gas turbine engine but it uses something called a turbo shaft technology, which is a slightly different technology from the gear box that is used, there is no gear box here okay. Now gas turbines are also used in marine applications. Many of the big vessels use gas turbine engines rather than diesel engines to drive them. Some other lesser or lighter vessels use diesel engines to drive the propeller shaft but the bigger ones and the modern ones use a gas turbine engine to drive the propeller shaft okay.

These can also be used for LAN based power generation application. You can also use a gas turbine engine for generating power. So this can be coupled to a generator to generate power. The advantage of a gas turbine power plant is that, practically any kind of oil can be burnt in the combustor. You can use furnace oil, heavy oil any of those oils can be burnt here for generation of power. So this is a viable application for LAN based power generation also.

So it is used not only for aircraft like here turboprop, it is used in helicopters, it is used in ships, marine applications and also for LAN based power generation applications.

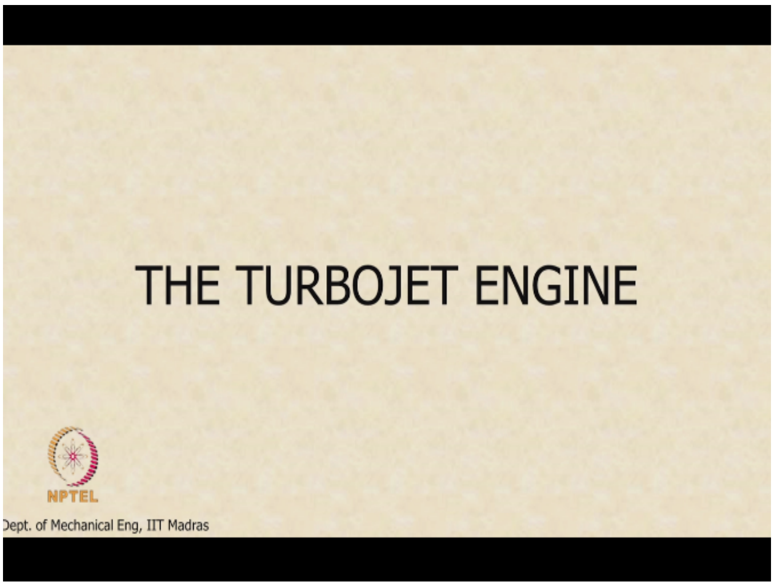
(Refer Slide Time: 35:16)



Now, one of the things that you should probably note in this slide is as you go from one application to another, you can see increased number of turbine stages in this thing here when compared to these 2 for example. The increased number of turbines stages here shows that we try to extract as much of the enthalpy as possible from the fluid because the fluid does not have to go to a nozzle to produce thrust.

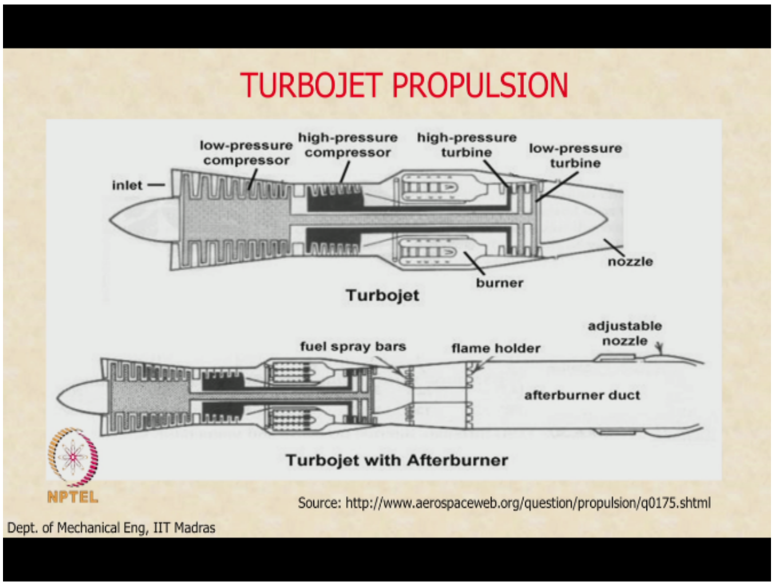
When the fluid has to go to a nozzle to produce thrust, that means we cannot extract all the enthalpy. We must leave some enthalpy behind which can be converted to kinetic energy. Whereas in these kinds of applications, there is no need to do that. So I have increase the number of turbine stages to extract as much enthalpy as possible before sending it out okay. So, that is something that you see from these 2 in the last 2 applications okay.

(Refer Slide Time: 36:08)



Alright now let us turn our attention to aircraft engine applications. And the first one that we will look at is the simplest engine.

(Refer Slide Time: 36:17)



Which is the turbo jet engine. So schematic of the turbo jet engine is shown here. So you can see a very small inlet. As I said for subsonic flight mach numbers, the inlet plays no role. Its only when you want sustained cruise at supersonic mach numbers that the intake becomes a crucial component right.

So we have a small intake, low pressure compressor, high pressure compressor and then we also have combustion chamber as you can see here, high pressure turbine and a low pressure turbine and then the fluid goes into a nozzle okay. So this is the simplest form of the turbojet engine. Now in the afterburning version of the turbojet engine, what we do is, we take this part of the engine, the nozzle part and we make the nozzle part longer and provide an after burner duct.

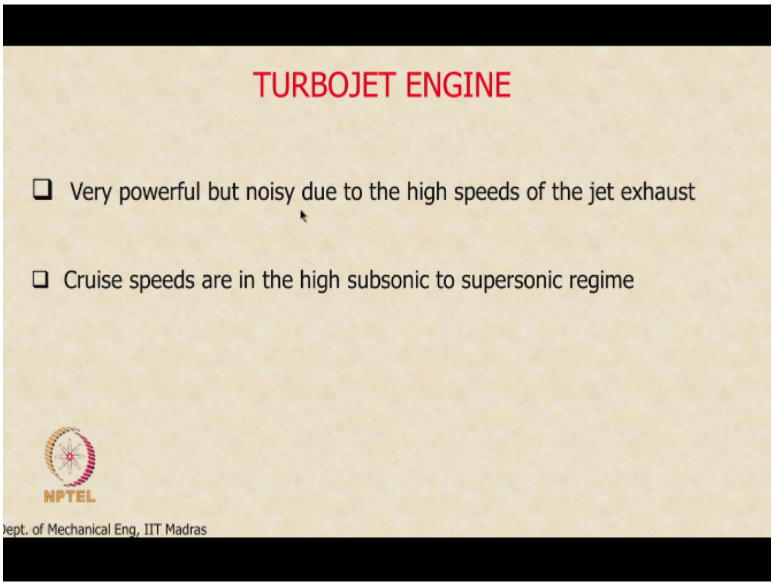
So you can see an after burner duct here, constant area duct and the nozzle also has to be changed because as we saw earlier, when you use an afterburner, the stagnation pressure decreases and the stagnation temperature increases. When the stagnation temperature increases, we need to increase the throat area of this nozzle. So you need a variable area nozzle when you use an afterburner.

So this has to be changed and you can also see the flame holder and the fuel spray bar. So the air at the end of this turbine, low pressure turbine, the air comes out and then we inject more fuel in to this air, normally in a gas turbine engine, there will still be plenty of oxygen left in the exhaust gases. So we spray fuel into the air because the air is moving with at speeds of may be 200, 300 meter per second.

It takes a while for the fuel to mix with the air and combustion starts you know at some distance downstream, which is why we have these flame holders. To facilitate combustion and combustion starts here and the fuel starts burning and produces increases the stagnation temperature there by increasing the thrust. But this can be utilized only for short durations of time. To punch through the sound barrier to attain a supersonic flight speeds for short durations of time.

Because this can be extremely inefficient from a fuel consumption stand point of view. But for military aircrafts, especially for bursts of acceleration, this is an extremely good technology to use okay. For taking off from an aircraft carrier and for sudden bursts of acceleration during combat maneuvers and so on. This is a very good technology to use. But for sustained cruise, we need to employ a different technology okay.

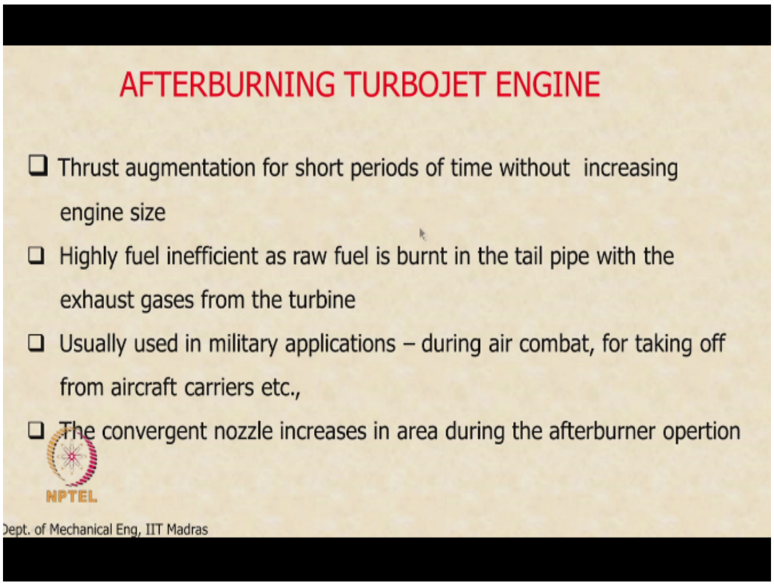
(Refer Slide Time: 38:55)



So the turbojet as we said produces thrust by causing a large velocity change to the fluid. So because the fluid comes out at a high speed and mixes with the ambient air which is pretty much (()) (39:10). It creates a lot of noise, aerodynamic noise. The propeller creates a lot of mechanical noise. Whereas the turbo jet creates a lot of aerodynamic noise. So when a turbojet engine takes off at certain points, if you are sufficiently close, the noise levels can be as high as 140 to 150 db.

So the aerodynamic noise can be very, very high okay. So propeller produces mechanical noise, whereas this produces aerodynamic noise. But we can cruise at high subsonic and with an afterburner even reach supersonic speeds okay. So these are some of the down slides to the turbojet engine.

(Refer Slide Time: 39:52)

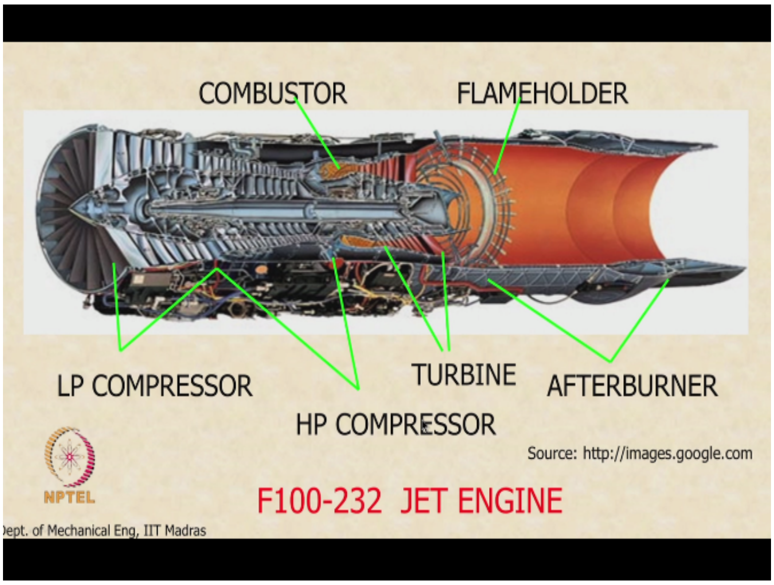


So the after burner as I said can give thrust augmentation for short periods of time without increasing the engine size too much right. If you want the same acceleration, if you want to fit another engine, you can do that. But that adds a tremendous amount of weight right. So without increasing the engine size too much, we can actually have thrust augmentation for short periods of time okay.

Its highly fuel inefficient as the afterburner is not at all assign to be a combustor. It is just a constant area duct, where you dump a fuel and you burn it. So it not really a combustor, it is just a duct. Which is not a very efficient way of doing combustion. As I said, it is usually used in military application during combat for taking off from aircraft carriers which have very short runways and so on.

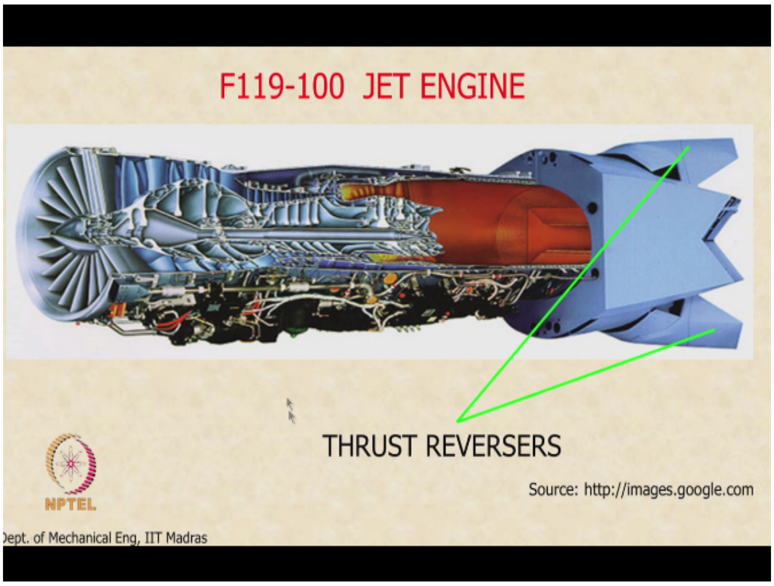
Even with the catapults that you use in an aircraft carrier, the afterburner is required to actually get airborne when thrown from an aircraft carrier. The runway length is just too short in an aircraft carrier. So the after full afterburner operation is required for taking off from an aircraft carrier and as we saw in our gas dynamics lectures the conversion nozzle area has to be increased for during the afterburner operation okay. Let us just take a look at couple of an after burner engines before we complete this lecture.

(Refer Slide Time: 41:07)



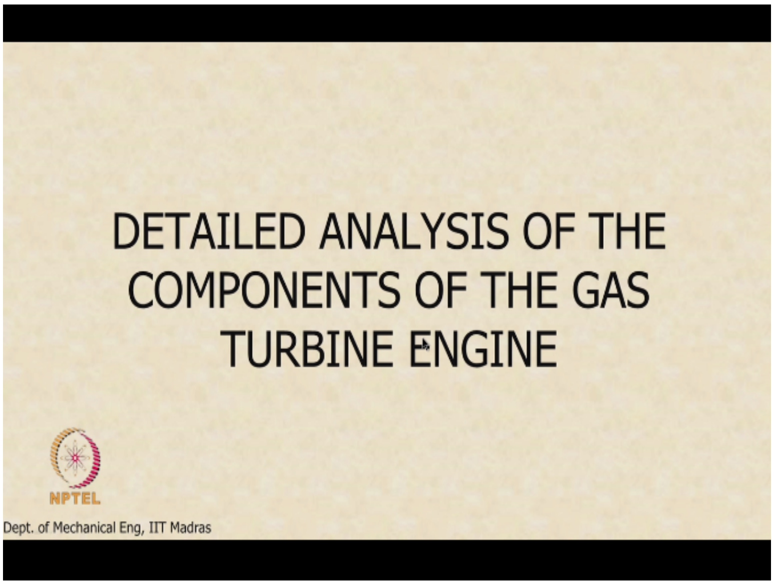
So this is F100 afterburner engine right. So you see the normal engine up to here and then you see the flame holder, the afterburner duct and you see the nozzle, which is actually a variable area nozzle. I will show close up views of this nozzle later on okay.

(Refer Slide Time: 41:28)



One more, this is another F119 jet engine, similar kind of technology. You see the compressor blades, you see the turbine blades over here and you see the afterburner duct and in this case you also see the thrust reversers. We will take a close up look on the thrust reversers later on when we discuss the propulsion nozzles okay.

(Refer Slide Time: 41:51)



So we will stop there and look at detailed analysis of the components of the gas turbine engine in the next class.