Gas Dynamics and Propulsion
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Lecture – 27
Components of the Gas Turbine Engine

We begin today's lecture by starting to look at a detailed view of each one of the component of a gas turbine engine. So we looked at the neat gas turbine engine in the previous class.

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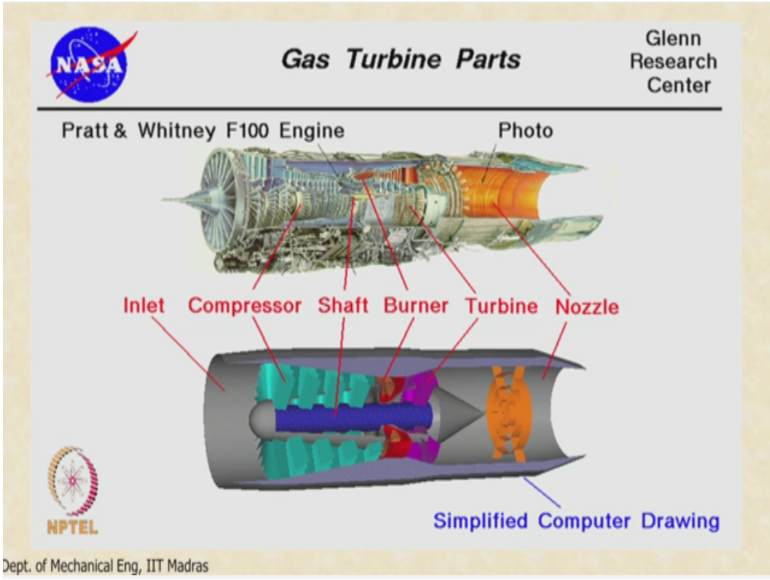

So now we will start a detailed look at each one of the components of a turbo jet engine. As you can see the major components are an intake, compressor, combustor which is also called the burner, turbine and a nozzle. Nozzle itself can have variations for example nozzle of a simple turbo jet engine or an after burning turbo jet engine which happens to be slightly more complicated.

So we will start our discussion with a look at intake which is actually not very crucial for a subsonic flight. But for supersonic flights it is very important. So subsonic flights are not very crucial but it is always present, so we will start our discussion with that.

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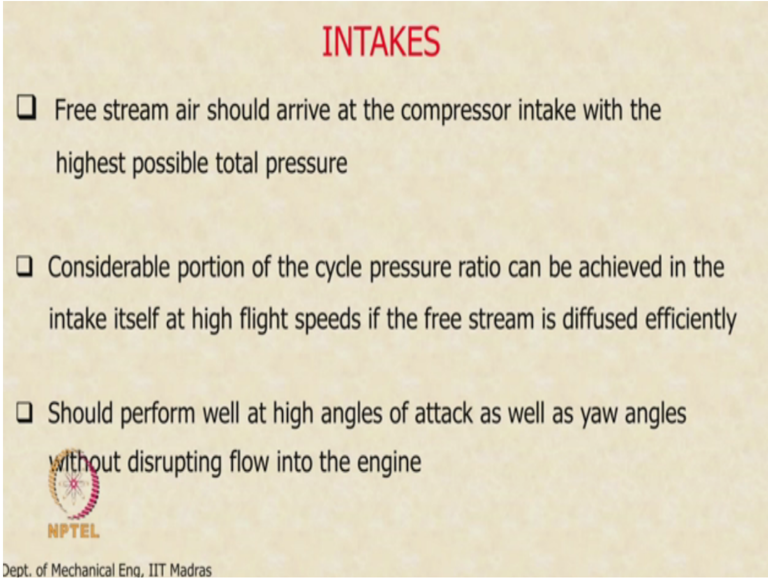

The basic objective of an intake is to provide the air at the entry to the compressor with the highest possible total pressure that is the function. Now in the case of supersonic aircraft or aircraft which fly at supersonic speeds as we discussed earlier a considerable portion of the cycle pressure ratio can be achieved in the intake itself if we decelerate the flow properly. If the flow is decelerated properly, we can convert the momentum of the high speed air into a pressure rise.

So that means rather what done by the compressor is less or the compressor itself can be completely dispensed with, if you are able to really go to high flight speeds. So the idea is to convert the momentum of the incoming air or free stream air to pressure in the intake that is the primary function of the intake. The other important aspect is that the intake should be able to perform well.

So it must continue to deliver the required amount of mass flow rate to the engine at different angles of attack as well as yaw angles without disrupting the flow. So irrespective of angle of attack or the orientation of the intake with respect to the flight direction it must be able to give the required amount of air to the compressor, that is very important otherwise if sufficient air is not given to the intake.

Then it is not going to start or the engine may have flame out, which is then going to make things extremely difficult. So the intake must continue to provide air to the engine at all angles of attack as well as yaw angles.

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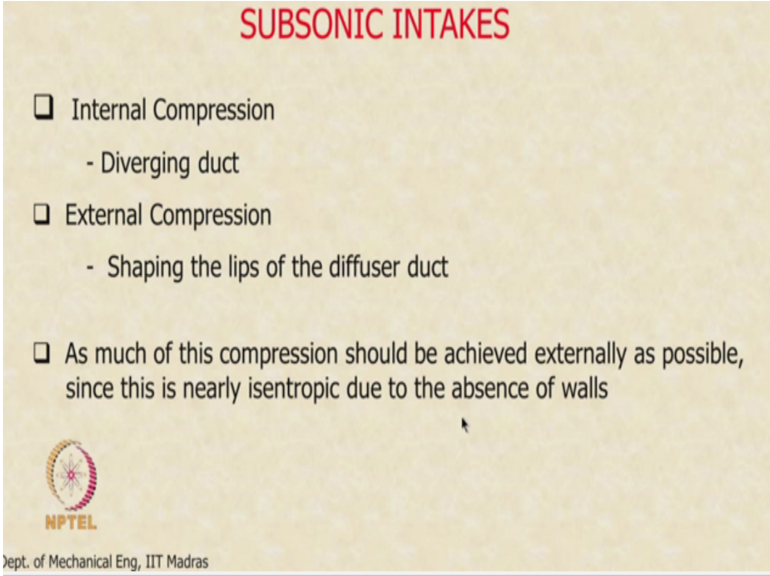

Since we are talking about decelerating the air and converting the momentum to pressure we are basically talking about compression process. Now intakes generally try to achieve compression in 2 modes, one is through so called internal compression. So you can take for example a subsonic flow and make it flow through a diverging passage automatically the velocity decreases and the pressure increases, static pressure increases so that is internal compression.

So you basically allow the flow to go through a diverging passage and here we are talking about subsonic flight speeds. We are not talking about supersonic flight speeds. So that is one part of it. The other part of it is to shape the diffuser duct itself in such a way that the air stream approaches in a certain way.

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For example, if I look at the intakes here, so these are typical intakes that are used in subsonic aircrafts. So you see the intake here and you can see the divergence of the passage from the intake here to the compressor inlet, so there is a small divergence of the duct that you can see here. You can see that here also, so these are all circular intakes

The intake in a Boeing 737, so Boeing 737 has this type of an engine, it is magma engine and the intake here as we can see is not entirely circular it is slightly flatter down the bottom and that is because of the wing height from the ground. If use a completely circular intake on this aircraft configuration during take-off or landing there is a possibility that it can touch the ground surface. This is why the intake is slightly squashed and not circular in this particular case.

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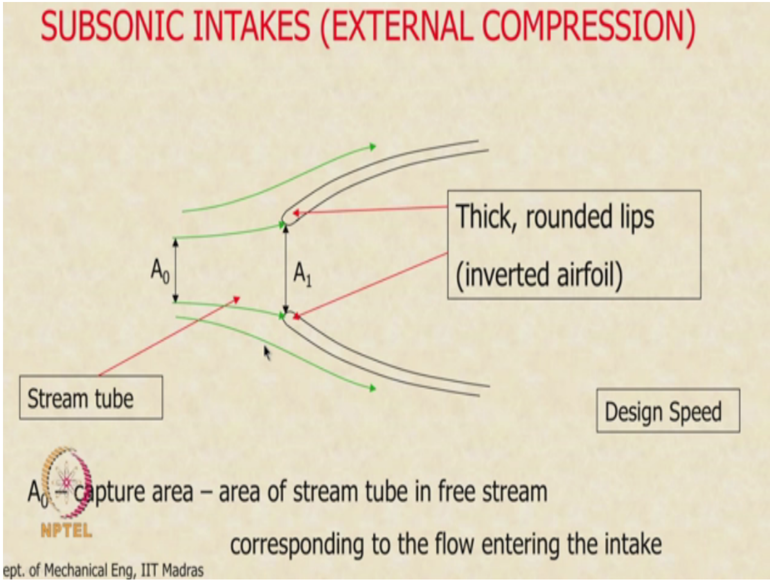

But generally intakes are circular for all these engines and you can see the idea here is to do both internal and external compression. What did I mean by external compression that is shown here. So under design operating condition we can see that this is the intake, so you can see the diverging area inside. So the flow is further decelerated in the diverging area as the flow goes like this, the area of cross - section increases, so the flow is further decelerated that is internal compression.

But because of the way in which the passage itself is designed, if you look at the stream tube, free stream tube that enters the intake, you can see that the area of cross-section in the free stream is actually smaller than at the intake itself, which means there is a diffusion of the flow, as the flow comes from the free stream and enters the engine intake. So you try to design these passages in such a way that can happen, okay.

So that is the A0 is a capture area and you can see an increase in the capture area here. And this increase in the capture area is also going to cause deceleration of the free stream and compression. So that is why we say that there are 2 modes of compression, one is the internal compression and another one is the external compression.

Now external compression as I have said here is achieved by shaping the lips of the diffuser duct, so you basically adjust the lips of the diffuser duct so that the free stream tube is in a certain way and there is compression in the free stream also that is one aspect. The other aspect is external compression is highly desirable because it is very close to being isotropic. There are no surfaces, right, there is no loss due to friction, and there is no irreversibility.

So external compression is almost isotropic compression, so it is very highly desirable. But we cannot do too much of it because if we try to do too much of it then you run into certain problems, okay. So you can see that the lips of the diffuser duct are shaped in such a way as it comes here it has a thick rounded lip which is almost like an inverted air foil. So this causes the flow to approach the smaller free stream capture area compared to the intake entry area

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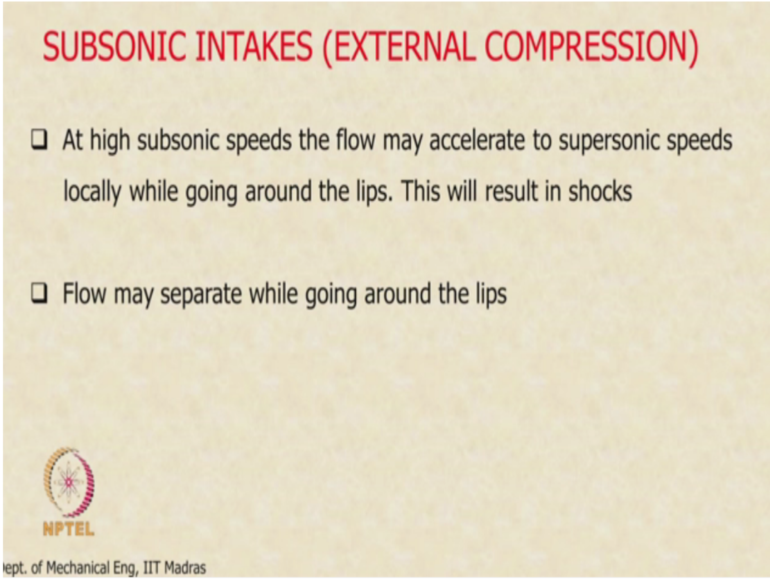

And you can do a little bit of this because if you try to do too much of external compression what happens is; you know as the flow goes around at higher subsonic speeds, as the flow goes around the lip of the intake it can actually accelerate to supersonic speeds and if it is not designed to handle supersonic speeds then there can be a, you know loss of stagnation pressure due to shocks and other things.

If the equipment is designed to handle supersonic flow, then it will handle it properly. But for equipment which is designed to handle only subsonic flow local supersonic flow can cause problems. So you should not try to do too much of external compression try to minimize it, minimize the loss of stagnation pressure. So that at all flight speeds you have good, reasonably good efficiency.

So that is something we must avoid and again if the flow velocity is at very high at large angles of attack you may have flow separation as the flow goes around the lips. If the angle of attack is very high, then you can have flow separation. So these are some undesirable aspects so the lips have to be designed properly because we are saying that the lip is very thick at higher angles of attack you can have separation.

If it is a sharp lip, then the possibility of separation is minimized and if it is a very thick lip then possibility of separation is much more. Even in a sharp lip we can have separation but only under extreme angles of attack. For a reasonable range of angles of attack, you can still have attached flow. But if the lip is thick then you will have separation even for probably slight departures from optimal angles of attack.

So that is why, those are some of the drawbacks with the, with subsonic intakes. But the compression that you are going to get is not very large. Basically the intake provides distortion free flow into the fan at a reasonably high stagnation pressure that is the general idea in an intake in a subsonic aircraft. We will look at intake for supersonic aircraft later on when we go to Ramp jets and so on where the intakes have to be designed very carefully. We have already done examples and we have also seen the theory behind supersonic diffusers.

You know that there are lots of problems associated with them so we will take a closer look. So what we said in the beginning of the propulsion lecture that there were 2 thermodynamic processes that we wanted to do, one was to increase the pressure we said we wanted to increase the specific enthalpy and you do that by increasing the pressure and by increasing the temperature**.**

“Professor – student conversation starts “So the first thing we are going to look at is increasing the pressure because if we try to do it the other way around and let us say you increase the temperature first and then increase the pressure. Is there any downside to that or is it okay? The specific enthalpy increases when you increase these two terms. Does it matter; does the order matter, the order in which we do this? Is it important? Yes, sir. Why is that?

Both have, we are going to compress that particular pressure is more at higher temperature. Yes, basically the simple thing is it requires more effort to compress hot air than cold air which means that we must compress first before adding heat. If we heat the air too much then it is going to take a lot of work to increase its pressure which is much more than what the turbine can possibly provide which is why you compress first and then add heat which is why after the intake we have the compressor, okay **“Professor – student conversation ends”.**

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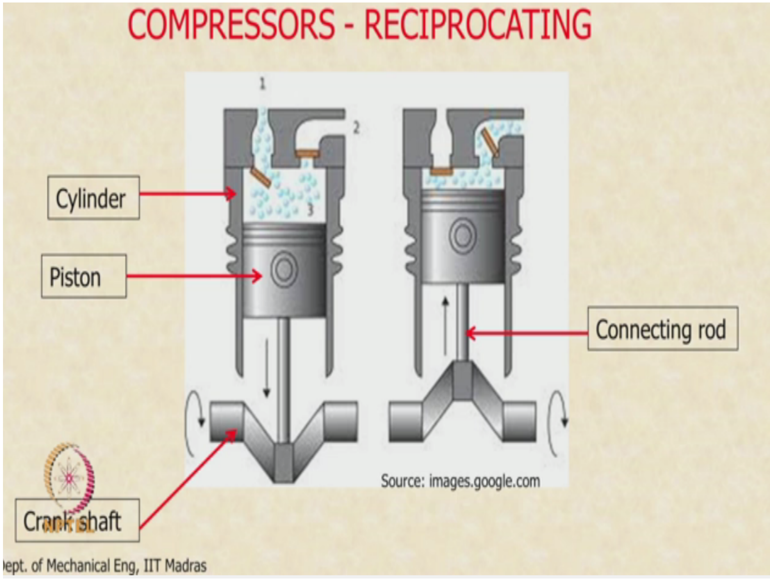

Now the compressor itself can be of different kinds and remember we are talking about what kind of pressure ratios, we are talking about for a typical aircraft engine. As we said earlier talking about pressure ratios around 40 and that is the kind of pressure we want to reach. So the compressor itself can be accomplished for example using reciprocating compressors, so these are something like in internal compression engines where we have reciprocating piston air is drawn in like I have shown here, the air is drawn into the cylinder through the valve.

The valve is then closed, the air is then compressed and once the pressure reaches a certain value, the outlet valve opens and the high pressure air release. This is how a reciprocating compressor operates. Now there are certain problems with this reciprocating compressor for aviation application.

One of the most important problems with this is that. **“Professor - -student conversation starts “**fluctuating pressure **“professor – student conversation ends** “the pressure fluctuates right again as we said earlier when we compared jet engine with an IC engine the operation is not continuous here. During the intakes flow we do not have high pressure air being delivered, right and high pressure air is delivered only during the exhaust stroke for instance.

Of course we can avoid this problem by adding more cylinders. We can add more cylinders to this but that is going to add to the weight and as I said weight is a critical issue here number 1. Number 2 the flow rate also tends to fluctuate. Even if you add more cylinders the fluctuations may go down but they will not vanish. The pressure is going to still fluctuate and that is not really good for aviation application it is not very desirable.

The weight is the most important thing, the weight increases for a pressure ratio of 40. If the pressure ratio is 2 or 3 then reciprocating compressor may be a suitable candidate. But for a pressure ratio of 40 reciprocating compressor is not going to be a suitable candidate which is why we never use reciprocating compressors for aviation application. We always use rotary compressors Rotary compressor itself there are 2 kinds, one is as you can see the radial or centrifugal compressor and the other one is the axial compressor.

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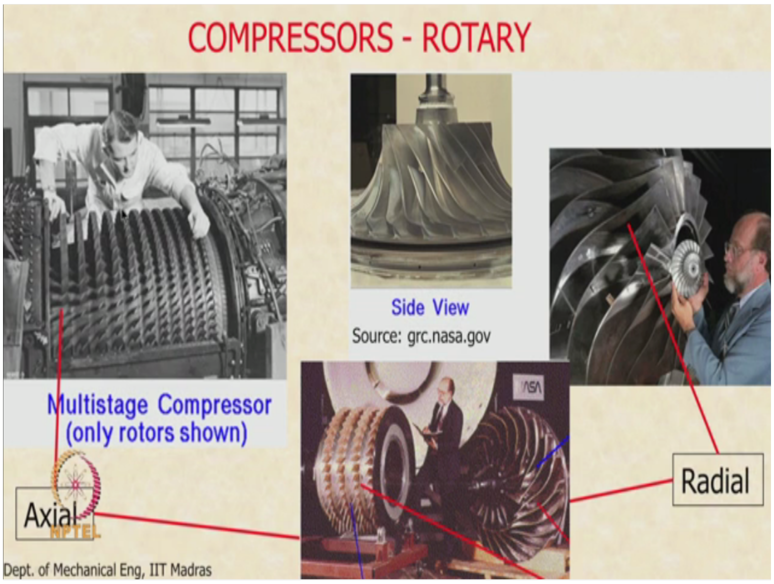

The terminology itself is based on the fluid mechanics of the device. This compressor is called axial because the shaft is like this and the air flows along the axis of the shaft, okay. So the rotor rotates like this and the air flows along the axis of the shaft. That is why it is called an axial compressor. So the blades are all mounted on a drum as you can see from here. The blades are mounted on a drum and here I have shown only the rotors meaning the blades that rotate with the drum.

There are also stator blades in between each one of these rotator blades that we will see next, okay. So the blades are mounted and the blades rotate like this and the air itself flows from inlet to outlet along the axis of the shaft which is why these compressors are called axial compressors. Now in the case of a radial compressor if you orient the shaft the same way.

Let us say the shaft is still like this so the shaft rotates like this the air will enter along the axis and then flow out radially. That is why it is called a radial compressor. **"Professor - -student conversation starts ".** Now the question is why must it enter axially and flow out radially? Why cannot it enter radially and flow towards the axis? The centrifugal force can be used to compress the air.

So it is going radially outward. But what is the, is there any mathematical relationship or anything that states that it is always should be that way? Right that is something that we must ask. Intuitively it seems that is correct but we must also able to back it up with you know ideas from fluid mechanics which is something that we will do. So the air enters axially, shaft rotates like this, the air enters axially and then leaves radially, okay.

That will actually be an issue when we later on look at application into something like an aircraft engine. So keep this in mind, we will come back to this point. **"Professor - -student conversation ends"** Now how does the compression process? So we are going to do next is the following.

How does compression process or how is compression achieved in these compressors? So we start from the inlet for example here and then we proceed to the outlet or we start from the inlet here and then proceed to the outlet, okay. So we want to take a closer look at the nature of the compression process in these 2 devices. So we start by doing the following.

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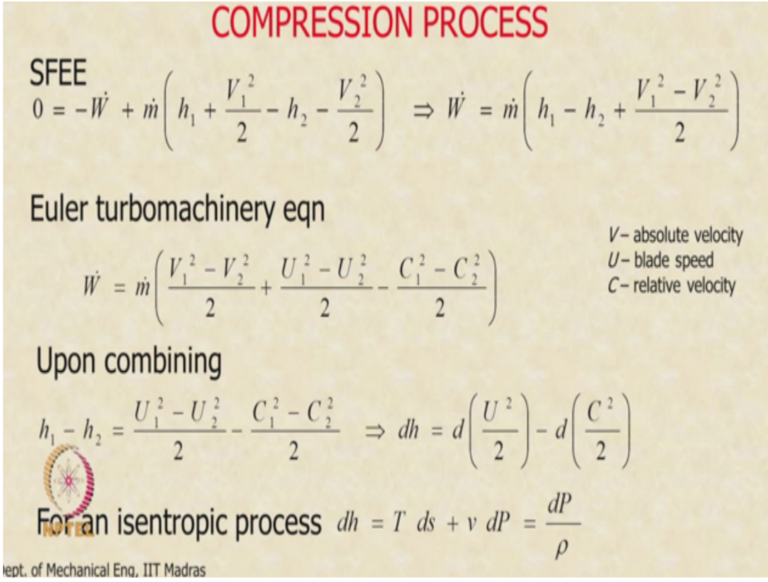

We start with the Steady Flow Energy Equation assuming that the compressors are operating at steady flow. This is the steady flow energy equation which all of you are familiar with from your first level course in thermodynamics, right. We have assumed no heat loss right steady flow operation. So you can see that there is external work being input into the compressor and this is the change in enthalpy and kinetic energy.

These are the absolute velocities that the flow goes through. So W dot is m dot times this, from the Steady Flow Energy Equation. So the work that we are putting in is causing change in the velocity and a change in enthalpy and if it is being compressed then the outlet enthalpy is going to be higher than the outlet enthalpy which is h2, is going to be higher than the inlet enthalpy.

And remember work is being put into this device so that means thermodynamic perspective W for this is negative, okay. So that is something we will keep in mind. Now remember these are rotary machines, so I can also use another very famous equation from turbo machinery which is the Euler turbo machinery equation what this states is, across the rotor taking 1 to be the rotor inlet and 2 to be the rotor outlet.

Across the rotor the work that we are putting in can be related to the change in kinetic energy. This is based entirely on fluid mechanics. This is based on thermodynamics, right. This equation is thermodynamics. What connects these 2 equations? W dot, right, W dot is the term that connects these 2 equations, right. These 2 must be the same, correct, the W dot from here and the W dot from here must be the same.

Notice that here we are using the following notation, V refers to the absolute velocity, U is the blade speed, okay and C is the relative velocity. And this relative velocity is the velocity that an observer will see if the observer is attached to the rotating blade itself, okay. So that is relative to the blade or in a frame of reference were the blade appears to be stationary, okay.

So if I equate these 2 terms what do I get? I can, I get the following. I get this that the change in enthalpy between inlet and outlet, 1 is the inlet 2 is the outlet. So this is the change in the thermodynamic property is related to the change in the velocity, fluid dynamic properties in this fashion. So now we are able to relate changes in fluid dynamic quantities to changes in thermodynamic quantities, okay.

So this is between inlet and outlet of a compressor, of an entire compressor, inlet and outlet of an entire compressor. Now if I take a streamline from the inlet to the outlet and follow that streamline all the way from inlet to outlet I can also write this as a, in a differential form where this differential form tells me the pressure rise in the streamline as I go through the turbo machine. That is what I have done here to the right.

I have written this in differential form as dh equal to this. So if we take an incremental part of a streamline, the change in enthalpy here is related to the change in velocity and the change in this blade speed and change in relative velocity. So in this case U is the blade speed, but you can also think of U as the component in the theta direction of rotation of the flight. So the fluid has velocity in all these directions, right, that is what this is.

So change in enthalpy is related to these 2 quantities. But I also know how to relate dh to other thermodynamic properties because I know my T ds relationships, right. T ds relationship tells me how to connect dh with other thermodynamic properties. So if I do that I get, dh = T ds+v dp. This is a well-known relation. If you assume, we have already assumed that in this, when we wrote this equation we already assumed that there is no heat interaction.

So we said q dot = 0, if I further assume that the compression process is isotropic I can set this ds term to 0. So when I write the ds to 0 and use the fact that the specific volume here is the reciprocal of the density, this dh becomes = dp over rho. So now I finally have what I was looking for, how does the pressure rise take place as the fluid flows through the turbo machine, right.

Now I have an equation which connects dp which is the pressure rise to the flow in the turbo machine, okay. So let us combine these 2 and finally write this equation like this. So you have dp = df U square over 2 where U itself is the blade speed which is = r omega at any point in the blade. At the root of the blade r will be = the radius of the root, at the tip it will be = tip radius, in between we will have some other value.

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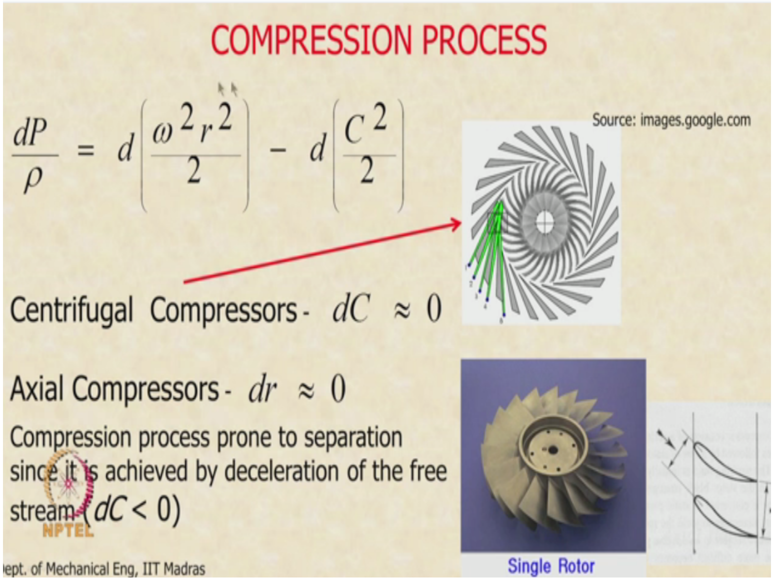

So I replace U with r omega, so you can see that dp over rho is equal, is given by this expression. So what this tells means that any change in pressure happens due to 2 effects. First one is obviously the centrifugal effect. Second one is obviously the change in relative velocity. So this is equivalent to what we saw earlier and let us look at this term by term.

Now let us assume that in a centrifugal, for example in a centrifugal compressor dc is usually 0, remember dc is the change in the relative velocity. That means in a frame of reference where the blade appears to be stationary, so what I have shown here is the centrifugal, this is the rotor of the centrifugal compressor and this is the stator, so that does not rotate.

So if I focus my attention on the rotating blades, then in a frame of reference where the blade is stationary, the fluid enters this passage with a certain velocity and then we can see that there is a very small increase in the area of the passage, right. So when I cause a one dimensional force you know that since flow area is changing only by little the change in relative velocity is going to be very small because the passage area itself increases only by a small amount.

Remember since we are looking at the rotor in a frame of reference that is stationary, I should look only at the relative velocity. So the, when the rotor is frozen the relative velocity, the flow enters with a certain relative velocity and if the passage area increases then the relative velocity will decrease, correct.

So you can see that here the increase in area is very small which means dc, change in relative velocity for a centrifugal compressor is going to be relatively small. The absolute velocity may be large but what we are saying is change in relative velocity is small. Notice that the stator you can see there is a substantial increase in the cross sectional area for the stator because the absolute velocity of the fluid when it comes out of the rotor is very high.

So we increase the area so that the absolute velocity decreases and it is converted to static pressure where as in the rotor so when we look at the stator, we look at what happens to the absolute velocity because it is stationary and in the rotor because it is rotating we look at relative velocity to make it stationary. So dc is 0 in the centrifugal compressor. So if dc is 0 in this equation, that means you only have this term and this is the pressure change in a streamline going from inlet to outlet.

So if I want a compressor, I want, what do I want dp to be, the sign of dp to be, dp should be **"Professor - -student conversation starts "**positive **"Professor - -student conversation ends "So** if this term is absent I have only this term, omega is constant. This is going to be positive if and only if dr is positive. What does that tell you? So I have a streamline or a portion of a streamline, the pressure is increasing, for the pressure to increase dr is positive.

That means it must flow **"Professor - -student conversation starts** "radially outwards, okay. So what your intuition said is correct. The fluid mechanics and the thermodynamics aspects of this backs up what we thought earlier. So any radial flow turbine the flow always flows from higher radius towards the centre. So any centrifugal compressor the flow is always from lower radius or the centre outwards. **"Professor - -student conversation ends"**

That is what this equation tells you. So we can have compression only when dr is positive. If you are extracting work, then dr will be negative. So there is a reduction in pressure along the streamline, okay. Now if you look at an axial compressor and if you remember earlier we saw the axial compressor and the flow direction we said was predominantly axial. In fact, the streamlines also will more or less be moving at the same radius.

So in other words it is not like a centrifugal machine, where you start a lower radius and then you start moving to a higher radius. If you look at the streamlines they are more are less at the same radius, there may be different radii but there is no change, significant change in the radial location of a streamline as it flows through the compressor which means that dr is very small in an axial compressor.

That means compression in an axial compressor is achieved predominantly through this term. Notice that for compression to be realized in a streamline dc has to be **"Professor - -student conversation starts "**negative **"Professor - -student conversation ends** "So that means the absolute velocity, relative velocity must decrease. So if you look at the rotor of an axial flow machine, this is the single rotor of an axial flow machine and if I look at the cross sectional area of the blade passage, this is what the blade passage looks like.

So in a frame, so what I have done here is I have, so I have a rotor which rotates. So I peel the outer surface and if I peel the outer surface along with the blades and then I arrange them out along like this horizontally. This is what I will see. So this is the developed view of the rotor. So the rotor has blades all around, I cut it like this and then I peel it open like this and I lay it down.

This is what it will look like, right. So for relative velocity you see that the passage area increases which means the relative velocity will decrease from inlet to outlet and that is how this compression is achieved. Now the problem is this is a very poor way of achieving compression because as you decelerate the flow, as you know from your undergraduate fluid mechanics the boundary layers near the wall will have a tendency to separate because the pressure is increasing in the direction of the flow.

The free stream decelerates and the pressure increases in the direction of flow so the boundary layer will have a tendency to separate which means that if I have a rotor like this the amount of pressure rise that I can realize here is going to be very small probably only, may not be, the pressure ratio may not be much higher than 1, okay. In reality the pressure ratios are actually only about 1.15 and so no more than that.

That is pressure at the outlet, static pressure at the outlet divided by the static pressure at the inlet is not much more than 1.15 in this kind of compression process, centrifugal compressor can be more, okay. So this brings out the essential fluid mechanics aspects of this compression. These will also, this has important bearing on any decisions that we make down the line in an actual application.

So judging by this discussion what would be the logical choice for an aviation application though we compress, we have already decided that axial, the reciprocating compressor is not suitable. So we are looking at rotary compressor, we have 2 choices. We have looked at the pros and cons. So what do we decide now? Which is better? Centrifugal compressor, right, good.

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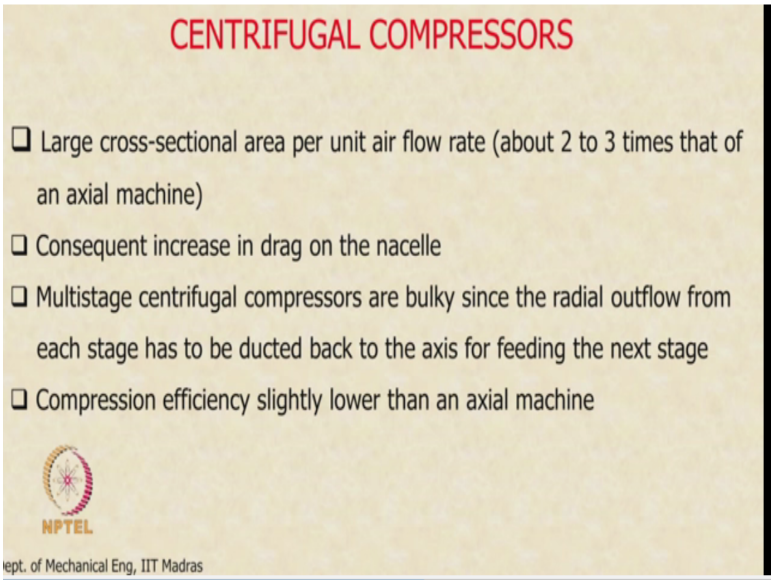

So let us look at other things about centrifugal compressors because the flow is radially outward in a centrifugal compressor, the cross sectional area will have to be very large, okay. It has to be quite large, per unit mass flow rate the cross sectional area has to be very large. Remember we are taking air in at the centre here through a smaller area and then the air flows out.

So for a given mass flow rate and the pressure rise, the cross sectional area will be very large. And if the cross sectional area is large then you know that there is going to be an increase in the drag. The nacelle will have to be large, so there is going to be a large frontal crack that is one downside. And what is the pressure ratio that we wanted across this compressor about 40 which means that we cannot do that with a single centrifugal compressor.

It will simply be too huge to carry on an aircraft which means what does it do? That means I have to do multistage compression. So maybe I will achieve a pressure ratio 4 in 1 compressor and then stack up 3 or 4 of this in tandem. So that I achieve the overall pressure ratio 40 that I am looking for. If it is only 4, pressure ratio 4 then I can do with 1 machine. But if it going to be more than that then I will need to stack up the machines in tandem.

Now if we actually imagine doing this, so I have the first centrifugal compressor here, so the flow enters axially and comes out radially. So I collect all the air now I have another centrifugal compressor here. How do I feed this centrifugal compressor? **"Professor - -student conversation starts"** radially **"Professor - -student conversation ends"** I cannot feed it radially, there the air for the compressor remember my equation tells me that dr has to be positive for compression to take place.

That means I take the air from all the way around here, put IT in a duct, bend the duct, bring it down like this and then take it to the inlet of the next compressor. So that means I have to have a very complex ducting from one to the other to take it all the way like this. It has to enter only near the axis then flow radially outwards. So the ducting is also very complicated and there can be tremendous losses of pressure, stagnation pressure in the ducting in between, okay.

So they become very bulky each stage can do a lot, multistage compressors are bulky because of all these additional considerations. Now compression efficiency of a centrifugal machine is also generally lower than an axial machine. Axial machines have very steep efficiency curves. So the maximum point is high but any departure from off design operation will lead to large changes, large reduction in efficiency.

Centrifugal compressors did not have a flat operational curve. The maximum value is lesser but they are more stable for departure from design operating condition whereas centrifugal, axial compressors will operate very well at the design point. But operate very poorly in off design condition. So the efficiency of a centrifugal machine is also less than that of a comparable axial machine. These are some of the disadvantages of the centrifugal machine.

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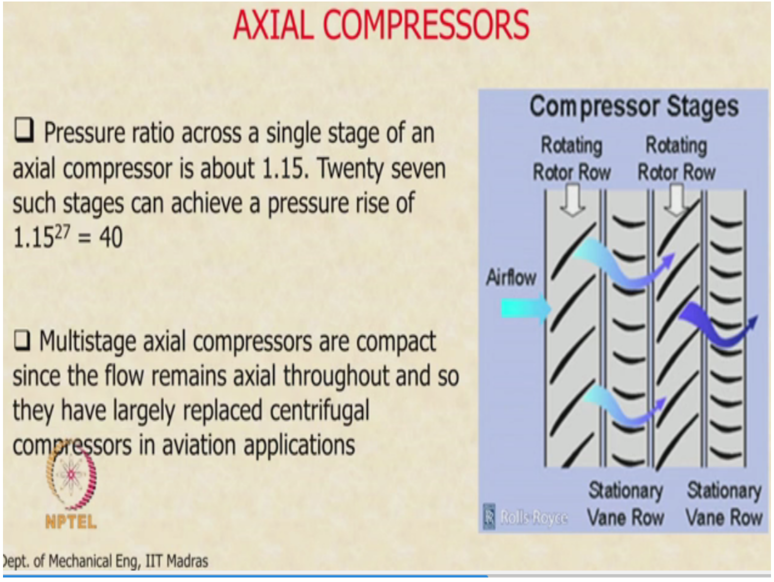

So for this reason, remember just few minutes back I said that from the fluid mechanics and thermodynamics perspective the logical choice was a centrifugal machine. But when it actually comes down to the application. What choice do we make? We make the exact opposite choice, right. That is the reason why we must learn the theory and understand the applications.

But in an actual application there are other considerations, okay. So in an actual application, aircraft engine the axial compressor is used. The downside is that as I said the pressure ratio always is going to be only around 1.15 no more than that because if we try to do more than this the flow will separate. Because you are diffusing the flow in the passage, you are decelerating the flow in the passage, it is always about to flow separation.

So it must not diffuse too much which means I am going to lead a lot of stages to accomplish a pressure ratio of 40. But fortunately for me this kind of compression is actually a geometric progression not an arithmetic progression. In other words, the number of stages required is not 40 divided by 1.15 but 1.15 raised to the power of something = 40, right. At each stage the pressure ratio is at a certain value.

So the pressure rise actually goes in a geometric progression not in a linear fashion, right. So it goes in a geometric progression which means that I need only 27 stages to accomplish a pressure ratio of 40. The linear progression would have set something around 35 or so. You may wonder is it the addition of 8 more stages. Does it make so much difference? Right, even what if it is linear only 8 more stages, right.

The implications are tremendous because each one of this stage will have about 100 rotor blades and 100 stator blades that is 200 blades per stage. So 8 stages mean how many blades? 1600 blades with the commensurate number of blades in the turbine side. If you are going there 8 more stages in compressor that means you need to have more stages, there.

Perhaps not 8 more stages in the turbine may be half as much. So 1600+may be 500 to 600 that is about 2000 blades means they can add up to a lot of weight, right. And remember the most important metric for the aircraft engine is power produced per unit weight of the engine. So if I am able to get rid of 2000 blades that means I have done a lot even to begin with, okay. So 8 stages may not, when you just look at it as 8 stages, may not mean much.

But if you look at the other implications it means a lot, okay. So that is one reason why the axial compressor has almost replaced centrifugal compressors in all aviation application. There are still some small engines which use centrifugal compressors. But by a large most aviation application today uses axial flow compressors. The advantage, the other advantage is they are very compact. The flow is axial throughout.

So there is no entering axially and going out radially and then coming back axially and so on. The flow is axial throughout that means I can design it much better. So the compressor also tends to be compact. There are other advantages the same design can be used for many different engine ratings. So if I have, if I require a pressure ratio of 40, I use 27 stages. If it is a smaller engine which requires only a pressure ratio of 30 I can simply remove a few more stages.

The engine becomes shorter and again gets different pressure ratios. I need not start from scratch. So it is very effective that way. The addition or removal of stages can actually allow me to use or produce engines for different ratings. So that is the reason why axial compressors have largely replaced centrifugal compressors in aviation application which is surprising from a fluid mechanics perspective because a single stage of the centrifugal compressor can achieve pressure ratios as much as 4 or 5.

But the real life design decisions are made not based purely on fluid mechanics, thermodynamics or gas dynamics, but also from other perspectives. That is what we must understand as engineers. The concepts are very important. The concepts allow us to make very intelligent choices. But sometimes we also have to make choices which do not agree with the concepts that you are learning. That is alright. That is what makes real life interesting and life challenging for engineers, okay.

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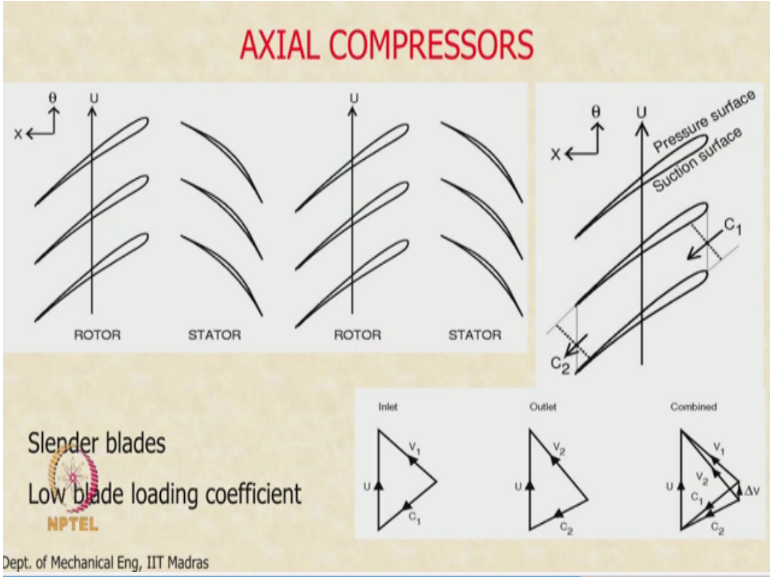

Let us take a closer look at the operation of an axial compressor. So here I have shown an axial compressor. The flow, as we can see from here the x coordinates runs from right to left. So the flow enters from the right and then moves to the left in this way. And you see a multistage compressor here. There is a stator, there is a rotor. What is the need for a stator?

Let us just quickly go to the previous one and see. So you can see that when the air flows through a rotor blade which is rotating like this. The air comes out with the velocity vector. It enters this way and comes out through the velocity vector which is like this. So before I can feed it to the next stage. I need to straighten it out, turn it back so it can be fed to next stage properly.

As you can see from here it needs to be turned back and the turning back is done by the stator blades which is why we need stator blades. Otherwise if I try to feed this directly to the next rotor, the rotor design for this will have to be different from the rotor designed for this and so on. It keeps going like that. So across 27 stages we cannot have 27 different rotor designs. This way I have only one rotor design, each one produces 1.15 pressure rise.

I know exactly what is happening in each stage. I do not have to worry about whether it is a first stage or the second stage which is why we actually turn it around. But there is also a downside to this. The downside is what are these stator blades doing for me besides turning the flow? Nothing, right. So it is adding to the weight and it is not doing anything useful for me. It is only turning the flow, right.

So these are when I start, when I want to reduce weight, these are things we must look at and see whether we can do something better and we will this when we look at the new frontiers and what kind of things the engine companies are doing, the engine manufacturers are doing, okay. So these are the questions that you must ask. So if you look at the axial compressor we can see the stator.

The purpose of the stator as I said is to make sure that flow is directed properly on to the rotor blades. So in a frame of reference where the rotor is stationary, the relative velocity vector must be tangential to the blade surface at entry and tangential to the blade surface at exit. This is the relative velocity vector not the absolute velocity vector, okay. So in a frame of reference where the blade is stationary this is what the relative velocity vector should look like, okay.

So each one takes the velocity, absolute velocity, the stator takes the absolute velocity vector turns it back so that it approaches this in a correct design angle, okay. We can also see for example the, this is the air foil shape of the blade cross section and you can see that the cross sectional area increases as you go from inlet to outlet, not by much because the pressure ratio is only 1.15.

So we cannot have large increases of cross sectional area in the case of a compressor and that is also the reason why the blades are very slender. If given the blade, if given a blade how do you tell it is a compressor blade or a turbine blade? If it is very slender, it is going to be a compressor blade. Turbine blade will be much thicker and we will see that when we go to our discussion on turbines further down.

So these are very slender mainly because the compression that I am trying to achieve, pressure ratio is only 1.15 no more than that, okay. Other important aspects about the, fluid dynamic aspects about the blades: So here we have the velocity triangle at the inlet to a rotor. So you can see that the blade speed vector is in this direction. The blades are rotating like this, right. We know that the relative velocity must be tangential to the blade surface.

So given a blade profile I can draw this relative velocity vector, okay. And you know that the relative velocity is nothing but the absolute velocity minus the blade speed which means that the absolute velocity is the relative velocity plus the blade speed. So you can see that in this vector addition you can see relative velocity plus the blade velocity gives me the absolute velocity, correct.

Notice the direction, the change in the direction or orientation of the relative velocity vector and the absolute velocity vector. The relative velocity vector is actually like this but the absolute velocity is like this. So it has to be turned properly so that it will glide on to the surface of the rotor blade in this thing. So the stator blade accomplishes that. That is the inlet velocity triangle. Exit velocity triangle, remember this is an axial engine.

So the blade speed remains the same, right and there is reduction in the relative velocity. We said that the relative velocity must decrease from inlet to outlet because we are diffusing the flow by decelerating the flow. So C2 is going to be < C1 and because of this blade profiles or you can also see that C2, the angle is also different. But whenever design an axial flow compressor normally we will try to keep the axial velocity the same which means that the axial direction is given here x is along this.

So the axial component of the velocity is this, right. So we can see that between inlet to outlet we are trying to maintain the axial velocity the same but C2 is < C1. U is also the same between these 2. So the outlet velocity triangle then looks like this C2+U = V2, right. So we have 3 things.1 the blade speed remains the same between inlet and outlet that is this one. Axial velocity, axial component remains the same for an inlet and outlet.

So that means this component is equal to this component and relative velocity at the outlet is less than the relative velocity at the inlet. So that is what this triangle shows. If I combine these 2 triangles, then I have this triangle. This is the combined triangle which is drawn on the basis that U is the same for both. So I have taken this U to be the common base for both the triangles and then I have drawn the triangles.

And you can see that the reduction in relative velocity from here to here. But most importantly you can also see the relative change in the vector, absolute vector between inlet and outlet. This combined velocity diagram is rich in information, okay. For example, what are the inferences, given a velocity triangle like this? What are the inferences that I can draw from the velocity triangle?

Number 1 the blade speed is constant, this tells me that this is the velocity for an axial machine, correct. Number 2 the change in the velocity vector delta v is in the same direction as the blade speed which tells me that, remember what is that tell me? This is the change in the absolute velocity of the fluid. If it is at the same direction as the blade speed that means we are doing work to increase the velocity of the fluid in this direction, right.

So blade speed and this are the same that means work is done on the fluid to change its velocity in this direction. Since we are doing work to increase the velocity what kind of a machine is it? It is a compressor. So that tells me that it is a compressor, it is the next piece of information that we can infer from this. Judging by the relative velocity C1 is not = C2. There is a change in the relative velocity between inlet and outlet.

That tells me that this is a reaction machine and not an impulse machine, right. That means that there is a change in the relative velocity in the blade passage and due to the work transfer. So it is a reaction machine and not an impulse machine. Those who have studied turbo machinery should be able to relate it to that. So the magnitude of the relative velocity has changed.

If the magnitude of the relative velocity does not change, remember if the magnitude of the impulse machine does not change then it is an impulse machine. If the magnitude of the relative velocity changes within inlet and outlet of the rotor, then it is a reaction machine. The amount by which the change is usually related to a quantity. What is that quantity? Degree of reaction, okay.

Remember it is the change in magnitude that we are talking about not the change in the direction, okay. Change in magnitude of relative tells me that in this case because the relative velocity has decreased. This tells me that it is actually being diffused in the blade passage and so it is a compressor. This also tells me that this is a compressor. I can also infer that this is a compressor by looking at the magnitude of the change in velocity is not very large, either this or this is not very large.

So this tells me that the flow turning inside the blade passage is very minimum, right. This is very small that flow turning is also very small. The flow turning is small that means that the flow turning is related to something called blade loading coefficient. The blade loading coefficient refers to how much work is being transferred into the fluid that is the blade loading coefficient.

If the he blade loading coefficient is very large that means lot of work interactions is taking place. If it is small, then work interaction is small. The blade loading coefficient is directly related to the delta v which is in the direction of this. The component of delta v which is parallel to U is the work interaction that is taking place. If you have studied turbo machinery before, you would know that the work is related to a component called vw, the world velocity component.

Remember, that is the component which is parallel to U. If delta v has a large component parallel to U that means large amount of work is being put in and if that happens then the flow turning will also be very large. So here, as you can see, from here to here you can see that the flow turning is not very large. That also tells me that it is a compressor blade.

All this happens because we chose to use diffusion process for compression. Because it is a diffusion process and prone to separation I am restricted to 1.5. Because I am restricted to 1.5 I need to have 27 stages to accomplish the pressure ratio 40.And the work transfer that I put in per stage is also limited because the pressure rise has to be limited which means that the blades have to be, the flow turning is not very large.

Because my work interaction is not very large, the flow turning is also not very large, flow turning is very small which means what does that say about? So far we have looked at sequence of events based on a single decision that we made. We decided to use the second term in that equation that we derived, dp. So that meant that there is a problem with that process.

So I will restrict it to 1.15,1 I have large number of blades. Number 2 each blade the work transfer is small; the blade loading coefficient is small that means the flow turning is small. The flow turning is small what does that say about? The thickness of the blades. The blades have to be very slender, right. The blades have to be thin and very slender. If they are not thin and very slender then there will be large changes in the blade passage area, right.

The blades have to be thin and very slender. Now we have gone from fluid mechanics, implications of that decision on the fluid mechanic aspects. Now we are moving on to structural aspects. So the blades are long and slender and thin then there are tremendous structural attributes.

How do we make them stiff? So that is the material and structural design aspects. So the single decision that you take in the early part of the design cycle has tremendous implications down the line, right. So that is the most important thing that you get from such a velocity diagram and the fluid mechanical aspects of this rotors, okay.

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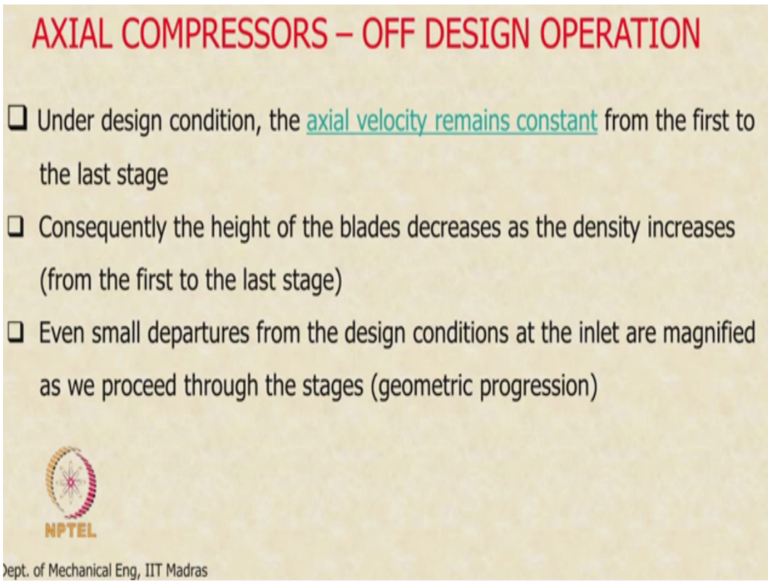

So we will continue the discussion from the next class onwards we will look at off design operation concepts for axial compressors which is actually a major challenge in aviation application.