Gas Dynamics and Propulsion
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Lecture - 28
Components of the Gas Turbine Engine

In the previous class, we looked at velocity triangles for an axial flow compressor.

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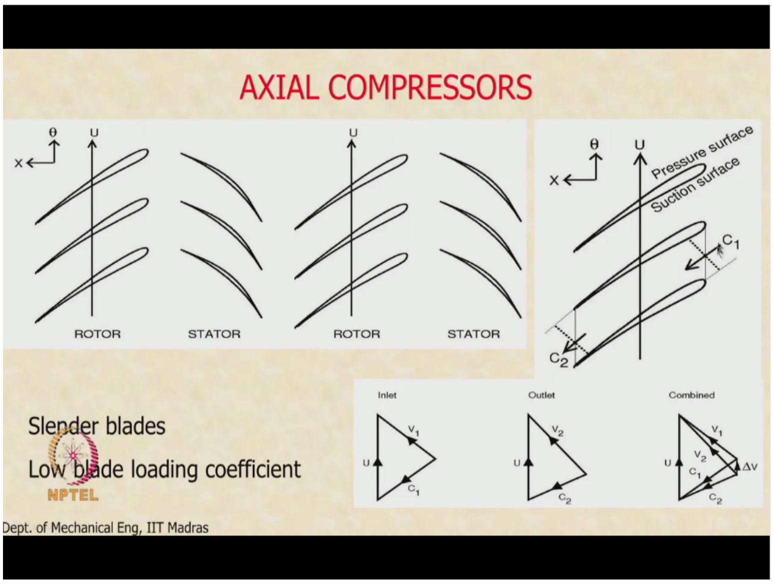

And we saw that under design conditions, the pressure rise across the compressor stage. Each stage is about 1.15 and we also saw that the compression process is primarily due to diffusion of the relative velocity. So the relative velocity magnitude decreases from C1 to C2, there is a reduction and there is also increase in the cross-sectional area, which causes the pressure to increase.

And we also saw that the relative velocity vector, under design conditions this relative velocity vector enters is tangential to the surface of blade. So the flow enters tangentially to the surface of the blade and also departs tangentially at exit under design operating condition, but in the case of a complex piece of equipment like the aircraft engine, it is not always possible to operate under design conditions.

There are going to be departures from design conditions and the design must be robust enough to handle such departures from design operating condition.

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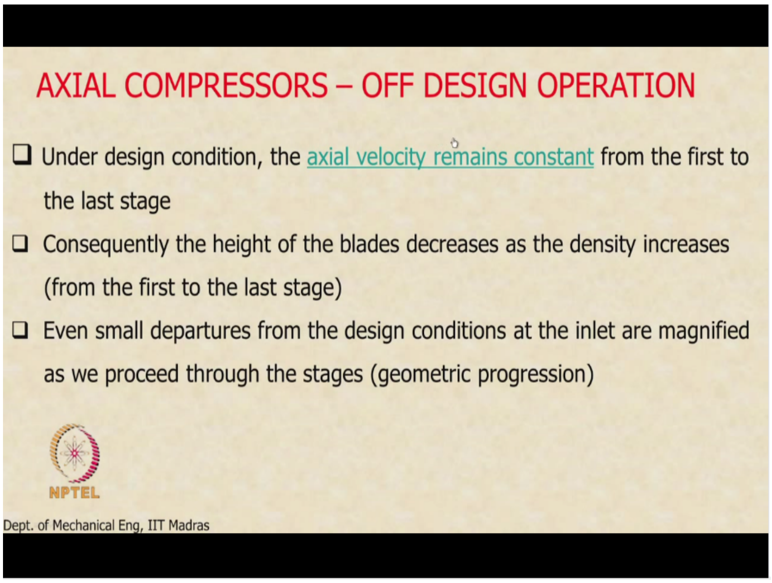

So what we wish to see next is what happens when these compressors are operated under off design conditions? What are the issues and how do we address these things or design them so that this kind of things can be handled right? Now one of the probably widely practiced aspect in design of this compressor blades is that the axial velocity more or less remains constant from the first to the last stage.

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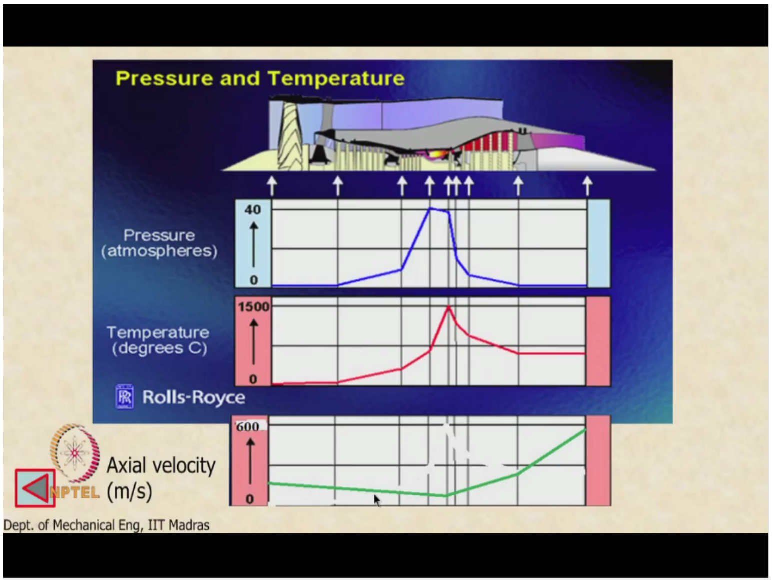

That is a widely used industry practice and if you remember we saw this earlier when we looked at the slide we can see that, so here are the compressor blades. The fan, the intermediate pressure compressor and the high pressure compressor and you see that the axial velocity here more or less remains constant definitely up to entry into the combustor. So it is always good to design these for constant axial velocity.

Because several things become simplified from one stage to another. So there is not too much of a departure from one stage to another and it is easy to design it for constant axial velocity. So that is something that is always done and you also notice that the rise in pressure across each one of the stages as you can see is from beginning to end, you can see that it is a geometric progression and not a linear variation from here to here.

This was something that we discussed yesterday. So the rise in pressure is in geometric progression and axial velocity remains constant in most of the stages under design operating conditions. So when you design the blade that way, the height of blade decreases because as you know m dot is rho times A times axial velocity that is the mass flow rate passing through each section and if the velocity is to remain constant, the density increases from inlet to outlet.

So when the density increases from inlet to outlet, velocity remains constant so you need to bring the area down right. So the height of the blade decreases as the density increases. So previously, we had the blade height at the beginning if we can see here the blade height at the beginning you can see is quite large. So this is the blade height and you can see the blade height decreasing as you go from the first to the last stage here.

Then when you go to the high pressure stage, we can see the area reducing even further right. So the height of the blades decreases when you go from the first to the last stage. Unfortunately, because the pressure rise across each stages in geometric progression, any small departure from equilibrium from design condition in the first stage will also be magnified in a geometric progression from the inlet to the outlet.

So there is a small departure in the flow rate or velocity in the first stage, it gets magnified in a geometric progression from inlet to outlet and that is one of the major problem in off design operation of this compressors. So we have to design for that. How do we handle such a situation? So off design operation can arise from many different situations. For example, let us say you try to start the engine.

So when you are starting the engine, the entire engine is filled with air atmospheric pressure right so it is all at the same density. So the density remains more or less constant throughout the entire compressor, but if you remember when we designed the last stages, the last stages were designed assuming the velocity to be constant and density to be at a high value and the density increases.

But now the entire compressor including the last stage is filled with air at normal density. So that means the last stage is now operating at a condition, which is far away from its design operating condition. So you experience off design operating condition for example when you try to start the engine because the density is far below the design value. If you tried it over the same mass flow rate, you can see that the area is very small.

Because I design for a high density and a constant velocity, so consequently the height of the blade as we saw earlier is very small, but now if I try to operate with the lesser value of density and height is also small, then the velocity will no longer remain constant and in the later stages the velocity will easily achieve the sonic value because it almost is like a throat you know because the height is so small.

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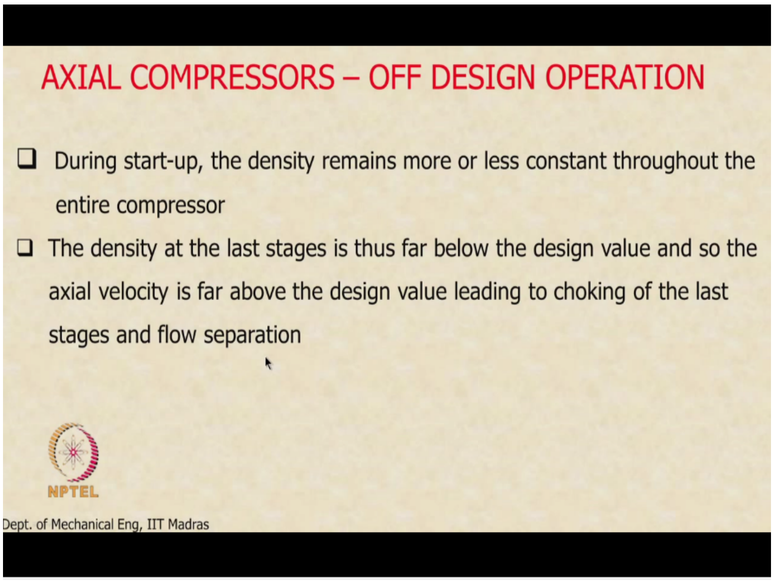

So when the later stage is choked then we have problem. As you know, once the latter stage is choked, we cannot push anymore mass flow rate into the system because they are already choked right. We cannot have any more mass flow rate pushed into it, so we run into a problem. So here what is happening is the actual axial component of velocity remember mass flow rate is m dot s rho times A times Vx where Vx is the axial velocity.

So because the density in this case is far below the normal value, the area remains constant that is the geometric feature, now Vx has increased. So Vx now is well above the design value so that is one kind of departure from design operating condition where the Vx has become much higher than the design value. You can also have situations where the Vx is much below the design value.

For example, let us say we tried to adjust the mass flow rate through the engine, there is some change in the speed right. So a change in the speed normally it is picked up very easily in the initial stages, but the entire compressor has about 27, 28 stages so it takes a while for this change to go through the entire compressor all the stages. So what will happen is you have a situation where the first few stages are operating have responded.

And operate at a velocity which is less than the design value whereas the later stages are operating with velocities, which are more than the design value. So you can get off design operating condition either during start up or during change in an operating condition. So you are operating at a certain velocity and then let say you spin down the compressor or spin up the compressor and then that causes a change in the operating condition.

So these are 2 situations where you encounter off design operating condition. So basically what we are looking at is if the axial component of velocity Vx, if it is more than the design value what is the flow look like and if it is less than the design value what is the flow look like and how do we handle these 2 situations right? So we are going to go and take a look at the velocity triangles and see what happens when the value is different from the design value.

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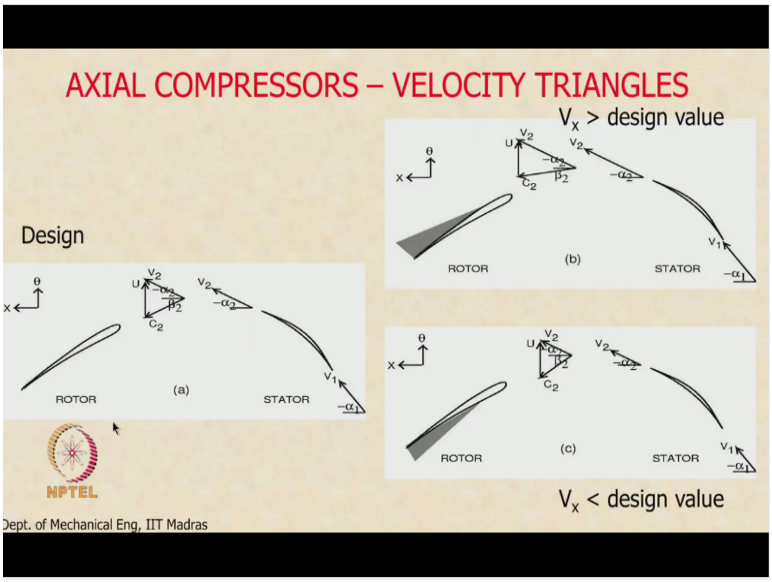

So on the left here you see the design velocity triangle, so you see this stator blade, this is called as stage, a stator+rotor combination is called a stage. So you see the stator so all the stator does is deflect the velocity. So the fluid comes in with an absolute velocity V1 and with the angle of inclination alpha 1 like this and the stator deflects the flow keeping the magnitude the same.

So V2=V1 in this case and remember V is the absolute velocity right. So V2=V1 so all that has happened is the fluid has been deflected by a certain amount that is all the stator does. It makes sure that this angle alpha 2 is such that when you take the vector sum of C+U, the angle alpha 2 should be such that C is tangential to the blade profile. So the stator blades are designed so that the angle alpha 2 will ensure a smooth gliding on and gliding off from the rotor right.

So here you see that the velocity vector C2 is tangential to the blade surface that is all this does. This is under design operating condition because the flow is incident tangentially. There is no flow separation and the compressor operates at the design operating condition. This is what we saw yesterday. Now remember this is the axial component of velocity right. The x direction is like this.

So the projection of the absolute velocity or even the relative velocity onto the x direction, so this is the x component of the velocity. This is the design value. So we are going to look at 2 situations where the x component is 1 more than the design value and 2 less than the design value. So here we are looking at a situation where the x component of velocity is more than the design value.

So you can see that V1 here is more than what we had before. So the velocity here is higher than design velocity. So the stator does not do anything except redirect the flow. So it has again taken this at V1 whatever the magnitude be and it has deflected it to alpha 2. So V1 and alpha 2, V2 and alpha 2 where V2=V1. Now if you draw the velocity triangle right, this is V2 at the same value of alpha 2 as earlier correct.

This also remains the same. Blade speed remains the same. Now notice that the x component is higher now. So if you look at this, the x component is higher right than the design value. So now if you construct the velocity triangle, this is the same value but it is longer now. As a result, this relative velocity vector swings over to the upper side, swings over to the top as we can see from here.

Because this has become longer, V2 has become longer or Vx2 has become longer, U remains the same. So this C2 swings this way. So that means the flow is incident like this upon the blade. It is not incident tangentially, which means that you can see that the flow will go this way and there is going to be a region of separated flow on the suction side of the blade this I think is what we call as suction set correct we just check that quickly.

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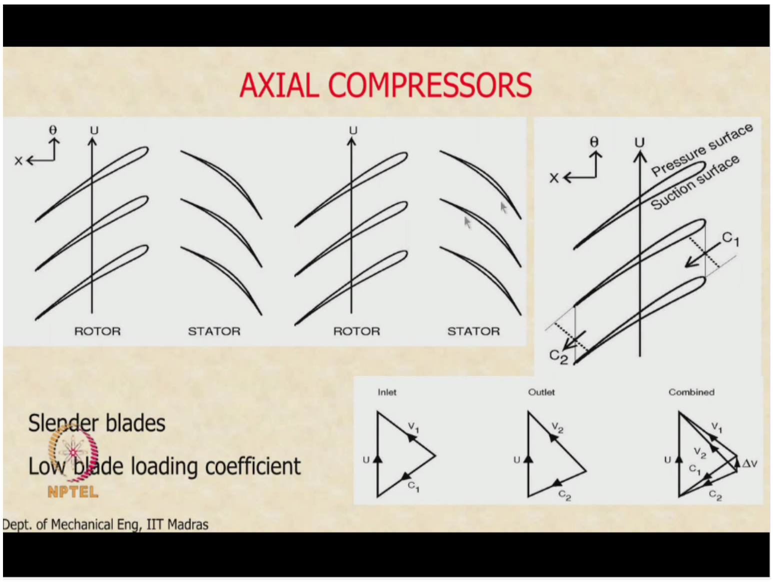

That is the pressure surface, so the top side is the pressure surface. This is the suction surface so this causes separation of flow on the surface of the airfoil because of the incidence because of the relative velocity after being this way it causes separation on this side of the airfoil. This is for a case when Vx is more than the design value. Now if you look at a case where Vx is < the design value you see the same thing right.

V1 is now less then what we had in the design operating condition right. We can see that this is less than this, angle remains the same, this does the same thing. It takes whatever comes in and deflects it. Now this is the same, this has decreased Vx2 has decreased now. So this has become shorter, which means that this relative velocity vector now swings the other way. Previously, it was swinging this way, now it swings this way.

So which means now you are going to get a separation on the suction side of the airfoil. So off design operating condition whether it is more than the design value or less than the design value causes flow separation. Once the flow separates, the compressor will begin to stall. The later stages are choking because the height is very small and the density is much less than the design value.

So the later stages are choking and the front stages are stalling. Once it begins to stall like this, the operation will become very unsteady. The pressure wise will show fluctuations, it will do this. So this is the problem this is called stalling of the compressor blades. So there are 2 things that are happening simultaneously, 1 is stalling of the compressor blade, another 1 is choking of the latter stages.

Both these things happen when you are operating an off design operating point. So we need to have ways by which we handle this kind of a situation. This cannot be avoided in a real practical application right. We have to start the engine so when you start the engine that is an off design operating condition right that has to happen and during flight also there will be continuous changes in the engine requirement.

So we need to be able to handle these types of off design conditions gracefully and that is what we are going to look at. There are 2 strategies, which are actually used in engine technology today to handle these types of operating condition. So you must understand these velocity triangles very clearly. So you see that in 1 case, the relative velocity vector swings this way.

In another case, it swings this way. So the reduction in axial velocity is something we have to live with that is going to happen. So even if the axial velocity is reduced, how do we make sure that this velocity vector still is tangential to the blade surface that is what we need to look at. So we do not try to correct the reduction in axial velocity, we try to accommodate the reduction in axial velocity in a graceful manner right.

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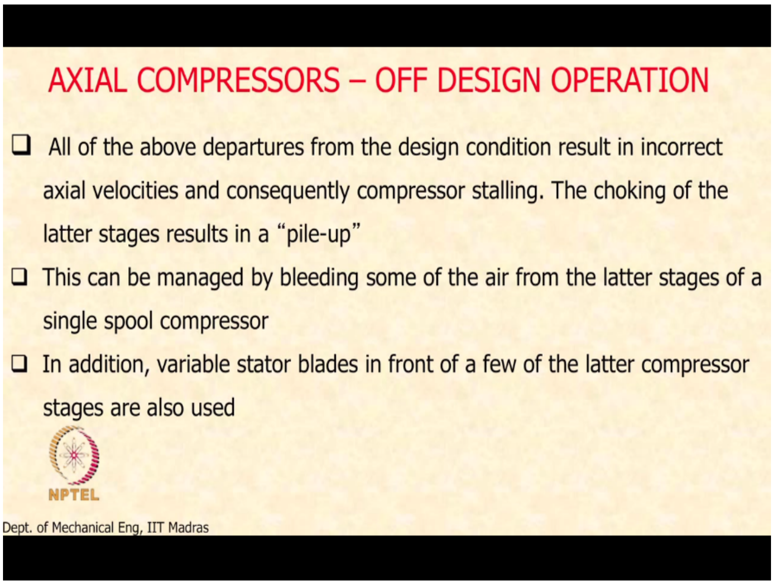

That is what we are going to look at next. So to sum up what we just said so all these above departures whether it is above the design point or below the design point causes incorrect axial velocity and compressor stalling. We saw that the blades are stalling. Choking of the latter stages results in pile-up meaning it is already choked so it cannot really pass more mass so it causes the flow to build up in the later stages of the compressor.

Now we have already seen situations like this. One way to handle this which is what is normally done during startup of an engine is to bleed some of the air from the later stages okay. So you have an opening, its mass is piling up so you actually bleed some of the air so that the later stages can unchoke and allow the more mass to go through so that is one thing that is commonly done that is the strategy which is utilized.

Now if this departure from design condition happens during operation, during startup we can bleed the air that is not a problem, but that is not possible when you are actually flying the aircraft. It will be a very difficult thing to do so what is done is, there are 2 strategies which you can use, 1 is to use something called variable stator blade.

So here what we are trying to look at is the stator blade in all these cases whether it is design condition this or this, it is only deflecting the flow, but what I am asking is because this velocity vector is swinging this way and that way, is it possible to swing the stator blade appropriately so that the relative velocity vector is always tangential right, that is 1 possible strategy.

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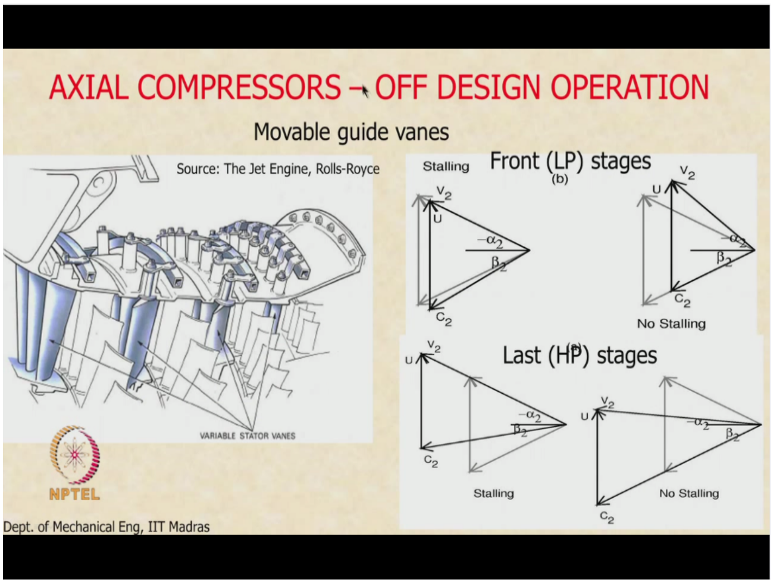

So that is what we mean by variable stator blades okay or movable guide vanes as it is called okay. It is also called movable guide vanes. So here let us look at this and then we see how it is actually implemented in an engine. So here as we can see we are looking at this type of a situation right. So you see that this is the design velocity triangle, the 1 in grey is the design velocity triangle okay.

Now as a result of reduction in axial velocity, so this is the reduction in axial velocity, you can see that the relative velocity vector swings over this way. So we have superimposed the 2 velocity triangles. So what we are going to do is something very simple, when the axial velocity reduces you swing the entire triangle up so that it counteracts the swinging the tendency to swing this way that is what this is doing.

This is the design velocity triangle in grey, so now as you can see I have changed this angle alpha 2 now. The axial velocity is still less than the design value, but I have increased this angle alpha 2 now using my guide vane. So that this velocity vector nicely aligns itself with the design velocity vector right. So this will not stall, it was stalling here because this velocity vector is not aligned to the design relative velocity vector.

Now by increasing this angle this way I have actually forced this off design velocity vector also to line up with the design velocity vector by moving the guide vanes appropriately. Other situation so this is when the axial velocity is less than the design value, now when the axial velocity is more than the design value that is what is happening in the last stages right they are choking.

Because the axial velocity is more than the design value so again you see the design velocity triangle in grey and when the axial velocity is more you see the relative velocity vector swinging this way because in all these cases the absolute velocity vector is always aligned with the relative velocity in the absolute velocity vector in the design condition.

Notice that here the absolute velocity vector in dark black is aligned with the design absolute velocity vector so we have the design velocity triangle and the new velocity triangle. The absolute velocity vector is aligned in both these cases and that is what causes the stalling because the absolute velocity vector is aligned, the relative velocity vector swings due to the change in the axial velocity.

The idea here is to move the absolute velocity vector, but adjust the relative velocity vector so that there is no stalling that is what the movable guide vane does. Now it is in this case the absolute velocity vector is moved this way as you can see. So you move it this way so that this relative velocity vector will nicely line up with this and that is what you see happening here.

So by moving the guide vanes either this way or that way, we can even for off design operating condition we can ensure that there is no stalling and the compressor will operate perfectly. So here you actually see how it is implemented in a real engine. So you see these guide vanes here. So you can see the guide vanes and on the top you know you see these pillars, which is connected to the actuator.

And you can see that they are connected to the actuator this way. So by moving the actuator this way or that way, we can make the guide vane swing this way or that way right. So that is how you can see the connection here and the actuator. So this allows the guide vanes to be moved this way or that way and when you do that you get this relative velocity vectors lining up nicely with the design relative velocity vector.

So the idea is to line up the relative velocity vector under design and off design conditions not the absolute velocity vector. So a fixed guide vane can only line up the absolute velocity vector. So a movable guide vane can line up the relative velocity vector, which is what is desired in off design operating condition so you can see that there is no stalling. This is only 1 strategy that is possible in this case.

Remember all we are trying to do is if you look at these 2 velocity triangles, you see that the stalling happens because certain things are kept fixed. If you keep this angle fixed, then it stalls so we had just saw a strategy where we change this angle we can eliminate the stalling. What is the other way of addressing this? Making sure that this lines up with this. Think geometrically, the other way is to what happens if I reduce the blade speed here right?

Then also this will line up right and here if I increase the blade speed, I can increase the blade speed so that it lines up here.

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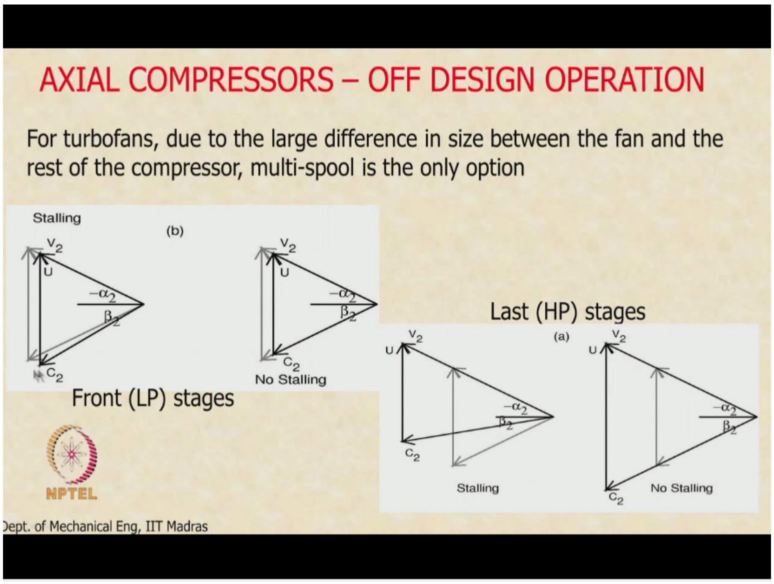

That is another strategy, which is also utilized in the industry so we can see here this stalls right because we have kept the blade speed the same, the angle the same, this one stalls. The velocity vector swings this way. What if I reduce the blade speed? Keep this angle the same, stator blades are fixed, I change the blade speed slightly now the velocity vector will line up nicely and in this case it stalls because I have kept U fixed and also alpha 2 fixed.

What if I keep alpha 2 fixed and change U? I spin up the compressor little bit, here I am spinning down the compressor little bit, here I spin up the compressor little bit so now also you can see that this happens. This is also a strategy, but remember when you want the front stage to be you know to be slowed down and the later stages to be speeded up that means you now need to have multiple shafts and engine manufacturers like Rolls-Royce use 3 shafts.

So they grouped sets of blades, you have 3 shafts, 1 is the low pressure compressor and fan, another 1 is the intermediate pressure compressor, another 1 is the high pressure compressor. So you have 3 shafts, all sliding within each other so that the individual spools or shafts can be controlled independent of each other okay. So that is 1 way of controlling stalling operation also.

So both these strategies are possible, their trick lies in adjusting the velocity triangles. In fact, the combination of this is also used. Engine manufacturer like GE typically use only 2 spools, but also use movable guide vanes okay. So the combination also works very effectively. So off design operation does happen in real life and the design must be robust enough to handle such departure from operating conditions gracefully.

It should not fall apart okay. You cannot design an engine that will operate only at one operating point and not at any other operating point. So it is very important to take these things into account. Now we go on to other things. We have looked at the aerodynamic aspects of compressors, thermodynamic aspects also and fluid dynamic aspects. Now we go on to look at operating conditions and material selection, choice of materials.

We will just kind of look at some of the requirements and what materials are used you know this is the course on propulsion and material so we will not go too much into this, but it is important for propulsion engineers to know this.

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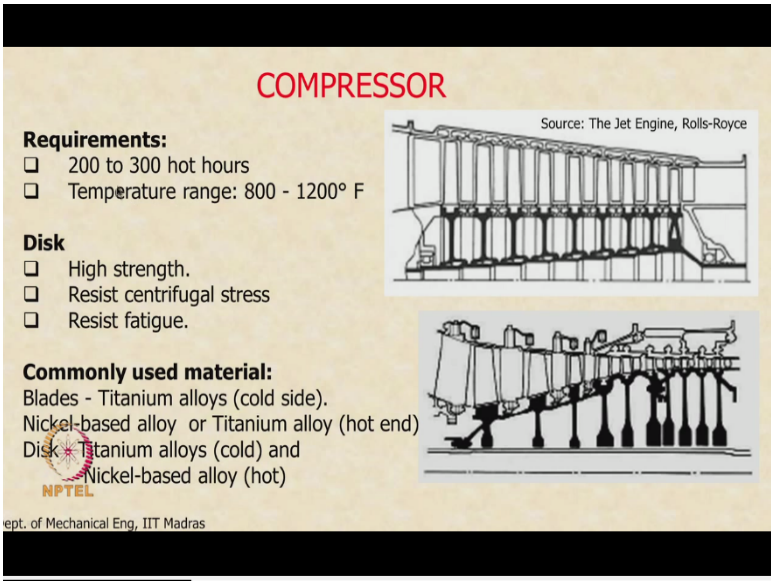

So general requirement is that you know it should work for 200 to 300 hot hours. This is classified differently, the number of hours usually determined based on duty cycle of the engine. A typical engine will go through for example takeoff, climb, cruise, descend, land, reverse thrust and shutdown. So that is the duty cycle so depending on how much time is spent in each one of this operations.

So the cruise is the lightest part of the entire operating cycle. That is when the load on the engine is the least. The other parts takeoff and landing, takeoff especially is very heavy or hard on the engine, landing is also very difficult on the engine. So number of hours spent in different modes are given different weightages and then you add them up and then you determine the hours and it has to go for service every so many hot hours of operation okay.

So depending upon the severity of the duty cycle. For example, an airliner which is flying let us say constantly from London Heathrow to Chennai. So the flight last for about 11 hours, out of the 11 hours, 10 hours is spent in cruise, only 1 hour is spent in the other aspects of the flight that is much better than aircraft which is constantly flying from Chennai to Bombay, Bombay to Delhi and so on right.

That spends almost the same amount of time in takeoff, landing, you know descend as cruising. So you can see how the duty cycle so for these engines they have to go overhaul and maintenance much more frequently than the other engines. So the severity of the duty cycle is calculated based on hours spent in each phase of this operation okay. So one advantage with the compressor is that the temperatures are relatively not very high.

If you remember the earlier slide showed that the temperature at the end of the compressor is probably about 700 degree Celsius or so no more than that okay. That is not actually high in aircraft engine operation okay. So the requirements and again we are now using a new term called disk. So far we are talking about the blade. In the case of compressors as you can see from here, the blades are not directly mounted on the shaft.

Here you see the shaft, these are 2 designs. Here you see the shaft. The blades are not directly mounted on the shaft because that will cause too much centrifugal stress and the blades will have to be very heavy to withstand such stresses. What is normally done is the blade is bolted on to these things in black. These things in black is called the disk. The disk is connected to the shaft and the blades are then attached to the disk okay.

You see 2 different types of designs here. You can see a design where you see the root of the blade also. It is almost like a tooth going into the gum. So there are 2 different ways in which the blade can be connected to the disk. You see 2 different connections here. So here you see something like this. So what happens is if you assume the disk is like a band, which is circumferentially arranged like this.

Let us say that the shaft rotates like this so disk is a band like this, so you make a circumferential groove and the blades are then slid into the circumferential groove and that is what is done here. So you can see the blade in the circumferential groove in this cut section view. The other way to do this if the disk is like this so you make axial grooves and then put the blades into the axial grooves that is the other way of fastening the blade on to the disk and that is what you are seeing in this design okay.

So you can attach the blades in both ways and you can see that this region between the top of the disk and the shaft this region is hollow. There is nothing here, you can see that this region is hollow. This is very important not only from a weight saving perspective, but also from some other perspective, which we will discuss next okay. So the disks have to be very strong and centrifugal stress is the most important load for this disks.

Fatigue comes because of the duty cycle you know you are constantly going from takeoff thrust setting, which is the maximum thrust to cruise thrust which is the minimum thrust. So you are constantly cycling between this. So it undergoes some fatigue also so that is very important. So for the blades normally titanium alloys are used on the cold side, probably fan low pressure compressor and maybe part of the intermediate pressure compressor.

And on the hot end normally nickel-based alloys are used because nickel gives you resistance to oxidation and high temperature capabilities. So the hot side blade made out of nickel and on the cold side they are usually made out of titanium. The disk again is made of titanium on the cold side and nickel-based on the hot side okay. The high temperature is not really a major issue for the compressor.

Because highest temperature is only about 700 to 800 degree Celsius or so compared to the peak temperature in the cycle, which is around 1500 degree Celsius, 800 is not very high okay. That is the general this thing, one of the probably the most challenging aspect of manufacturing such an engine is to ensure minimal clearance between the casing and the blade tip.

The clearance between the blade tip and the casing should be as small as possible as otherwise the air would flow over the blade and not through the blade passage as if it goes over the blade it is not going to be compressed right. So we want the air to flow through the blade passage and not over the blade, which means the gap must be very, very small and the challenge is how do we maintain this gap under all operating conditions?

And how do we maintain the gap to be at the desired value throughout? That is probably one of the most challenging aspects of manufacturing this engine and that is where the hollow regions in this compressor casing comes into use right.

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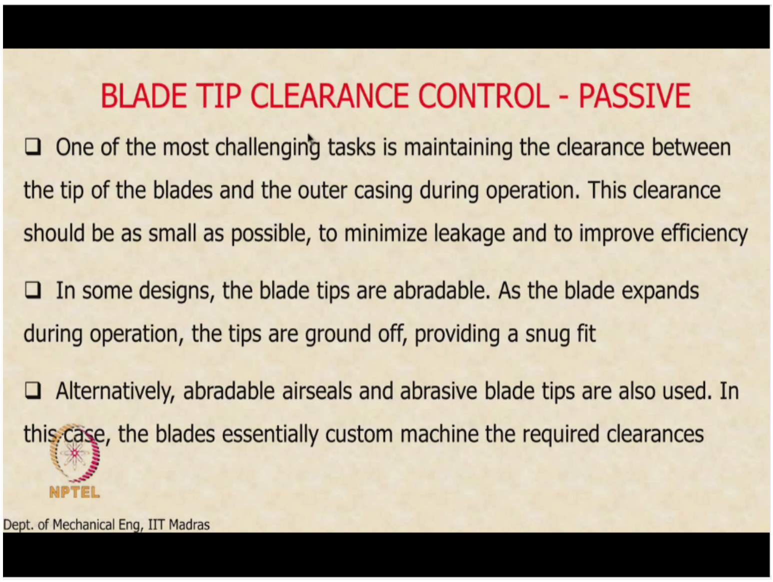

So how do we maintain the blade tip clearance control? Two strategies are possible, 1 is a passive strategy okay and as I said this is probably one of the most challenging tasks in the manufacturer and operation of a compressor okay. So the clearance should be as small as possible as we said to minimize leakage. So the air leaks around the top of the blade, it is not going to increase its pressure, it is of no use to us right.

So we need to make sure that the leakage is minimum so that the efficiency is as high as possible. What is normally done is in certain design, the blade tips are actually abradable and remember the cold end is at a temperature let say at sea level the cold end will be at a temperature of 300 kelvin let say 300 kelvin, hot end is going to be at a much higher temperature.

So that means that the thermal expansion of the blade is going to be different at different end so we need to take that into account so some of the blade tips are made abradable so that as the blade expands and tends to touch the case, it is shaved off either the blade is shaved off or the casing is shaved off. So that the engine will custom machine their own requirement. So the blade is actually like a machine tool.

So the custom makes the tolerances to their need so it provides a very snug fit so the tips are actually ground off and you get a very snug fit okay. Alternatively, you can also the air seals which are sitting in the compressor case can also be made of abradable material. So the 2 abrade against each other and machine themselves to the required tolerance.

This is the passive strategy, which is normally adopted when the engines are manufactured and are send to service so that the clearances are set up properly, but how do we adjust the clearances during operation right as when the operation takes place there is going to be continuous expansion and contraction of the blade metal. How do we control the tip clearance in such situation? So for that you need active control.

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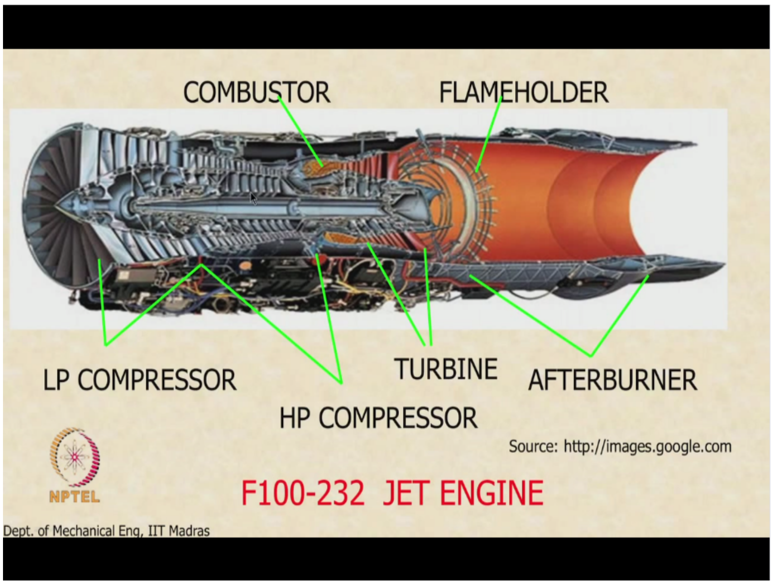

What is done in these cases is let us see whether I can so here we can see the cutaway view of the engine, you see the disks right, you can see the blades and you can see the disks here right, these are the disks, you can see the disks. You can also see that this area as I said earlier all these regions are hollow. So it takes cool air from the front of the engine and send that cool air in a controlled manner into these hollow regions.

So the cool air actually tends to shrink the disk so when the disk is trying to expand due to elevated temperature, you try to shrink the disk. So the blades are exposed to the higher temperatures and they are trying to expand.

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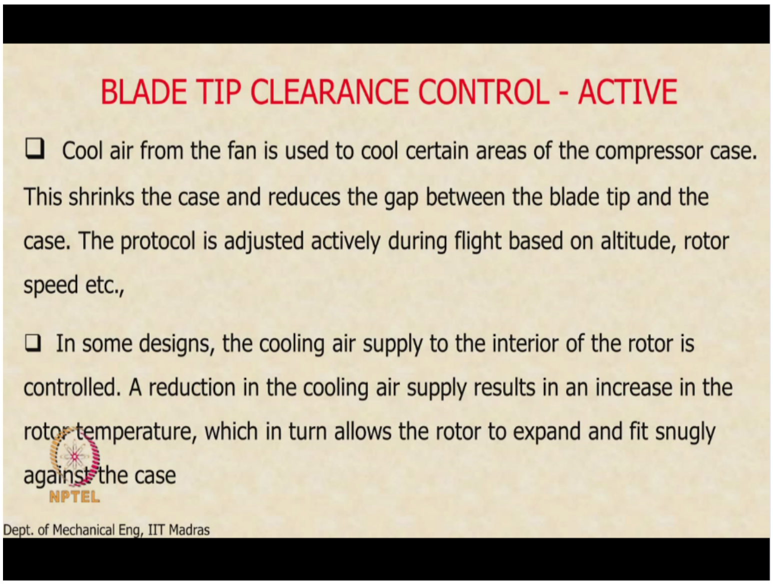

So you control the expansion and shrinking of the disk and the blade in a controlled manner by sending air into the compressor case or into the rotor, both are possible. You can send air into the compressor case, which is on the top or you can also send air into the rotor, which is also hollow. So by controlling the amount of air so this is done actively during flight based on many of the settings that you have, altitude, rotor speed, flight speed you know engine condition and so on.

So it is adjusted actively so the amount of air that is sent into these regions is controlled actively so that the tip clearance is always maintained at optimal value. So you reduce the cooling air supply right then that means that it will allow the rotor to expand. You increase the cooling air supply that means the expansion is going to be arrested or if it is even more it is actually going to begin to shrink, it is going to contract.

So you control this actively during flight depending upon the operating condition so that an optimal tip clearance is maintained under all possible operating conditions. This is an extremely difficult thing to do, but it is done very routinely as you can see. The efficiencies of these engines are extremely high mainly because of small features like this. These are operational difficulties.

These are things which we cannot foresee when we look at the thermodynamic fluid mechanical turbomachinery or gas dynamic aspects of the compressor right. These are operational issues, which come when you put things together, but there are solutions for this. These are the solutions that are adopted in the industry today. Any questions? **“Professor - student conversation starts.”** Where does that output goes miss this one central part?

The air actually normally this air which does not the air that is used for this kinds of cooling and also for the blade cooling is usually taken out, mixed to the exhaust and then sent out that way. It will not produce any thrust because it has lost its pressure in going through these passages so that will be exhausted separately. **“Professor - student conversation ends.”**

So the amount of air that we can use for these things should also be as small as possible because if you take too much of the air from the fan or the compressor and then use it for this remember this is air that will not produce thrust. You have to optimize this also but this is necessary. So we have seen so far we have looked at the inlet very briefly for this types of situations.

We have looked at the compressor, the challenges and the design of the blades. We are now moving onto the next component, which is the combustor. So you can see that the air from the compressor blade goes into the combustor like this. So you can see the air going in directly from the compressor blades into this. So the air from the compressor there is an intermediate element here which is a flange.

So the combustor is attached to the flange of the compressor case and the air directly goes into the combustor from here. So we are going to take a look at the combustor, which is the next component here.

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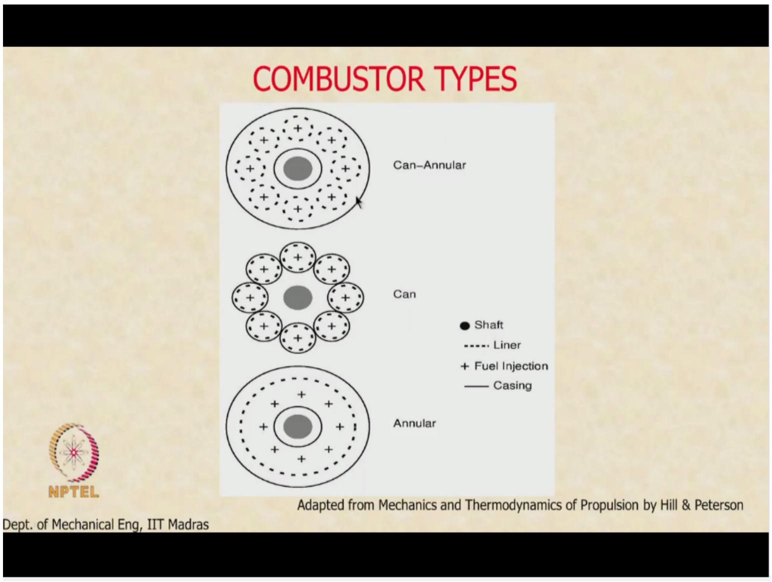

Now in aircraft engine, 3 types of combustor designs are possible okay. The common elements in all the 3 design is that you have for example here we are looking at the combustor (()) (36:44) so this is the shaft right. The one in the center the grey circle is the shaft, so I am looking at the combustor from this end or the other end, so this is an end view of the combustor.

So you see that there are 3 common functional elements in a combustor, 1 is the liner, which is shown in dash lines, another 1 are fuel injectors and the other 1 is the casing, which encloses the entire combustor. So depending upon how you arrange the liner, the casing and the fuel injection you get different designs okay. Simplest design is this is called the can combustor.

Each one of this is called a can because it looks like a can okay. The liner I will show you a picture of the liner little bit later. The liner actually is a perforated plate so the liner is actually a perforated plate through which air can come in and mix with the combustion gases, combustion can take place on the other side. So we inject fuel in the middle of the can, each can is generally independent from the other.

Although they are all connected through a tube for help with starting, when you start once combustion takes place in one can, that can propagate to the other canes also and get the engine started. So normally they are connected but from operation perspective we may assume that they are independent because each one has a separate casing because each one has a separate casing we can essentially think of this as multiple combustors arranged in a circumference around the shaft.

So the air from the compressor comes in like this. So we have a can like this, the air from the compressor comes in to each one of the canes right. So that is this can design, which was used initially during World War II, in the early years of aircraft turbojet engine this was the design that was used. The next design that was generally used was something called an annular combustor.

The annular combustor is used even today. Most modern engines use the annular design. So here we can see the casing and a liner, which runs around the entire circumference and different fuel injection locations. So this is one combustor, it is annular because the combustion takes place in this annular space okay. I will show you a picture of these 3.

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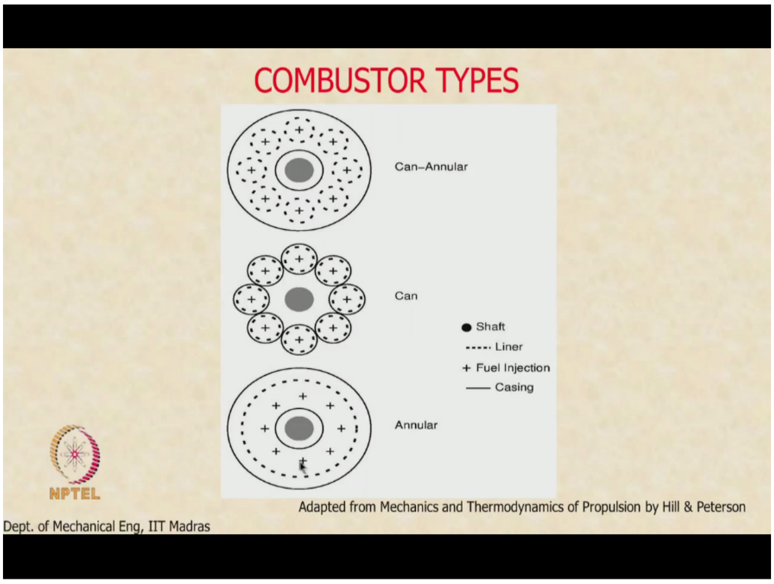

Now the can annular combustor is a hybrid of the can and the annular. So here you can see that it has a single case outer case like the annular combustor and it has multiple fuel locations like the annular combustor, but each one of the fuel injector is surrounded by a liner like a can combustor okay. Since each one of them does not have its own casing, they are common but they have a separate liner.

They are separated by liners so because in this case each one has its own casing, it is more or less completely isolated from the other cans. Here the cans are not completely isolated from the others. They do not have individual casings. They all share the same casing. This is called the can annular combustor. All these 3 designs have been used. The annular and the can annular are probably more widely used than the can combustor itself okay.

So let us take a look at the picture of this combustor so here you see the first design.

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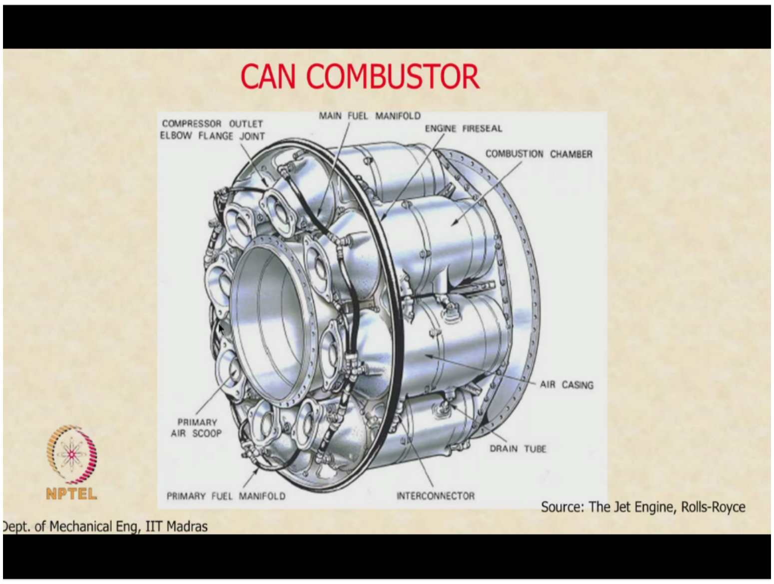

This is the can combustor okay so you see individual combustor cans, but as you can see from here there is also an interconnector, which kind of make sure that they all run at the same pressure and they can all share the hot gases little bit, so that the combustion takes place in one can it will be initiated in the other cans also. So there are no pressure fluctuations across the cans.

So they all operate more or less at the same pressure, pressures are equalized by the interconnecting tube. So you can see that this side so the compressed air comes from this side so this end connects to the compressed air right and you can see the space for the shaft to go through so this is the inner casing, the shaft goes through this passage. This side connects to the turbine.

So the hot gases from here directly flow into the turbine blade okay. This side connects to the compressor.

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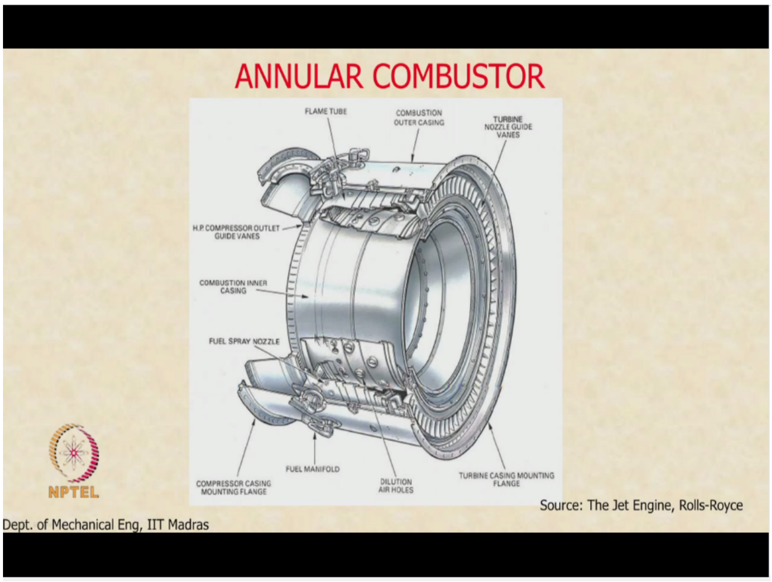

Now the next one is the annular combustor okay. So here you can see this side connects to the compressor, this side connects to the turbine and you see the passage for the shaft, you see the inner casing, you see the outer casing, and then you see the liner. So here is the liner, liner on the flame tube. So this goes in the entire circumference. Combustion takes place across this annular space right.

So the high pressure air comes in here through these guide vanes directed properly here and then they go out here again you have these guide vanes, which directly feed this hot air into the high pressure turbine blade. The shaft sit here. Notice that this is the only portion where the hot air comes out okay. So the hot air comes out only through this passage into the turbine blade right.

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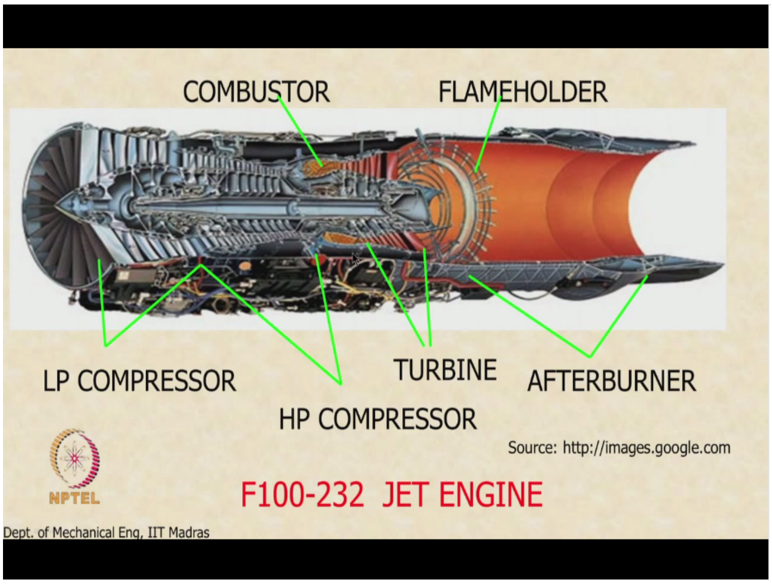

So you must keep that in mind let say quickly take a look. Notice that the air enters the combustor through this small blade passage. Remember we said that the height of the blades decrease so the air flows only through the blade passage. So the air enters the combustor through the small passage and then it leaves through the small passage into the high pressure turbine blades okay.

So that is why you see that the air goes out only through these blade passages into the high pressure turbine blade. This is the space for the shaft and other things, support structures and so on. This is the annular combustor. The can annular combustor is the hybrid, again this end connects to the compressor, this end connects to the turbine and again you see these blades which direct the hot gas flow onto the low pressure turbine blades and you see the difference now between the can combustor and this.

Notice that the outer air casing is the same for all the canes. The outer air casing runs across the entire circumference. Just like this one here, the outer air casing runs across the entire circumference. So in the same way this one also the outer air casing runs across the entire circumference. Inner air casing also runs across the entire circumference just like the annular combustor.

However, instead of having separate casing for each one of these liners they are now mounted between these 2 air casings right. That is what we said here also. So a simple schematic that is what we said here. There is an outer air casing, inner air casing just like the annular combustor, but each fuel injector is separated by a separate liner.

So that aspect is taken from the can combustor design having a single inner and outer air casing is taken from the annular combustor design that is why it is a hybrid design and this is also very widely used these days okay. All of them are interconnected again using interconnecting tube so that we can see the interconnector here. So they are all connected together to maintain the same pressure in all the combustors.

So that you do not have any non-uniformity in the temperature or pressure of the air that comes out of the turbine. It must be at the same pressure and temperature, uniformity of the flow when it comes out of the combustor and goes into the turbine is very, very important and remember these combustors they may look deceptively small, but remember during takeoff for instance these combustors handle about some other bigger engines about 1200 kilograms of air per second okay.

The biggest engines handle about 1.2 tons of air per second at takeoff. They may look small, but they are handling huge amounts of air okay.

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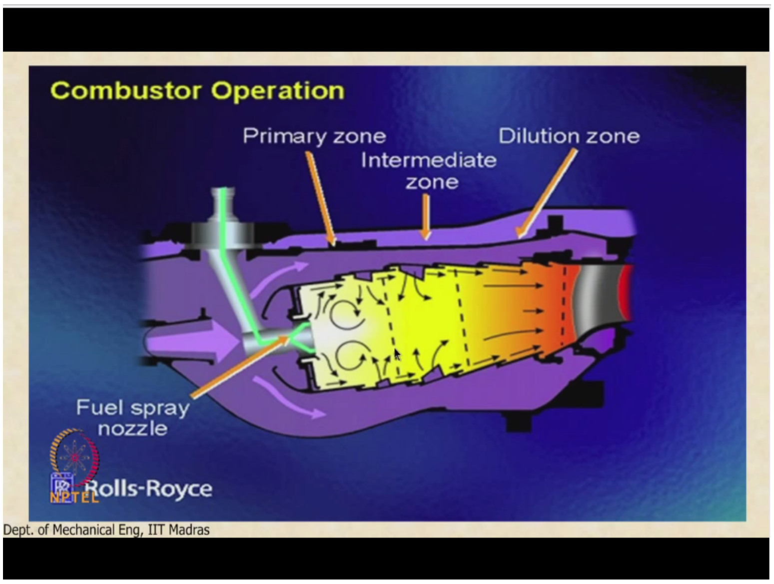

What we will do in the next class is take a closer look at the operation of each one these combustors from perspective efficiency, mixing, emissions and so on. That is what we are going to do in the next class.