Introduction to Airbreathing Propulsion
Prof. Ashoke De
Department of Aerospace Engineering,
Indian Institute of Technology - Kanpur

Lecture - 59
Axial Turbine (Contd.,)

So, let us continue the discussion on the turbine. And what we are in the middle of the discussion is that we have talked about the axial flow turbine and how the stage dynamics of a turbine that actually works and what are the different design related parameters and how one look at the different part of the turbine. And then towards the end of the last lecture, we are talking about one of the important aspect of the turbine blade, which is called cooling.

Now, just to remind or rather recall the situation that turbine blades are very, important component of any gas turbine design. If you think about the whole system of an aircraft engine, it starts with your all intake fan and whatever diffuser and then it comes to the compressor and then compressor it goes to combustor and then from combustor to turbine and then finally, pass through the nozzle, I mean, if it is an civilian aircraft engine, if it is an aircraft engine, which is used for the military application, that time you also use the afterburner into the system.

Now, having said that, if you look at what compressor does actually compressor actually increases the pressure so, you get proper pressure rise before the air enters into the combustion chamber and also you decelerate the flow so, that you avoid sort of an unsteadiness or any irregularities in the combustion chamber, because that kind of situation may lead to the flame blow up or some sort of an instability or unsteadiness inside the combustion chamber, which is absolutely undesirable.

So, and also that can lead to some sort of an pressure loss across the combustion chamber. Now, after that point of time the hot gas which comes out of the combustion chamber is actually passed through the turbine and that is the component which plays a key role in a gas turbine unit which produces the actual power. So, the whole design, if you think about it, which I repeatedly keep on emphasizing is that is one particular parameter.

Which controls the design towards the upstream and also towards the downstream is the inlet temperature of the turbine why because the turbine inlet temperature is a parameter, which is after the combustion chamber the hot gases reaches to certain temperature, but it cannot be any untolerable or acceptable or allowable limit, because every turbine blades are made up with some materials.

And we will see even in today's lecture, what are those materials and all these. So, it has certain limitation like every material has certain melting points certain limitation. So, turbine inlet temperature actually it creates that situation where if you go beyond certain acceptable limit these blades or the turbine blades that can melt or that can break. So, this will obviously restrict to your point or the range of operation so, one would like to have more and more temperature which pass through the turbine.

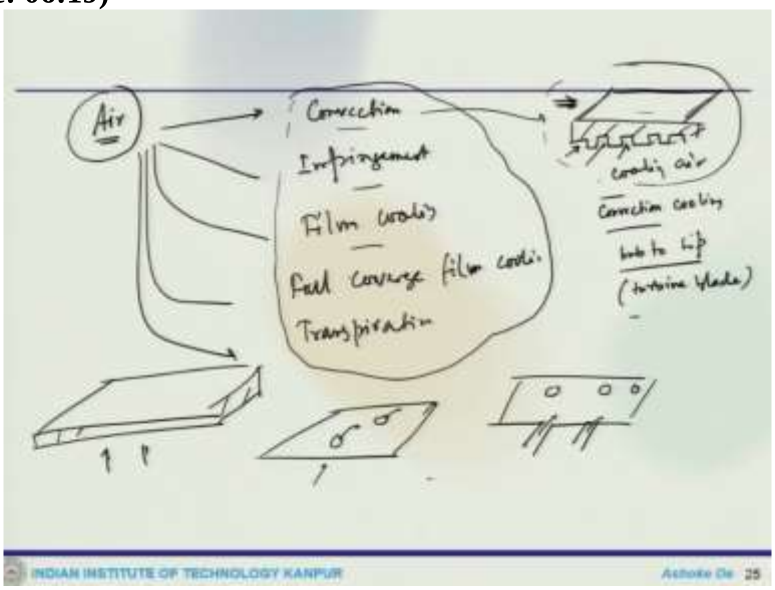
Because if you have more temperature, then due to the expansion process in turbine, you can actually extract a huge amount of thrust. So that is probably one would expect to have, but at the same time one as a designer, one has to keep in mind that the blade has certain limits. So, one should not cross that limits. If that happens that fails. And once the turbine blade fails, that means essentially, not only it is not going to contribute any thrust production also at the same time, the whole unit or the system is going to bed down.

So, now, there are different ways to I mean people have been trying to use some high temperature material, which can withstand high temperature. I mean obviously, it has reached certain limit the development but still we are limited with certain materialistic properties. Now, second point, all these blades because of these hot gases, they are also exposed to high thermal stress or thermal loading. And top of that the blades, especially the rotor blades, they are attached to the rotating shaft, I mean the disc and the disc actually rotate.

So, there is a huge thermal loading or thermal stress which gets developed and that can also lead to the failure of this blade, not only that, that sometimes the disc also fail. So, turbine disk is another important component. Now, what usually people do just to enhance the limit of operation which I already talked about that using some sort of an, if we can reduce the blade temperature to some extent, and that sort the cooling becomes very important.

And for aircraft application primary we do air cooling, because already as I mentioned, we avoid any liquid cooling, there are certain disadvantages with the liquid cooling. So, liquid cooling is not preferred in aircrafts application. So, we go by the air cooling and what it does by doing the air cooling actually it increases the limit.

(Refer Slide Time: 06:19)



And if you go back, this is where we were in the discussion, and just quickly I touched upon the points that different air cooling strategies, but we will close down those things today with proper detailing. So, what it does that, when you do these cooling or the blade which are cooled due to the cooling of actually your temperature operational limit can be enhanced by 400 Kelvin up to 400 500 Kelvin. So, that is the effectiveness one can see due to this cooling, because cooling can literally enhance the operational limit by a certain margin.

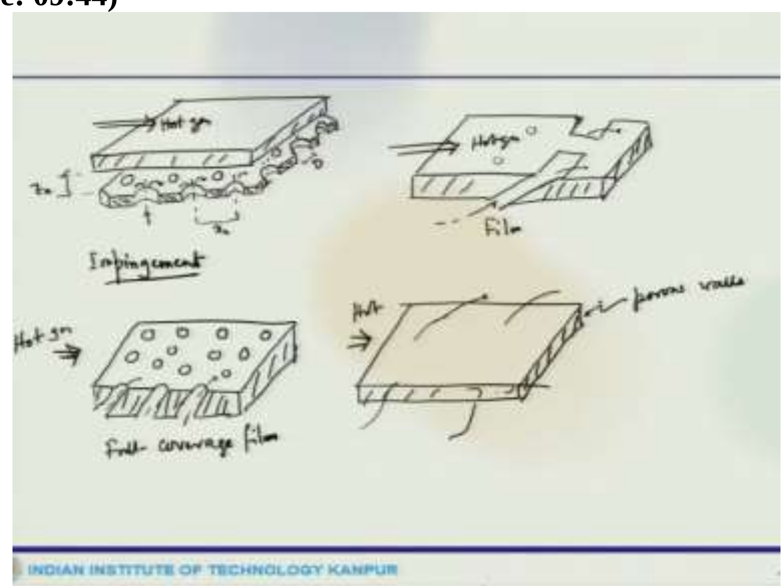
And that allows a lot of flexibility for the designer to design not only the turbine blade at the same time the other components which can operate. Now, as we looked upon these are the different air cooling strategies that one can adopt. So some sort of a convection cooling, then one can have impingement cooling. So, we will draw a proper picture today. I mean, try to draw some pictures and give you an idea how things happen and also do some comparison.

So, let us go one at a time. I mean, like, if I extend this picture itself, this is where the air comes to the hot gas comes through or pass through the surface. And these are the passages through with the, if you think about these are the passages where the cooling air actually pass through. So, this is a typical mode of convection cooling strategy and when the hot air passes through the surface, so, the cooling air which passes through those hole or the slot that cools down the thing.

Now, this form of cooling is achieved by designing this cooling air which is passing through these turbine blade or a vane and it can extract out the heat out of the upper surface. Usually the airflow through these slots are radial and also these are made in multiple passes and they are from hub to tip in the, I am talking about in the airfoil or turbine blade. So, this is a schematic how the principle of operation is, but in the turbine blade, this is how it works.

So, they are these things are taken care of, and this goes from hub to tip and this multiple passage are used. And these multiple passage actually allows to have efficient cooling. Now, the other one is the sort of an impingement cooling, which we can draw a picture.

(Refer Slide Time: 09:44)



Let us say we have an upper plate like this, where the hot gas will pass through. So, let us draw the upper plate properly so that you get an idea. So, this is the upper plate and then you can have some sort of an cooling hole like this then some sort of an cooling hole like this then then it goes like that you have hole like that. So, something like that. So, this if you try to draw some 3d aspect of it. So, this is how it looks so that is how it goes like that.

So, these are the surfaces so one can now you can see through which the, these are the things and there are holes which are there, just like a design is like that. So, these passes through like this. And these are the distance, let us say and this could be the height of that in the height probably this could be the diameter of the hole and this is where the hot gas pass through. So, this is your impingement kind of cooling. So, what it happens?

So, this is high intensity form of convection cooling because if you see the top surface where the hot gases is passing in the bottom there is the impingement. So, the cooling air is essentially blasted on the inner surface of this aero foil. I mean I think about an aero foil surface by high velocity jet. So, these are the jets coming in with high velocity which impinges on the back surface or the lower surface of these blades and permitting an increased amount of heat to be transferred from the upper side to the lower side.

This cooling method can be restricted to desired section of the aero foil to maintain impinge temperature over the entire surface, for instance, the leading edge of the blade needs to be cooled more than the mid chord of the section and or the trailing edge. So, this one can use it then you have a standard approach of film cooling strategy where you can have it easily. So, that is how the slot is this slot could be rectangular, this could be now, this is the slot where things comes this is the cooling gas it called film.

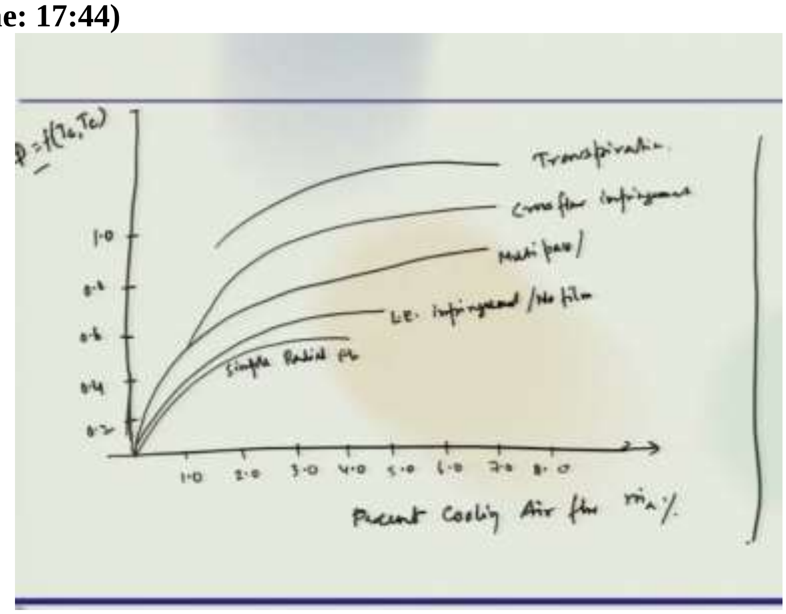
So, that is the surface here the hot gas comes in. Now, this is another standard strategy. So, the air is actually passed through the slots and then it mixes with the hot gas. So, this is injected through the blade holes on the blade surface. So, these are the blade surface where the slots could be there where it comes out and it mixes with the hot gas and due to the mixing with the hot gas, obviously the temperature comes down. So, that is strategy what one uses for film cooling.

Now then another one could be your full coverage film. So that one can design like this. So, you can have like a slot like this. So here the slots are on so, through which so there are full multiple holes are there on the surface and this is where it is injected, this is where the hot gas comes in this is called full coverage film. So, here if as you see, the whole surface is actually fully covered with different slotted holes.

So obviously when it mixes with I mean the when the cooling air is passed through these multiple holes and it mixes with the hot gas there would be efficient mixing and it will reduce the things or the other one which we could have is the transpiration so that is like it is both like this. You have a surface like that. So, this goes like that. So, this is the hot gas comes in and transpiration cooling is the method requires the coolant flow pass through the porous wall.

So, these are the sort of one can think about these are porous walls. I mean the surface on through which it passes through, and the heat transfer is directly between the coolant and the hot gas. So, this covers the entire range.

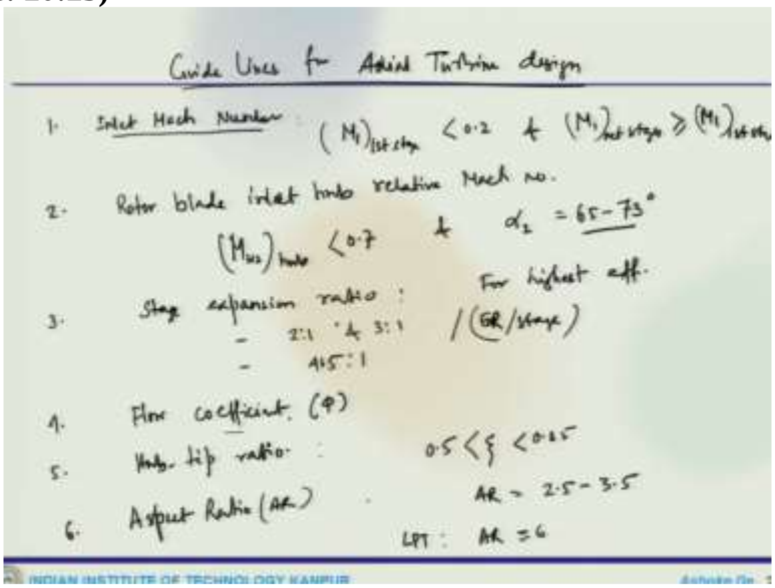
(Refer Slide Time: 17:44)



Now, if you look at it, some sort of a plot would give you an idea about let us say this is percentage percent cooling airflow, which is m dot a. So this was let us say 1 2 3 4. So, these are some schematic and these goes 2, 4, 6. So, this is effectiveness of the film cooling which is a function of hot gas cooling gas. So that is the ratio. So, the different kind of curves one can obtain so these can go like simple radial flow then this could be no film like that. So, this is simple radial flow.

So, this is leading edge impingement or no film. Now this will have multi pass this is some sort of cross flow impingement and this could be transpiration. So just give you an idea how this improves the different aspect of the blades. So, these are obviously is going to improve the sustainability or resistance of the blade material up to a higher range of temperature and that allows you to operate in a different range.

(Refer Slide Time: 20:25)



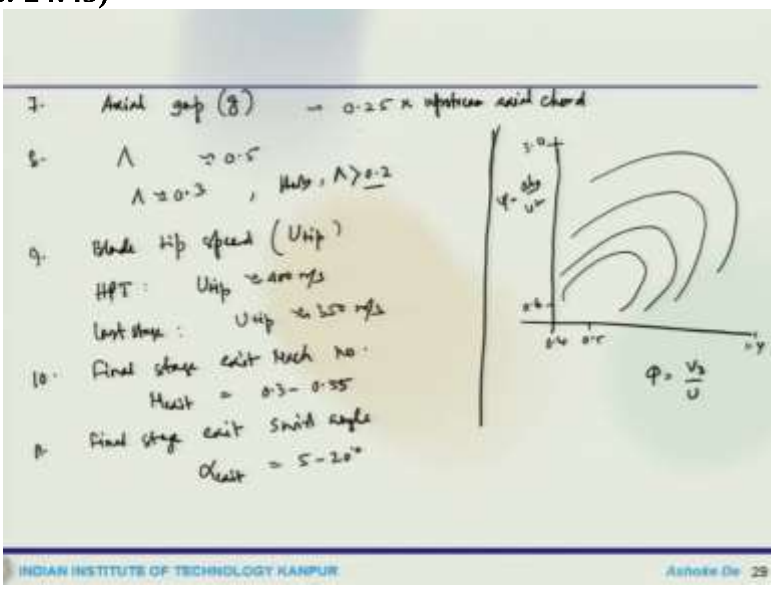
Now, just too quickly wrap up the things, so, there are certain guidelines for axial turbine design. So, these are some of the recommended practices, which are in axial turbine designs. One is the inlet Mach number. So, what it does to minimize the losses in upstream ducting and assure the gas acceleration in NGV. So, what have M_1 first stage should be less than 0.2 and M_1 next stages should be higher than M_1 of the first stage.

So, this is typically what is sort of kind of consider while doing the design. two is the rotor blade inlet hub relative Mach number. So, this also to ensure the acceleration relative to the rotor and avoid any possible separation at the rotor inlet, then one can have a condition M_{w2} at hub should be somewhere 0.7 and α_2 would be in a range of 65 to 73 degree. Again these are some of the recommended setting for design or this is not all third is the stage expansion ratio.

So, this is important. So, stage expansion for the highest efficiency for highest efficiency this expansion this show should be in the order of 2:1 3:1 the per stage this is expansion ratio, ER / stage. So, the highest expense ratio on a single stage turbine, it could be somewhere 4.5:1. Fourth the flow coefficient which is ϕ. So, the flow coefficient versus stage loading for different efficiencies already been seen that how it works so, from there one can choose then hub to tip ratio.

So, here hub to tip ratio is important just to minimize the secondary losses and losses due to tip clearance the hub to tip ratio should be in the range of psi 0.85 to 0.5 6 that is aspect ratio which is AR then the aspect ratio is based on the axial chord. So, let us say should be range of 2.5 to 3.5. Now for LPT it can be a little large or aspect ratio can go up to 6. So that is a low pressure turbine which we can do.

(Refer Slide Time: 24:45)



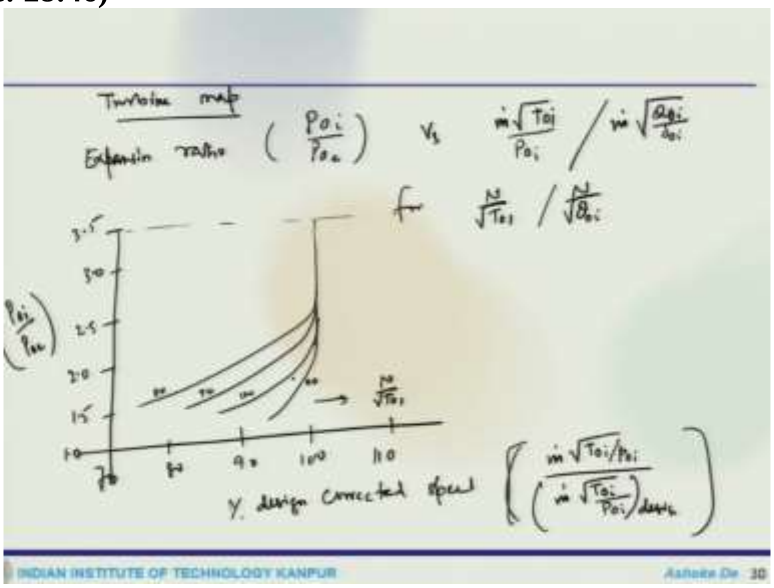
Then you have axial gap which is (g). Now this is to avoid the blade vibration difficulties. So, this would be some are approximately 25 times into upstream axial chord. So just to avoid those things. Now already so, just here these flow coefficients one can see a quick chart on the side like for flow coefficient there is a variation this is again a qualitative plot, it is not something starts from 4. So, it goes like up to 1.4 this is $\phi = \frac{V_z}{U}$ and this side is $\Lambda = \frac{\Delta h_0}{U^2}$ stress loading coefficients.

So, this starts from 0.6 it goes somewhere as again 3. So, the curves would be qualitatively they look like this. So, from this you can estimate this thing during design. Now, degree of reaction. So, for based efficiency this should be around 0.5, but the blade temperature is borderline with respect to the creep or oxidation, then this guy can be 0.3 or and hub. This could be always greater than 0. 2. Now, blade tip speed which is U tip.

Now for high temperature turbine that is HPT there is huge disk stress. So, that limits this you tip to roughly 400 meter per second for last stage or towards the LPT you can U tip should be around 350 per meter per second because HPT there is a huge disk stresses. So, then finally, final stage exit Mach number. So, just to avoid any big round inflow in turbine, downstream defusing duct, which is exhaust or jet nozzle pipe whatever the final stage Mach numbers should be in the some range that is 0.32 somewhere 0.55 and then final stage exit swirl angle.

So, exit swirl angle so, that is again to minimize the downstream duct pressure loss the exit swirl angle should be in the range of 5 to 20 degree. So, these are some of the design parameters are the numbers which are recommended and one can use those things.

(Refer Slide Time: 28:46)



Now, that the last component which we have also talked in details for compressor also for turbine there is a map and this is also generated through detailed experimentation or some sort of in computational analysis to see the under all off design condition. So, this can have in the expansion ratio or the pressure ratio whatever you call it that is let us say P_0 inlet to P_0 exit. So, depends on the station number.

So, this can be plotted versus non dimensional mass flow rate like

$$\frac{\dot{m}\sqrt{T_{0i}}}{p_{0i}} \Bigg/ \frac{\dot{m}\sqrt{\theta_{0i}}}{\delta_{0i}}$$

and that is for 4 different rotational split which is

$$\frac{N}{\sqrt{T_{0i}}} \Bigg/ \frac{N}{\sqrt{\theta_{0i}}}$$

so this turbine map can be drawn with respect to design condition. So that these parameters will be corrected mass flow rate. And then if you plot these like this let us say 70 80 90 100 110 train decide is your percentage design corrected speed, which is $\frac{\frac{\dot{m}\sqrt{T_{0i}}}{p_{0i}}}{\left(\frac{\dot{m}\sqrt{T_{0i}}}{p_{0i}}\right)_{design}}$.

So, this is how the speed is corrected and this side it can go 1 1.5 to 2.5 3 3.5 and this is the expansion ratio, which is $\frac{p_{0i}}{p_{0e}}$. So, the typical curves which start for example, let us say from here it comes like this and then it will have different speed. So, these are the increasing in $\frac{N}{\sqrt{T_{01}}}$ So, let us say 80 90 100 110. So, then you get these for varying speed, you get this expansion and ratio and the design characteristics.

So, additionally isentropic efficiency can be plotted. So, for each speed line as we have talked about that it can get you the compressor operating regime with the maximum allowable mass flow rate, etc. So, because also in this case choking occurs in the NGV, so this is what we wanted to discuss about pretty much on axial flow turbine. We will stop here and continue the other discussion in the next lecture.