Turbomachinery Aerodyanmics
Prof. Bhaskar Roy
Prof. A M Pradeep
Department of Aerospace Engineering
Indian Institute Of Technology, Bombay

Lecture No. # 21
Axial Flow Turbines: Work Done, Degree of Reaction, Losses and Efficiency

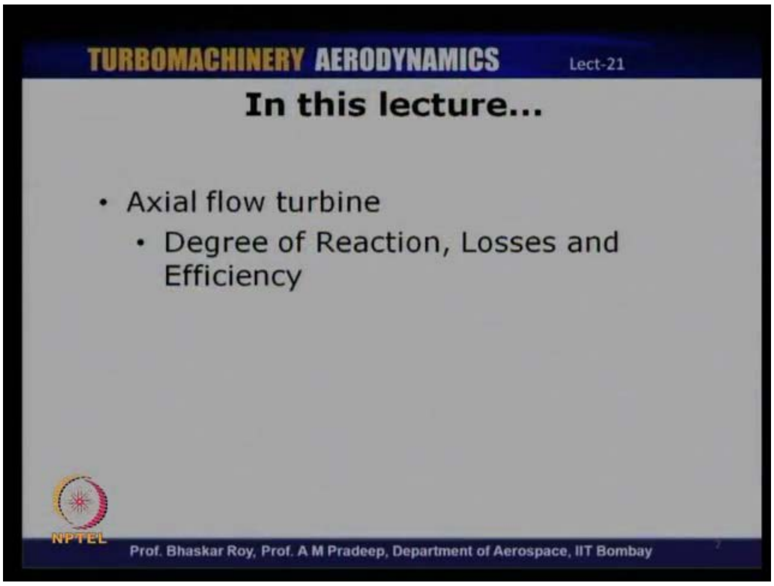
Hello and welcome to lecture number 21 of this lecture series on turbo machinery aerodynamics. We have been discussing about turbines, and in particular, axial flow turbines in the last few lectures; and we had a chance to discuss about quite a few things about axial flow turbines, we started off with the very basics of turbines in general, which is basically to do with the thermodynamics turbines; and after having a very detailed discussion on the thermodynamics of flow through turbines, we have also discussed about the types of turbines; and we have seen that there are basically three types of turbines possible: one is axial flow turbine, the radial flow and the mixed flow turbines.

And we have been talking about the axial flow turbines in the last couple of lectures; and in the last class, we have discussed about the fact that there are basically two configurations of axial turbines, which are possible: one is the impulse turbine and the other is the reaction turbine; and when I discussed about these two different types of turbines, I happened to mention that the reason why they are, this this distinct classes of turbines is the fact, that the way stagnation or enthalpy drop takes place in a turbine is different in these two different types of turbines.

Now, in a turbine stage, we know that turbine stage basically consists of a stator or a nozzle, followed by a rotor. There is certain amount of pressure drop taking place in the nozzle, and there could be certain amount of pressure drop taking place in the rotor as well, but there are certain types of turbines where the entire pressure drop or the enthalpy drop takes place only in the nozzle, and the flow simply undergoes a turn as it passes through the rotor. So, these types of turbines are called impulse turbines; and there are also types of turbines where the pressure drop or enthalpy drop is split or shared by both the nozzle as well as the rotor; and these are known as reaction turbines. So, these are the two different or distinct types of turbines, which we had talked about.

In today’s class, when we began with, we will basically be talking about a parameter, which can be used as a parameter to distinguish between these two types of turbines. So, that is one of the main things that we are going to discuss about; we will start the lecture with discussion on what is known as degree of reaction; after that, we will be talking about the losses encountered in turbine, what are the different forms of losses and subsequently, we will also be talking about the efficiency or different forms of efficiency in a turbine.

(Refer Slide Time: 03:04)



TURBOMACHINERY AERODYNAMICS Lect-21

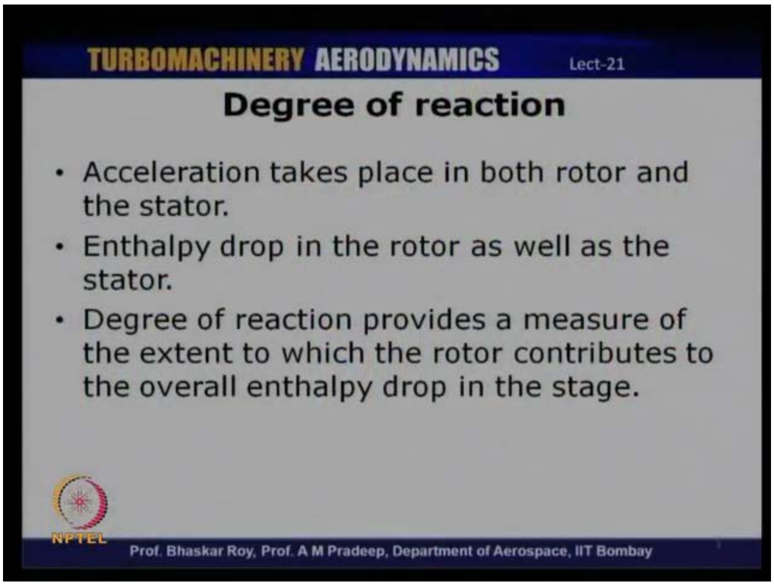
In this lecture...

- Axial flow turbine
  - Degree of Reaction, Losses and Efficiency

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

Now, when we talk about losses, there are… Well, we have already had a very detailed discussion on well 2-D as well as 3-D losses in the context of axial compressors. It is the exact same concept which can be also used in a turbine, therefore I will not really go into the details of different types of losses and how it can be estimated and so on, because we have already talked about that in the case of compressors, we can simply extent that to turbines and so rather not repeat the same thing here, but I will of course, go through the essentials of losses in a turbine, and also how it can estimated in a very generic sense and without going into too much of details, because they have already been covered in compressors; and then we will talk about efficiency, and what are different types of efficiencies, in fact, in turbines you can have different forms of efficiency, there are at least four or more different types of efficiencies that can be defined for a turbine, but we will restrict our discussions to two forms of efficiencies, which are more commonly used; one is known as the Total-to-static efficiency and other is known as the Total-to-total efficiency. There are also static to static, and there are other types of efficiencies which are not really used commonly, and so we will not discuss those in a great detail. So, let us start our discussion with degree of reaction, and what we mean by degree of reaction, and how it can used in a turbine.

(Refer Slide Time: 04:39)



TURBOMACHINERY AERODYNAMICS Lect-21

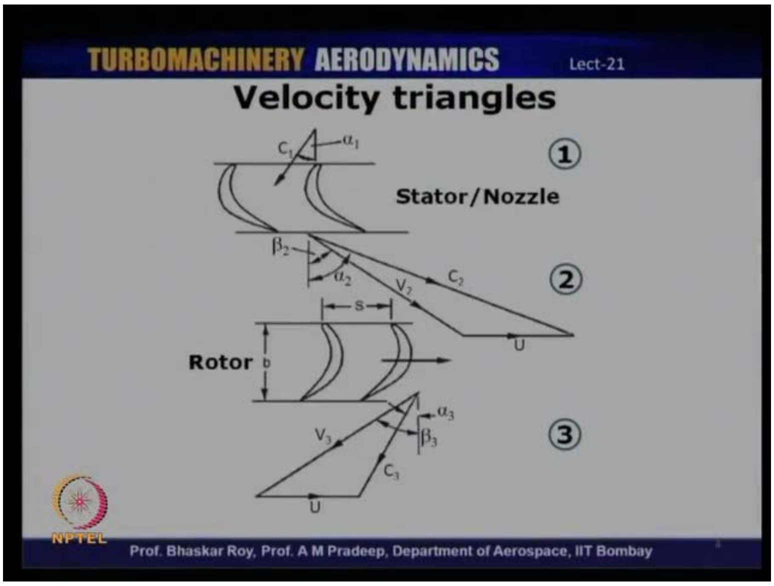
Degree of reaction

- Acceleration takes place in both rotor and the stator.
- Enthalpy drop in the rotor as well as the stator.
- Degree of reaction provides a measure of the extent to which the rotor contributes to the overall enthalpy drop in the stage.

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

Now, degree of reaction as you have seen in the case of compressors, is a concept which is used to kind of understand, how much amount of work sharing is done by the rotor as a comparison of the entire work done in a stage, and so in the case, in the context of a turbine, here the flow basically undergoes acceleration as you already know by now, that it is an accelerating flow in a turbine, and acceleration takes place both in the nozzle as well as in the rotor, and therefore as a consequence of that, there is an enthalpy drop taking place both in the rotor, well, in the nozzle as well as the rotor; degree of reaction gives us some idea about well, it it is basically an indicator of the amount of enthalpy drop that is taking place in the rotor or in the rotor as compare to the enthalpy drop taking place across the entire stage; so, that is the basic significance of degree of reaction. So, but before we go into details of degree of reaction, let us take a look at the typical velocity triangle, which I had discussed in detail in the last class; let me quickly recap what this velocity triangle means.

(Refer Slide Time: 05:53)


TURBOMACHINERY AERODYNAMICS Lect-21

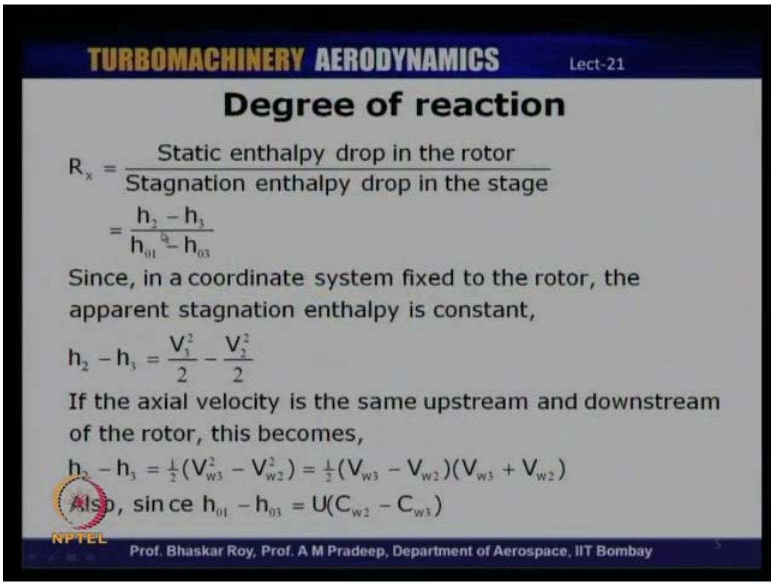
Velocity triangles

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

This is the typical stage of an axial turbine, which consists of a nozzle and a rotor. So, flow enters the nozzle at an absolute angle velocity of C 1, which is at an angle of alpha 1, leaves the nozzle at velocity of C 2, which is the absolute velocity, and making an angle of alpha 2 with the axial direction; V 2 is the relative velocity, which makes an angle of beta 2 with the axial direction; and then flow from this enters into the rotor, and leaves the rotor with relative velocity of V 3, making an angle of beta 3 with the axial direction, and C 3 which is the absolute velocity makes an angle of alpha 3 with the axial direction; the blade speed in both at the inlet as well as the exit of the rotor is assume to be the same and equal to U.

So, this is the very typical or a generic velocity triangle applicable to any axial flow turbine, and so our definition of degree of reaction is with reference to since its with reference to a very generic axial turbine, it can be used in whether in in the case of impulse turbines as well as for the reaction turbines, and what we will see very soon is that impulse turbine is a special case of zero degree of reaction turbine that is when the degree of reaction is 0, then that turbine refers is is basically an impulse turbine.

(Refer Slide Time: 07:35)



TURBOMACHINERY AERODYNAMICS Lect-21

Degree of reaction

$$R_x = \frac{\text{Static enthalpy drop in the rotor}}{\text{Stagnation enthalpy drop in the stage}}$$

$$= \frac{h_2 - h_3}{h_{01} - h_{03}}$$

Since, in a coordinate system fixed to the rotor, the apparent stagnation enthalpy is constant,

$$h_2 - h_3 = \frac{V_3^2}{2} - \frac{V_2^2}{2}$$

If the axial velocity is the same upstream and downstream of the rotor, this becomes,

$$h_2 - h_3 = \tfrac{1}{2}(V_{w3}^2 - V_{w2}^2) = \tfrac{1}{2}(V_{w3} - V_{w2})(V_{w3} + V_{w2})$$

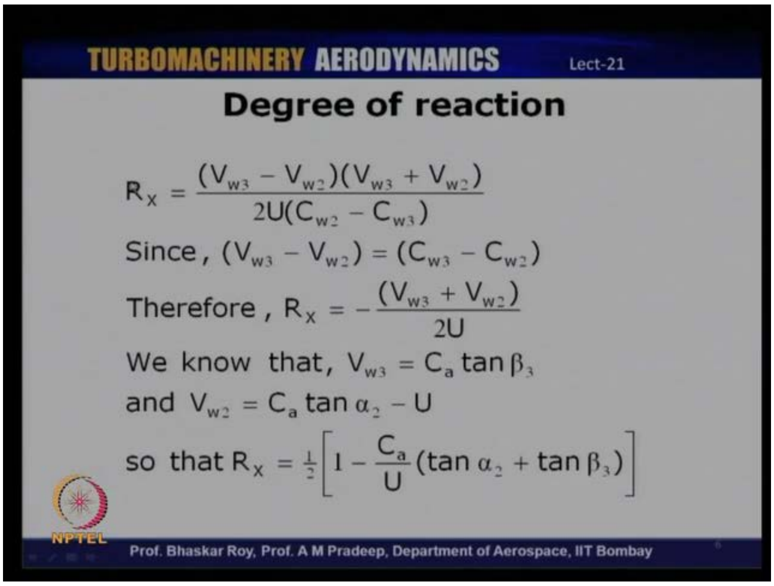
Also, since $h_{01} - h_{03} = U(C_{w2} - C_{w3})$

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

So, as I had mentioned earlier, degree reaction is defined as static enthalpy drop in the rotor divided by stagnation enthalpy drop in the stage. So, if you look at the rotor, these are the station, it is between station 2 and 3. So, static enthalpy drop is h 2 minus h 3 divided by h 01 minus h 03 that is for the stage; well of course, we can always say that h 01 is also equal to h 02, because in the stator, there is no enthalpy change - stagnation enthalpy change. Now, so if we if we look at a coordinate system, which is fixed on the rotor or in the relative frame of reference, the appearance stagnation enthalpy is basically a constant;

And so, we have h 2 minus h 3 is equal to V 3 square by 2 minus V 2 square by 2. So, if the axial velocity is assume to be the same upstream and downstream of the rotor, then this can be reduced to h 2 minus h 3, which is stagnation static enthalpy drop in the rotor, is a one-half of V w3 square minus V w2 square which is half of V w3 minus V w2 multiplied by V w3 plus V w2. We also know that the stagnation enthalpy change across a stage, which is give by h 01 minus h 03, is basically a function of the blade speed and the change in the tangential component of the absolute velocity that is U times delta C w is basically in this stagnation enthalpy drop. Therefore, h 01 minus h 03 is also equal to U times C w2 minus C w3.

(Refer Slide Time: 09:29)



TURBOMACHINERY AERODYNAMICS Lect-21

Degree of reaction

$$R_x = \frac{(V_{w3} - V_{w2})(V_{w3} + V_{w2})}{2U(C_{w2} - C_{w3})}$$

Since, $(V_{w3} - V_{w2}) = (C_{w3} - C_{w2})$

Therefore, $R_x = -\frac{(V_{w3} + V_{w2})}{2U}$

We know that, $V_{w3} = C_a \tan\beta_3$

and $V_{w2} = C_a \tan\alpha_2 - U$

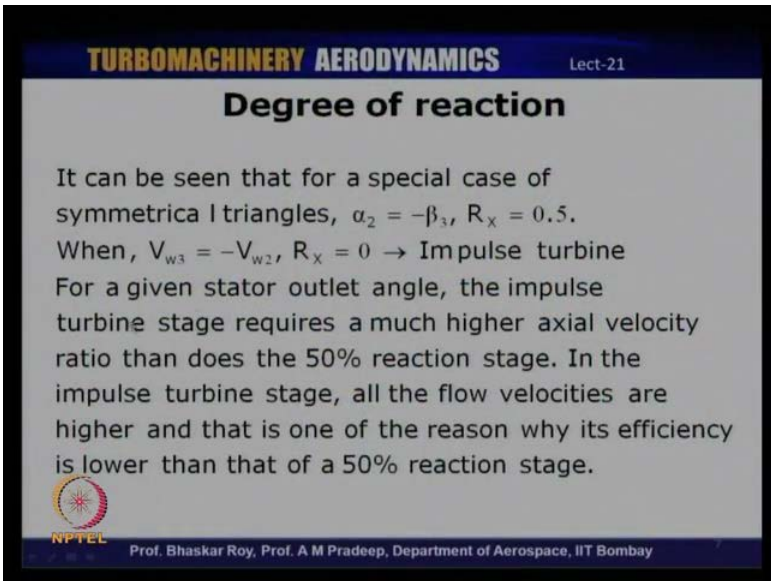
so that $R_x = \frac{1}{2}\left[1 - \frac{C_a}{U}(\tan\alpha_2 + \tan\beta_3)\right]$

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

So, let us simplify the degree of reaction here. So, degree of reaction would become V w 3 minus V w2 multiplied by V w3 plus V w2 divided by 2U into C w2 minus C w3. Now if you go back to the velocity triangle, let us go back to the velocity triangle here, if you look at the components or the difference between C w3 and C w2 that is basically equal to the difference between V w2 and V w3 that is in their tangential direction; therefore, V w3 minus V w2 is basically C w3 minus C w2 and so, this degree of reaction will basically reduce to minus V w3 plus V w2 divided by 2U. Now from the velocity triangle, you can also see that V w3, which is the tangential component of relative velocity at the exit of the rotor is C a times tan beta 3. Similarly, V w2 is C a tan alpha 2 minus U. So, degree of reaction basically reduces to half of 1 minus C a by U tan alpha 2 plus tan beta 3. So, this is one form of defining the degree of reaction that you can relate degree of reaction. We have seen this definition even for compressors and we have also seen that degree of reaction is a function of a few parameters; one of them of course, it is the ratio of axial velocity to the blade speed C a by U, besides that there are the angles alpha 2 and beta 3 in this case. So, it is a functional of the angles as well as the the axial velocity and the blade speed.

So, we can also simplify this, in in the sense that if you look at zero degree of reaction, and also look at a 50 percent degree of reaction turbine; we will see, what are these special cases of axial turbines where we can look at an impulse turbine, and then 50 percent degree of reaction turbine. So, degree of reaction starting from the fundamentals its basically ratio of enthalpy drop - static enthalpy drop in the rotor divided by stagnation enthalpy drop in the stage which we can simplify as we have seen, and relate degree of reaction to the flow coefficient which is C a by U, and the angles; in this case, it is the absolute angle, at the inlet of the rotor and the relative angle or the blade angle at the exit of the rotor that is tan alpha 2 plus tan beta 3.

(Refer Slide Time: 12:20)



TURBOMACHINERY AERODYNAMICS Lect-21

Degree of reaction

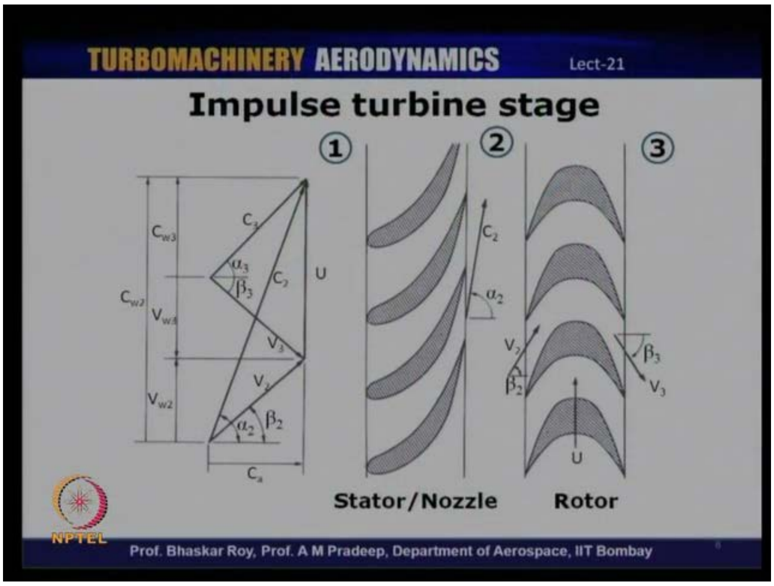
It can be seen that for a special case of symmetrical triangles, $\alpha_2 = -\beta_3$, $R_x = 0.5$.
When, $V_{w3} = -V_{w2}$, $R_x = 0 \rightarrow$ Impulse turbine
For a given stator outlet angle, the impulse turbine stage requires a much higher axial velocity ratio than does the 50% reaction stage. In the impulse turbine stage, all the flow velocities are higher and that is one of the reason why its efficiency is lower than that of a 50% reaction stage.

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

So, let us look at some special cases of degree of reaction. Now, if you look at a symmetrical velocity at triangle configuration where alpha 2 is equal to minus beta 3, what we will see that we get the degree of reaction as 0.5. So, this is known as a 50 percent degree of reaction turbine, we have seen this in the previous lecture as well; in other special cases, when V w3 is equal to minus V w2, then we get degree of reaction as 0, which is basically an impulse turbine. So, if we were to look at an impulse turbine little more carefully and compare that with degree 50 percent stage, for a give stator outlet angle that is alpha 2, the impulse turbine stage requires a much higher axial velocity than the 50 percent reaction stage.

In the impulse turbine, it is generally seen that all the flow velocities are higher, and therefore, it is generally also seen that the efficiency of an impulse turbine is usually lower than that of a 50 percent reaction stage, for two turbines which are generating the same power; that is of course, a generic general observation that because of velocity components are higher, the losses are likely to be higher, and therefore, efficiency is usually slightly lower than that of a 50 percent reaction turbine stage.

(Refer Slide Time: 13:51)



TURBOMACHINERY AERODYNAMICS Lect-21

Impulse turbine stage

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

So, let us look at these two special cases; this is the impulse turbine stage, we can see that the V w3 or V w2 will be equal to minus V w3; If that is so, then the degree of reaction becomes and 0, and such as turbine is an impulse turbine stage. So, we have V w3 and V w2, which are opposing each other and equal in magnitude that is what we have degree of reaction as 0, and what are the physical implications of this… In in degree of reaction 0, it means that there is nothing much happening in the rotor as far as enthalpy drop is concerned the rotor simply deflects the flow, and there is no change in the enthalpy in the rotor, and that is why degree of reaction is 0, because if there is no change in enthalpy in the rotor, the numerator is 0, degree of reaction is 0.

Now if you look at a 50 percent reaction turbine stage, then we have the angle it is a symmetrical velocity triangle, and therefore, alpha 2 will be equal to beta 3. So, if those angles are equal in magnitude, then you get velocity triangles which are symmetrically, you can see that this is the velocity triangles are basically mirror images, what you have at the inlet is mirrored at the exit. So, that is why you have symmetrical or mirror image velocity triangle; if the reaction turbine is a 50 percent reaction stage, and what it means is that the enthalpy drop is shared equally between the rotor and the stator, and that is what a 50 percent reaction stage basically means.

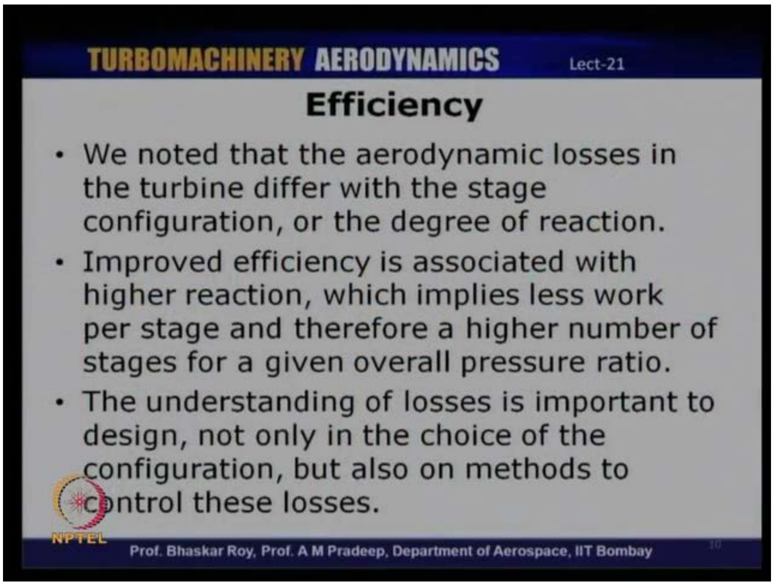
So, what we have defined in the last few minutes is, this is very important concept of degree of reaction, where which basically tells us the amount of enthalpy drop, which is shared between the rotor and the stator; and how we can, you know use that as a parameter to distinguish between these two types of turbines; impulse turbine where you have degree of reaction as 0, which means that there is no enthalpy drop taking place in the rotor, and we have seen that such a velocity triangle, we have the tangential component of relative velocity V w3 is equal to minus V w2; they are equal in magnitude, but they are opposite in direction, and that is why in the velocity triangle, you can see that they will oppose each other, when you take up their components; 50 percent reaction stage, velocity triangles are symmetrical, and you have alpha 2 is equal to minus beta 3. So, well these angles are same making the triangles symmetrical or mirror images across the rotor.

So, now that we have discussed about degree of reaction; let us move on to a very important aspect of performance of turbines that is the efficiency. I think, I have mentioned in the beginning of the lecture that efficiency, in the case of turbine unlike in compressors, we have in turbines defined in different ways, basically depending upon the application for which the turbine is being used. Now, there are certain applications, let us say in a land based gas turbine power plant where you you generate, you are using a gas turbine to generate power. So, here the application is such that you do not want the turbine exhaust to have any very high levels of kinetic energy, because that is getting wasted. So, you would like to use up as much as kinetic energy as possible from the turbine itself without having to waste kinetic energy.

So, here we would like to expand it to the minimum possible enthalpy - static enthalpy, and therefore, any kinetic energy that is there at the exit is considered a waste. So, in such turbines, we usually define efficiency in the form of what is known as Total-to-static enthalpy, and the other form of enthalpy that we are going to define is known as Total-to-total enthalpy, which is what is of interest to aero engineers, because in a gas turbine engine which is used in aircraft, for example, there is enough kinetic energy available at the turbine exhaust, which can be exact again expanded or further expanded through a nozzle to generate thrust, and you do not want the turbine exhaust to get or turbine to exhaust itself to the minimum possible kinetic energy, because you would also like to expand further in a nozzle generate thrust.

So, in such applications, you one would prefer to define efficiency based on Total-to-total or stagnation enthalpies. So, these are the two commonly used forms of efficiencies as I mentioned, there are also other forms of efficiencies, which are not very commonly used like static to static and so on. We will restrict our discussion to this two types of efficiencies: Total-to-static and Total-to-total efficiencies.

(Refer Slide Time: 19:04)



TURBOMACHINERY AERODYNAMICS Lect-21

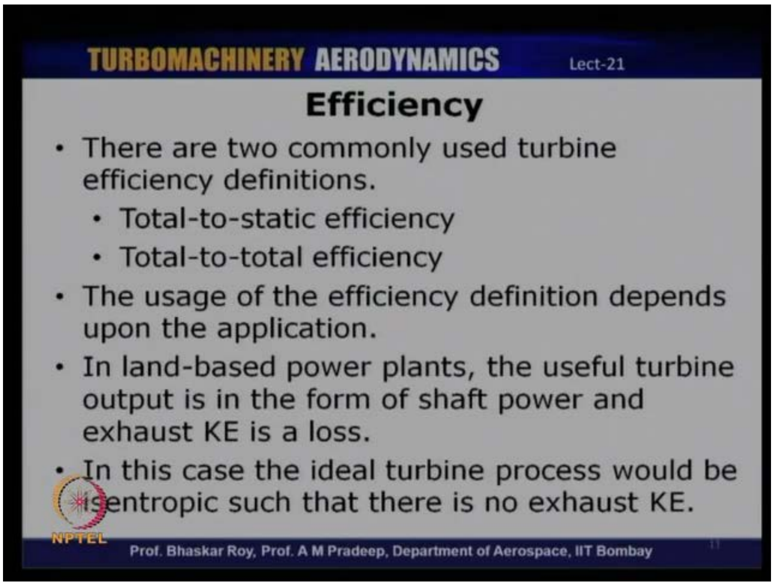
Efficiency

- We noted that the aerodynamic losses in the turbine differ with the stage configuration, or the degree of reaction.
- Improved efficiency is associated with higher reaction, which implies less work per stage and therefore a higher number of stages for a given overall pressure ratio.
- The understanding of losses is important to design, not only in the choice of the configuration, but also on methods to control these losses.

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

Now, so some general comments which I had main, let me list down here. So, the aerodynamics losses in a turbine as we have seen differ with the stage configuration are the degree of reaction, and so improved efficiency is associated with the higher amount or level of reaction, which implies less work per stage, and therefore, higher number of stages for a given overall pressure ratio. So, the reason why we need to understand efficiency or the sources of losses is that it firstly helps us in making a choice between different configurations either degree impulse or a reaction, but the other advantage is that it will also tell us how one can control these different forms of losses.

(Refer Slide Time: 19:54)



TURBOMACHINERY AERODYNAMICS Lect-21

Efficiency

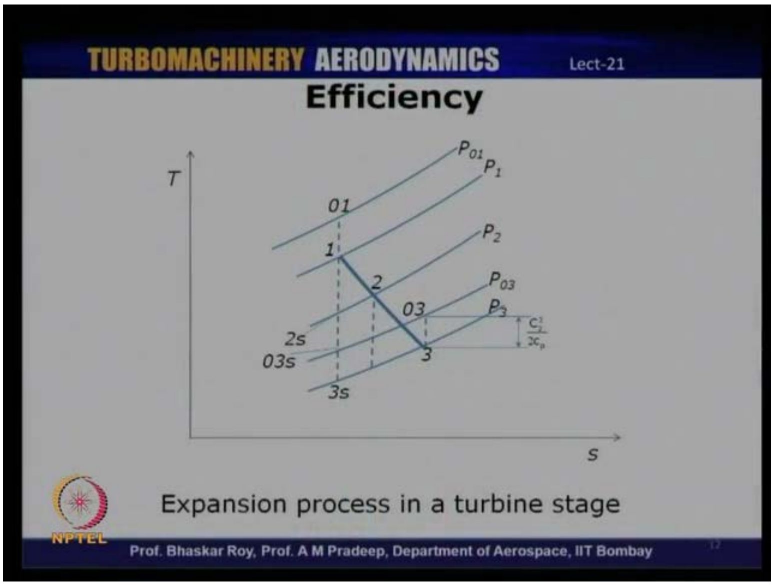
- There are two commonly used turbine efficiency definitions.
  - Total-to-static efficiency
  - Total-to-total efficiency
- The usage of the efficiency definition depends upon the application.
- In land-based power plants, the useful turbine output is in the form of shaft power and exhaust KE is a loss.
- In this case the ideal turbine process would be isentropic such that there is no exhaust KE.

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

So, based on our understanding, we can define two types of efficiencies, Total-to-static efficiency and the Total-to-total efficiency; and which efficiency definition to use will basically be determined by the application for which the turbine is being used. So, in let us say the land based power plant as I mentioned, the turbine output is a basically in the form of shaft power that is the turbine is connected to a generator which generates work out a electricity, and therefore, exhaust kinetic energy is is basically considered as a loss. Therefore, in such a case, the ideal turbine process would be isentropic such that there is no exhaust kinetic energy, that is the exhaust itself is static and there is no kinetic energy associated with that exhaust, and that is where we would define, what is known as Total-to-static efficiency.

In aero engines, the turbine exhaust is required to have certain amount of energy, which will further be expanded in a nozzle to generate a thrust. So, there you would not want to expand the turbine to such a level that it is static at the exit and very little kinetic energy, but you would like that some more kinetic energy left, which can be expanded further in a nozzle. So, there you would normally define the Total-to-total efficiency in such applications. So, let us take a look at a general turbine process or expansion through a turbine, and then we will come up with the efficiency definitions.

(Refer Slide Time: 21:28)



TURBOMACHINERY AERODYNAMICS Lect-21

Efficiency

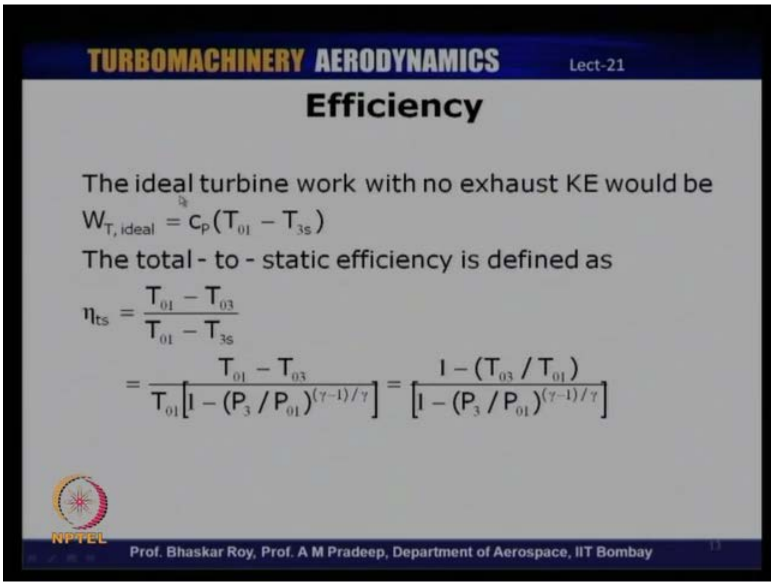
Expansion process in a turbine stage

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

So, this is an expansion process in a turbine stage, while where station 1 is the nozzle entry, 2 is nozzle exit and 3 is the rotor exit. So, 2 is also the rotor inlet. So, the flow initially has a pressure at the inlet stagnation pressure at P 01 and static pressure the entry is P 1. So, P 01 plus P 1 plus the dynamic head gives us P 01; so, we have plotted this on a temperature entropy scale. Now if this entire process were to be isentropic then the expansion takes place along these dotted lines. So, P 01 all the way up to the exit which is 3 s if it were if you are considering a static condition at the exit and so, the actual turbine process of course, is define by this solid line the bold line here between static pressure P 1, static pressure P 2 at the nozzle exit or rotor entry and P 3 at the rotor exit.

The corresponding stagnation pressure at the rotor exit is P 03, which is basically what you have the temperature at station 3 plus the dynamic head C 3 square by 2 C p will give us the stagnation temperature there. Now, the corresponding conditions in the isentropic case would be T 03 subscript s or at the rotor exit which is stagnation, and so, when we are defining efficiency in two different ways that we are going to discuss about; let us first take up the Total-to-static efficiency.

(Refer Slide Time: 23:30)



TURBOMACHINERY AERODYNAMICS Lect-21

Efficiency

The ideal turbine work with no exhaust KE would be

$$W_{T,\,ideal} = c_p(T_{01} - T_{3s})$$

The total - to - static efficiency is defined as

$$\eta_{ts} = \frac{T_{01} - T_{03}}{T_{01} - T_{3s}}$$

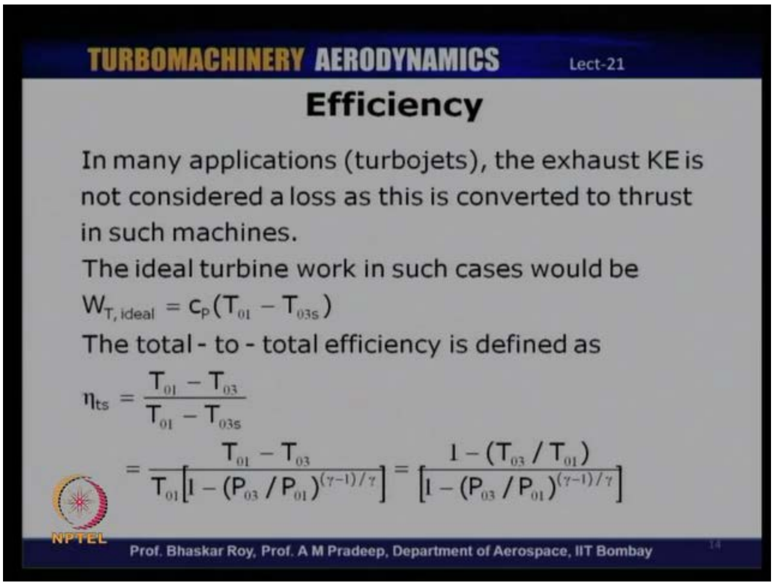
$$= \frac{T_{01} - T_{03}}{T_{01}\left[1 - (P_3 / P_{01})^{(\gamma-1)/\gamma}\right]} = \frac{1 - (T_{03} / T_{01})}{\left[1 - (P_3 / P_{01})^{(\gamma-1)/\gamma}\right]}$$

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

Now, in this case, we are talking about an ideal turbine work with no exhaust kinetic energy, which means that we have expanded all the way up to the station, which is given by this particular stage. So, from 01 all the way up to the station, and which means there is no more kinetic energy at the exit of the turbine. So, we have the ideal turbine work in this case would be C p times T 01 minus T 3s.

So, the Total-to-static efficiency in this case is defined as the… it is denoted by symbol eta t as which is Total-to-static. T 01 minus T 03 divided by T 01 minus T 3s that is T 01 minus the temperature corresponding to this T 03 divided by T 01 minus T 3s. So, that is the Total-to-static efficiency. The denominator we are going to simplify, because this is an isentropic temperature here; so this can be expressed in terms of the corresponding pressure ratios, and so we have T 01 minus T 03 at the numerator divided by T 01 into 1 minus P 3 by P 01 raise to gamma minus 1 by gamma, this follows from the isentropic relation. So, this is basically 1 minus T 01 by T 03 divided by 1 minus P 3 by P 01 raise to gamma minus 1 by gamma. So, this is the basic definition of Total-to-static efficiency.

(Refer slide Time: 25:05)



TURBOMACHINERY AERODYNAMICS Lect-21

Efficiency

In many applications (turbojets), the exhaust KE is not considered a loss as this is converted to thrust in such machines.

The ideal turbine work in such cases would be

$$W_{T,\,ideal} = c_p(T_{01} - T_{03s})$$

The total - to - total efficiency is defined as

$$\eta_{ts} = \frac{T_{01} - T_{03}}{T_{01} - T_{03s}}$$

$$= \frac{T_{01} - T_{03}}{T_{01}\left[1 - (P_{03}/P_{01})^{(\gamma-1)/\gamma}\right]} = \frac{1 - (T_{03}/T_{01})}{\left[1 - (P_{03}/P_{01})^{(\gamma-1)/\gamma}\right]}$$

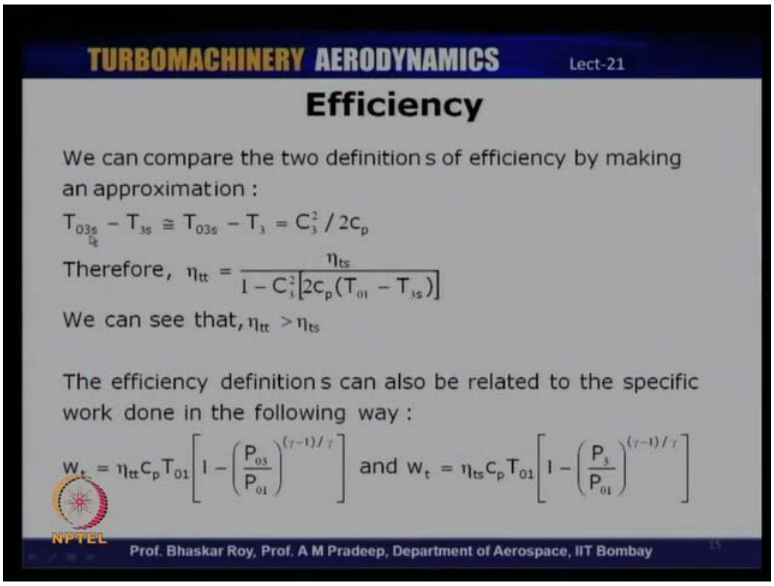
Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

14

Now if you look at an applications, typical application being turbojet engine where the exhaust kinetic energy not really a loss, it can be converted to thrust using a nozzle. So, in such cases, the ideal turbine work is not equal to the static conditions at the exit, but the stagnation conditions. So, the ideal work in such cases would be C p times T 01 minus T 03s and therefore, we define Total-to-total efficiency which is eta t t that is T 01 minus T 03 divided by T 01 minus T 03s and again the denominator we will express in terms of pressure ratios because of isentropic, we have 1 minus T 03 by T 01 divided by 1 minus P 03 by P 01 raise to gamma minus 1 by gamma.

So, we have defined two forms of efficiencies, the Total-to-static to static efficiency and Total-to-total efficiency; we can also now relate these two types of efficiencies, and see how these efficiencies can be compared, for the same type of… For the same configuration; if you were to compare these two different forms of efficiency of course, with certain assumptions, we can still compare Total-to-static efficiency and Total-to-total efficiency, and we will also see how using these efficiencies, we can calculate work done by a given turbine.

(Refer Slide Time: 26:40)



TURBOMACHINERY AERODYNAMICS Lect-21

Efficiency

We can compare the two definitions of efficiency by making an approximation :

$T_{03s} - T_{3s} \cong T_{03s} - T_3 = C_3^2 / 2c_p$

Therefore, $\eta_{tt} = \dfrac{\eta_{ts}}{1 - C_3^2 \left[2c_p (T_{01} - T_{3s})\right]}$

We can see that, $\eta_{tt} > \eta_{ts}$

The efficiency definitions can also be related to the specific work done in the following way :

$$w_t = \eta_{tt} c_p T_{01} \left[1 - \left(\frac{P_{03}}{P_{01}}\right)^{(\gamma-1)/\gamma}\right] \text{ and } w_t = \eta_{ts} c_p T_{01} \left[1 - \left(\frac{P_3}{P_{01}}\right)^{(\gamma-1)/\gamma}\right]$$

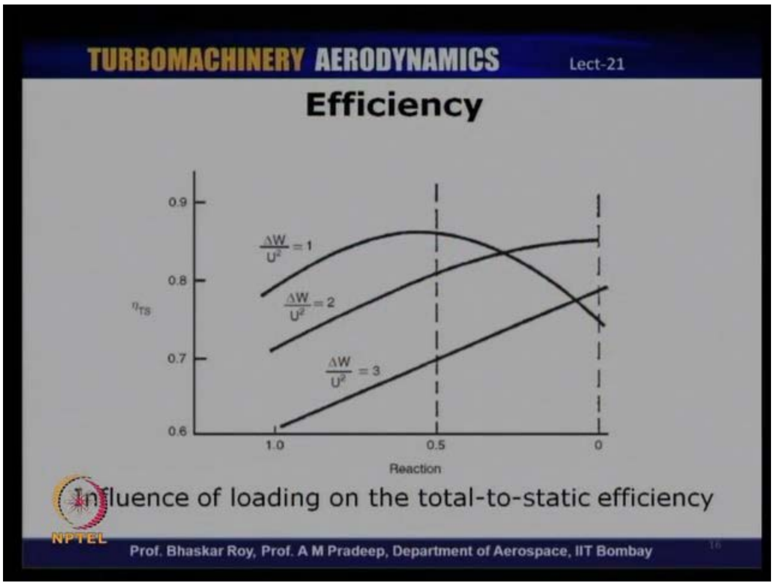
Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

So, if we if we were to make an approximation that T 03s minus T 3s is approximately equal to T 03s minus T 3 is equal to C 3 square by 2 C p which is let me go back to the diagram here. So, what we are saying is the difference between T 03 s minus T 3s and this and T 3 s is C 3 square by 2 C p; so which means that the effectively T 03s and T 3 they are not much different as you can see from this T-s diagram itself. So, it is a very much a valid assumption that we can make, and so if this this were to be the case, if you make this assumption, then we can relate Total-to-total efficiency as equal to eta ts divided by 1 minus C 3 square multiplied by 2 C p T 01 minus T 3s.

So, what you can see here is that if this assumptions were to be true, and you calculate the Total-to-total efficiency and Total-to-static efficiency for a turbine, we could see that the Total-to-total efficiency is likely to be greater than the Total-to-static efficiency which is also obvious from the T-s diagram that I had shown; if you look at the expansion process for the same turbine, if you calculate both these efficiencies, the Total-to-total efficiencies is likely to be higher than the Total-to-static efficiency. Now, so using these definitions one can also calculate or make use of these definitions to calculate the corresponding work done by the turbine depending upon the application itself.

So, if you were to use the Total-to-total efficiency then we have the work done or specific work done as in case where let us say in an application of gas turbine engine used in aero aircraft engine like an turbojet, then the work done by the turbine is related to the efficiency, which is Total-to-total efficiency multiplied by C p into T 01 into 1 minus P 03 by P 01 raise to gamma minus 1 by gamma and similarly, the work specific work related to the Total-to-static efficiency as eta t as into C p T 01 one minus P 3 divided by P 01 raise to gamma minus 1 by gamma. So, using the efficiency definitions and this specific applications for which these efficiencies have been define for we can use this efficiencies to calculate the corresponding work done by turbine the under this or different applications. So, let me give you one example to just indicate the effect of reactions.

(Refer Slide Time: 29:32)



TURBOMACHINERY AERODYNAMICS Lect-21

Efficiency

Influence of loading on the total-to-static efficiency

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

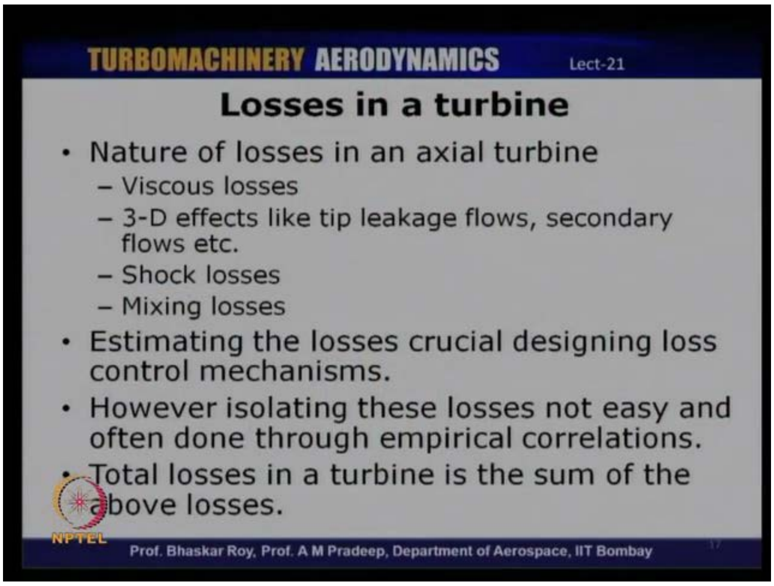
I think, I have mentioned when I was talking about impulse and reaction turbines that both these turbines in the last class, as well as I mentioned that there is a difference in specific work done and loading that both of these different types of turbines can handle, and also the fact that there is a certain difference in the efficiencies that one would get by using these two different configuration of turbines. So, let us take a look at the influence of loading on the efficiency, we will in this case, calculate Total-to-static efficiency; So, you have reaction on the x axis, the efficiency Total-to-static efficiency on the y axis and three different values of loading. So, one can see that as you increase the loading and keep changing the reaction what happens to the efficiency.

So, let us take a look at one of these cases, where let us say loading factor is equal to 1. So, as you change the reaction on the extreme right, we have an impulse turbine, which has a reaction of 0. So, as we start from an extreme, which is an impulse and we move towards, let say a 50 percent reaction case, you can see that there is a steady increase in the efficiency and after that of course, there is a drop in the efficiency this is for loading factor is equal to 1.

Now, if you look at a loading factor greater than 1, let us say loading factor of 2 or 3, then the trends or slightly different; in fact, you get the highest efficiency when the the reaction is equal to 0, that is for an impulse turbine stage, that is with higher amounts of loading your impulse turbine stage as a better efficiency than any other case of reaction, because the moment you have any amount of reaction it is no longer an impulse, it it basically becomes a reaction turbine and that is also true for higher values of loading between 2 and 3 and so on; and so, this is just to give some idea about what happens as we change the amount of loading with increase levels of loading, how does reaction influence the efficiency this is also linked to a comment add made earlier I would want you to think about why is it that as you increase the loading, an impulse turbine seems to at least perform better in terms of an efficiency, and what is the effect of increase in loading on let us see the efficiency of the turbine as you keep changing the level reaction from impulse which has 0 reaction; let us say to 50 percent reaction where the reaction is the enthalpy drop is equally shared by the nozzle and the rotor.

So, just give it a thought on why there should be drop in efficiency, as you move from impulse towards higher levels of reaction. So, let us move on to the next topic, we have for discussion in today’s class that is to do with losses in a turbine. I mentioned in the beginning that I will restrict the discussion to just the basics of losses, because I already had a detailed discussion on losses; when we are talking about compressors, and so most of the concepts, we have discussed there is applicable for the turbine as well; of course, the magnitude of the losses will be quite different for compressors and turbines, but the concept is still the same. So, I will not repeat the estimation of losses that we had discussed in detailed with reference to a compressor, because it is applicable for a turbine.

(Refer Slide Time: 33:31)



TURBOMACHINERY AERODYNAMICS Lect-21

Losses in a turbine

- Nature of losses in an axial turbine
  - Viscous losses
  - 3-D effects like tip leakage flows, secondary flows etc.
  - Shock losses
  - Mixing losses
- Estimating the losses crucial designing loss control mechanisms.
- However isolating these losses not easy and often done through empirical correlations.
- Total losses in a turbine is the sum of the above losses.

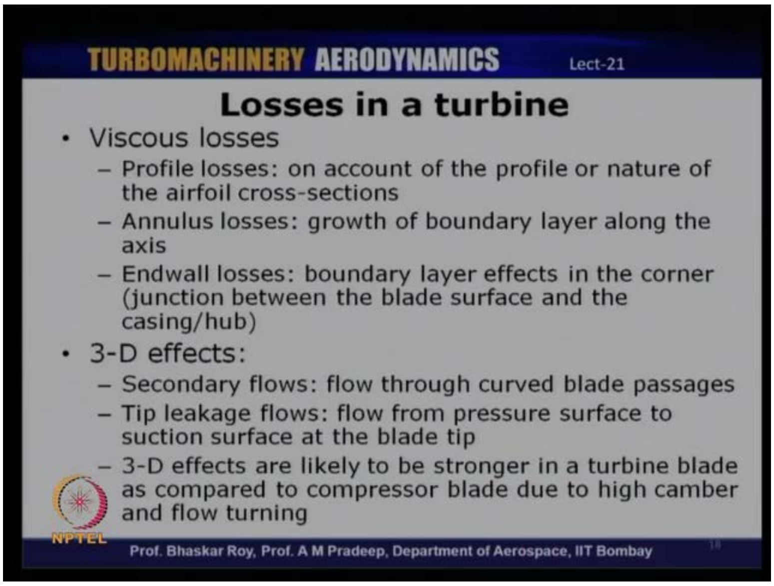
NPTEL

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

Now, when I discuss about compressors and losses in a compressor, I had mentioned that there are distinct forms of losses. They are basically we could classify losses as four sets of losses, one is on account of viscous effect are known as the viscous losses ,then there are three-dimensional effect like tip leakage flows and secondary flows; one may have shock losses and also mixing losses, and so if you were to isolate these losses, because if you have to estimate losses in a turbine and one would like to target, let us say different forms of these losses, and see if we can minimize these losses, one would need to know, let us say what is contribution of discuss loss, what is the contribution of 3-D losses like secondary flows or tip leakage flows and so on.

But, it is not very easy to segregate these different losses. There are empirical correlations for estimating all these different forms of losses; we had discussed some of them in in the context of compressors, one could extend the same for turbines as well. Total losses in a turbine obviously, is the sum total of all these different forms of losses, whether it is viscous loss or 3-D losses, which includes secondary flows and tip leakage flows, shock losses and the mixing losses.

(Refer Slide Time: 34:58)



TURBOMACHINERY AERODYNAMICS Lect-21

Losses in a turbine

- Viscous losses
  - Profile losses: on account of the profile or nature of the airfoil cross-sections
  - Annulus losses: growth of boundary layer along the axis
  - Endwall losses: boundary layer effects in the corner (junction between the blade surface and the casing/hub)
- 3-D effects:
  - Secondary flows: flow through curved blade passages
  - Tip leakage flows: flow from pressure surface to suction surface at the blade tip
  - 3-D effects are likely to be stronger in a turbine blade as compared to compressor blade due to high camber and flow turning

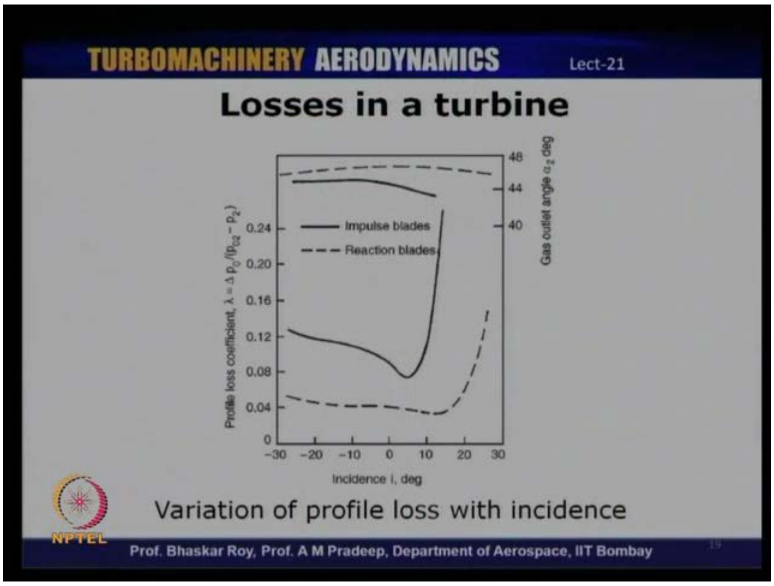
NPTEL

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

So, let us look at these losses in little more detail, but not too much as I had mentioned, some preliminary discussion on these losses; if you look at viscous losses, there are again differ components of viscous losses; there is one, on account of the profile or the nature of the airfoil cross section, and that is known as the profile loss. Annulus loss would refer to growth of boundary layer along the axis and end wall losses on account of boundary layer effects in the corner or junction between the blade surface and the casing or hub. Now, in 3-D effects, we have a secondary flow which is on account of flow through curved blade passages; tip leakage flows, which is basically the flow leaking from the pressure surface to the suction surface, and what is generally observed is that if you look at the 3-D effects, the losses are likely to be higher for the turbine in primarily, because of the fact that the flow turning is much higher in a turbine as compare to a compressor.

Secondary flow for example, is directly related to the amount of flow turning, and if you compare a compressor with that of a turbine, the flow turning in a typical turbine blade is much higher than that of compressor. Secondary flows are likely to be much higher in in the case of turbine; this is also true for the tip leakage flows, basically, because tip leakage is on account of the difference between the pressure surface and the suction surface and blade loading is usually much higher in a turbine than in compressor and therefore, leakage flows are are also likely to be higher in the in turbine and what complicate matter in a turbine is the fact that you also have higher temperature, and it is no longer just for your air, you also have a combustion product coming in from the combustion chamber which might complicate the flow behavior in the case of a turbine. Now, let me just give you one example of profile loss, I will as I mentioned, I am not going to details of estimating all these losses, we have done that for the compressor and you could easily extend that to the turbine as well.

(Refer Slide Time: 37:06)



TURBOMACHINERY AERODYNAMICS Lect-21

Losses in a turbine

Variation of profile loss with incidence

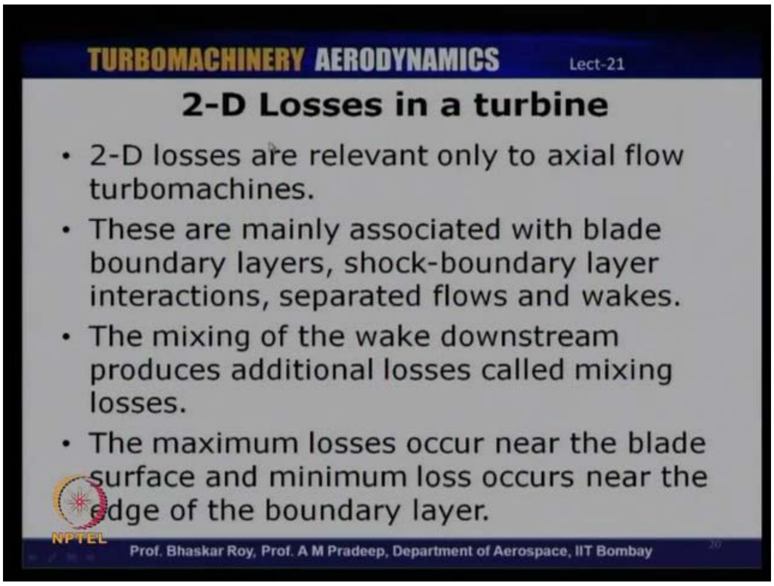
Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

Now, if you look at, let say the profile loss, and look at what happens as you keep changing the incidence? Now, I have these profile loss distribution for two distinct cases of impulse turbine and the reaction turbine. The solid line refers to the impulse turbine, and the dotted line is for reaction turbine. So, one can see that there is a significance difference between what happens in an impulse turbine and reaction turbine, the losses as you can see are much higher for an impulse turbine case and that vary significantly with the incidence. So, the sensitivity of impulse blades to incidence is much higher, especially positive incidence, you can see that after a round 8 or 9 degrees the losses increase substantially; there is a very sharp increase in losses at positive incidence around 8 or 9 degrees of course, this is for a very typical case of a turbine blade; on the other hand, if you look at the reaction blade, it is properly a little better adjusted to higher changes in incidence; of course, with very high incidence exceeding 20 degrees, there is of course, very steam increase in the losses even in a reaction stage, but if you look at the performance of a typical reaction blade it is not very sensitive incidence between let us say plus minus 10 degrees, whereas an impulse blade is quite sensitive to incidence and especially at positive incidence angles.

We also have alpha 2 plotted for both these cases, what we can see is that alpha 2 remains more or less well behaved, whether it is impulse or reaction turbine. Even though the incidence is different, the basic reason for this being true is the fact that in both impulse as well as reaction blade the flow is encountering an accelerating flow a favorable pressure gradient. So, even if there is higher level of incidence of the flow entering the nozzle, because it is an accelerating flow the flow is generally well behaved, which is unlike in a compressor where is the flow encounters an adverse presser gradient, and so the outflow would be extremely sensitive to the in incidence angle as well that is if incidence varies between a beyond a certain range the outflow angle also correspondingly changes drastically, because of the fact that the flow is encountering and adverse pressure gradient and so, the chances of flow separation is substantially higher, in in the case of a compressor which is not true for a turbine where the flow is almost always encountering a favorable pressure gradient and therefore, that partly explains why the gas outflow angle alpha 2 really does not change much and the the insensitivity of outflow angle is larger much larger for a turbine as compare to that of a compressor.

Now, if you if you now, we come back to the the types of losses in a turbine, if you recall when we discuss about losses in a compressor. We had classified them into two distinct sets of losses, one is to do with 2-D losses and one is to do the 3-D effects, like secondary flows and and so on. Now, if you look at just the 2-D losses for which the lot of empirical correlations available.

(Refer Slide Time: 41:15)



TURBOMACHINERY AERODYNAMICS Lect-21

2-D Losses in a turbine

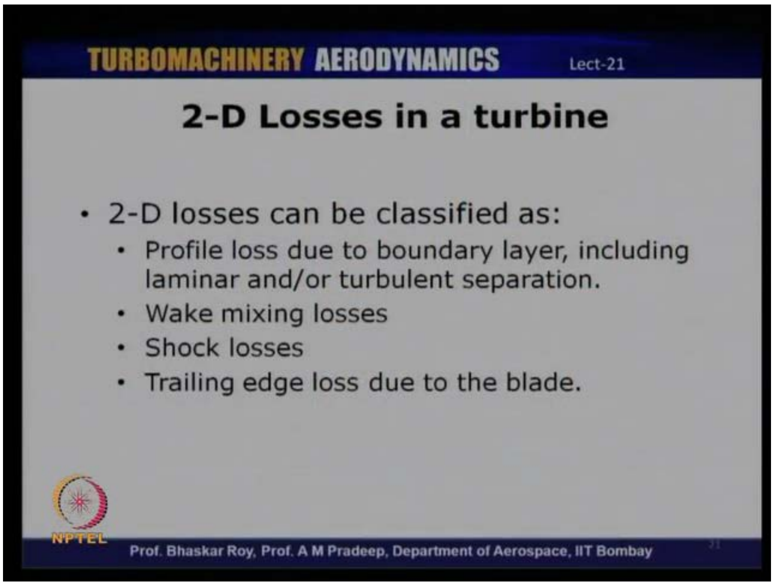
- 2-D losses are relevant only to axial flow turbomachines.
- These are mainly associated with blade boundary layers, shock-boundary layer interactions, separated flows and wakes.
- The mixing of the wake downstream produces additional losses called mixing losses.
- The maximum losses occur near the blade surface and minimum loss occurs near the edge of the boundary layer.

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

2-D losses basically are relevant to axial flow turbo machines and you have seen that in a compressor as well as that when you are discussing about axial compressors that if you if you look at 2-D losses, they are mainly associated with the blade blade boundary layers, shock boundary-layer interactions, separated flows and the wakes. some of these are of course, not really that significant for a turbine for example, these separation or blade boundary layers, which are fairly well behaved in the case of turbines and separation on the other hand; in in certain operating conditions, one might have a lead leading edge separation bubble in the rotor, but that is the the chances of such occurrence are very less there; unlike in the case of compressors where boundary layer behavior is always a concerned because of pressure gradients.

So, mixing of these wakes that come from the rotor blade with the nozzle downstream of the nozzle second next stage; obviously, creates a certain amount of losses and that is of course, something that can be estimated by mixing loss models which are available from which one can estimate to a certain amount of accuracy what is the effect of these wakes shut from the rotor on subsequent stages. So, if we look at 2-D losses in particular, we can classify two-dimensional losses into different forms.

(Refer Slide Time: 43:02)



TURBOMACHINERY AERODYNAMICS Lect-21

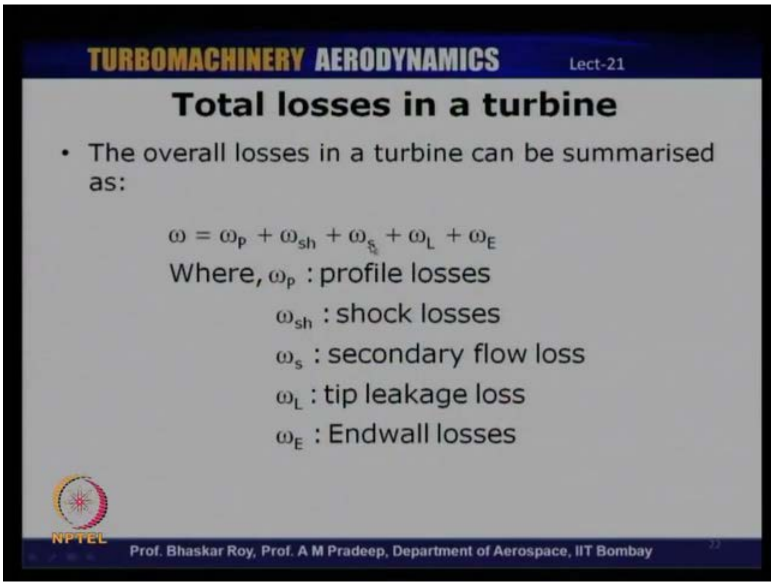
2-D Losses in a turbine

- 2-D losses can be classified as:
  - Profile loss due to boundary layer, including laminar and/or turbulent separation.
  - Wake mixing losses
  - Shock losses
  - Trailing edge loss due to the blade.

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

We have profile loss to tip the boundary layer and its effect and whether you have laminar or boundary layer separation which is of course, rather rare in the case of turbines, one may have wake mixing losses because of the wake from the rotor interacting with the subsequent stages. One may also have shock losses, which I will also discuss little more detail in the later slide and of course, the trailing edge loss due to the blade because trailing edge is usually rounded as we have seen in compressors, one may have to provide a certain rounding at the trailing edge there is certain amount of loss associated with that rounding as well.

(Refer Slide Time: 44:00)



TURBOMACHINERY AERODYNAMICS Lect-21

Total losses in a turbine

- The overall losses in a turbine can be summarised as:

$$\omega = \omega_p + \omega_{sh} + \omega_s + \omega_L + \omega_E$$

Where, ω_p : profile losses

ω_{sh} : shock losses

ω_s : secondary flow loss

ω_L : tip leakage loss

ω_E : Endwall losses

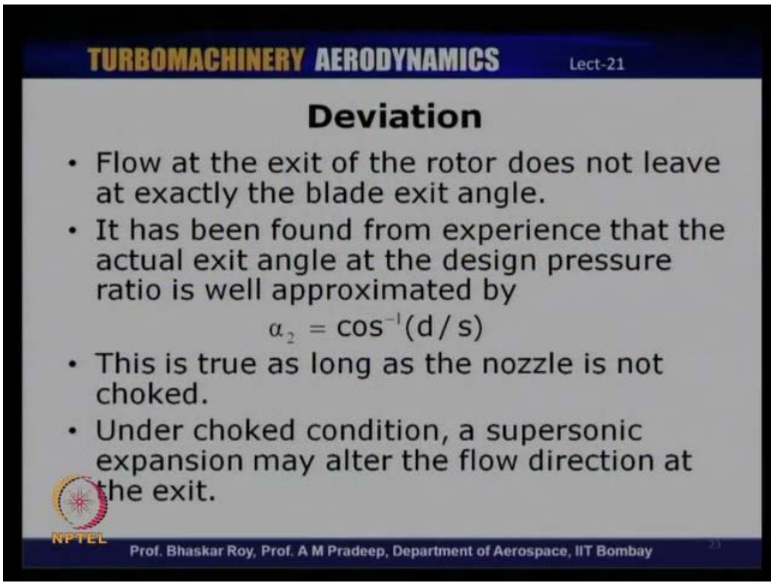
Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

So, the total a turbine like in the case of compressor is obviously, a sum total of all these different components. So, without going into details of how to estimate these losses, we can just summarize that the overall losses in a turbine is a sum total of all these different forms losses. One may have profile loss on account of the nature of the blade surface itself, one may have shock losses and secondary flow losses which can be quite significant in turbines tip leakage loss and of course, end wall losses.

So, if you make of comparison of these with a compressor, let us say a transonic compressor where also you may have a shock losses. The major distinguishing factor between turbine and a compressor in terms of losses would be the 3-D effects which are likely to be much more significant in a turbine like secondary flows and tip leakage flows as compare to a compressor where of course, these losses are still present, but if you were to make a one to one comparison The losses in in the case of a turbine when it comes to secondary flows and tip leakage flows are likely to be higher.

But of course, there are methods of controlling some of these in a turbine, because many of the turbine blades also have cooling mechanisms which again we will discuss in detail in later lectures. So, some of these cooling holes are also sometimes used to minimize let us say the tip leakage flows or secondary flows in some way or the other, we will discuss that in in some of our later lectures.

(Refer Slide Time: 45:13)



TURBOMACHINERY AERODYNAMICS Lect-21

Deviation

- Flow at the exit of the rotor does not leave at exactly the blade exit angle.
- It has been found from experience that the actual exit angle at the design pressure ratio is well approximated by

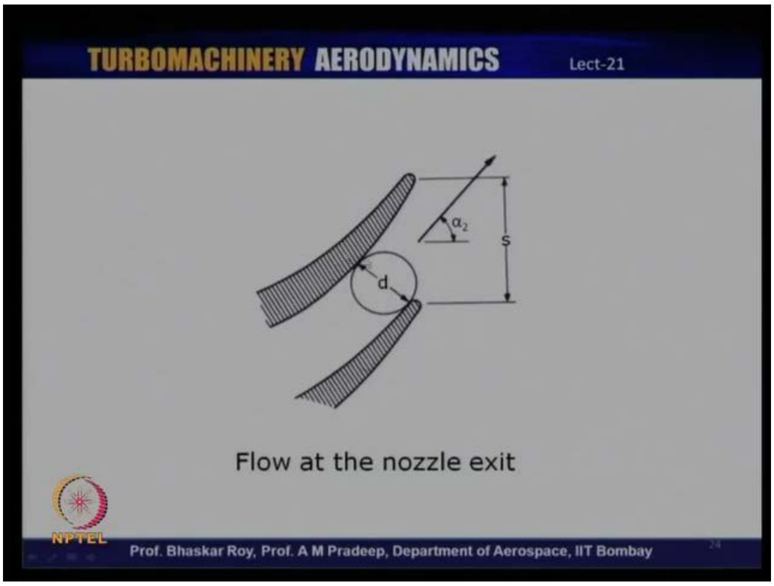
$$\alpha_2 = \cos^{-1}(d/s)$$

- This is true as long as the nozzle is not choked.
- Under choked condition, a supersonic expansion may alter the flow direction at the exit.

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

Now, there is another aspect, I wanted to have some discussion on that is to do with deviation and I will probably spend a couple of slides on this aspect as well. Now, this is also true with in the case of compressors, and then it is an it is an own fact that when the flow exiting the rotor does not really leave the blade at the angle for which it has been designed for. But it of course, in the case of turbines it is the easier to estimate the out flow angle, because the flow is encountering an accelerating flow passage and if the flow is not basically choked or if there are no shocks present at the exit of the rotor, then it is the exit of the nozzle it is relatively easier to estimate the amount of the outflow the gas outflow angle from the nozzle. But of course, if there are shocks present that something which I will show you little later then the outflow angle can be quite different from from what it has been basically designed for. So, what what is basically found from experience is that the actual exit angle at the design pressure ratio can be fairly well estimated by cos inverse of d by s as long as the nozzle is not chopped.

(Refer Slide Time: 46:35)


TURBOMACHINERY AERODYNAMICS

Lect-21

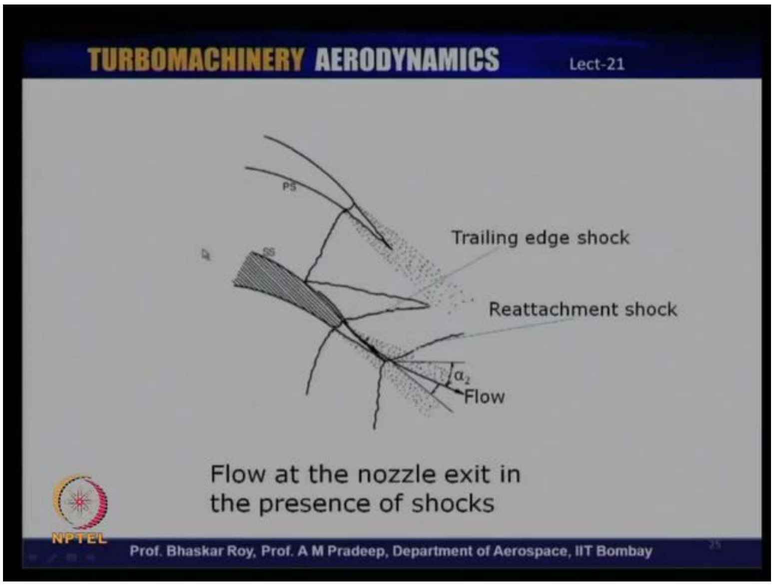
Flow at the nozzle exit

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

Let me just explain what I mean by cos inverse of d by s. So, if you look at typical nozzle exit flow when I had shown a picture of the cascade, I had mentioned that this is basically the throat of the nozzle and and the flow exits the nozzle at an angle of alpha 2. So, if you look at the pitch at the trailing edge which we have denoted by s and this is the throat and which is denoted by d, then one can estimate the the outflow angle the gas out flow angle alpha 2 as what is shown here that is cos inverse of d by s that is if you take an inverse of of course, that is still an approximation, but it is found that it is fairly well the approximation fairly well captures the at the angle at which flow exits the nozzle. Now, this is true as long as the nozzle is not choked, because once it choked the nozzle is choked operating under choked conditions then there is a possibility that at the outflow is supersonic which means that there is a possibility of the presence of shocks at the exit or trailing edge of the nozzle.

Presence of shocks can deflect the flow and causes certain amount of deviation and in such cases of course, you one cannot really estimate the angle exiting the nozzle as cos inverse d by s. So, if you look at a case where there is the flow is not choked it is unchoked, then is obviously, there is no the flow is not supersonic at the exit of the nozzle, and which means that the flow angle can be basically well estimated by just taking the inverse of d by s.

(Refer Slide time: 48:36)



TURBOMACHINERY AERODYNAMICS Lect-21

Flow at the nozzle exit in the presence of shocks

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

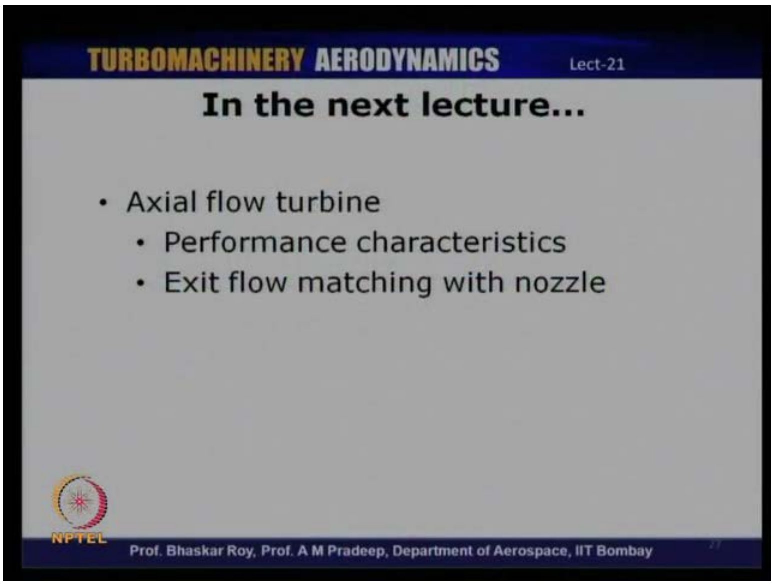
Now, if you look at the other case where there is a possibility of shock, in which case it is basically choked flow after the throat, because it is if you let me take you back here. After the throat you may have an expansion here which might cause the flow to become supersonic, if the back pressure is low enough, then you may have it is basically acts like a converging diverging nozzle, and one may have shocks emanating from downstream of the throat. If there is a trailing edge shock exiting at the flow exiting the nozzle, then the presence of the shocks obviously, can deflect the flow to differ angle. So, as you see here the flow is not really exiting at an angle that it was design for the presence of the shocks, there is a trailing edge shock or reattachment shock and so on; the presence of the series of shocks can cause the flow to get deflected or deviated at an angle which is quite different from what it has been design for.

So, in such cases as what you see here the angle alpha 2 is not well established or estimated by simply talking at d by cos inverse of d by s; of course, there are also a empirical correlations in this case to estimate the flow angle, because if you know the shock structure of the flow leaving the nozzle from the analysis of the flow through these different shocks, one can sort of estimate what is the angle at which the flow is leaving the nozzle, but that requires a much more complicated analysis than simply taking considering just the geometric parameters and estimating the exit flow angle to be a function of these geometric parameters.

So, in the presence of supersonic flow where there are shocks present, the flow structure is obviously, more complicated, and the flow undergoes deviation, which is more quite different from what one can otherwise easily estimate. So, I just brought up this aspect of deviation, because of the fact that in nozzle flow there is a possibility that the flow exiting nozzle can be supersonic, and therefore, the flow might undergo a deviation which is quite different from what is has been primarily design for which means that this flow entering into the rotor basically has a different angle than what is been design for and therefore, one needs to construct this aspect into account when estimating the flow through the entire stage.

Let me now quickly recap our discussion in today’s class; we had discussion on three distinct topics; We started off with degree of reaction, and I spent some time discussing about degree of reaction it significance, and how one can estimate degree of reaction and based on this estimation, how one can determine the configuration of the turbine whether it is in impulse or reaction and so on; we then spend some time discussing about losses the different type of losses the 2-D losses and 3-D losses, and I mentioned that there are certain aspects of losses which or the contribution of these different sources of losses is different in the case of turbine and a compressor, because of the very nature of flow passing through a turbine or compressor. We also discussed about the efficiencies and different definitions of efficiency, the Total-to-static efficiency and the Total-to-total efficiency, which is what we discussed in detail today and of course, towards end; I also discussed about the aspect of deviation, which is of significance especially, when the flow is unchoked, and especially when the flow is choked, and the flow exiting the nozzle is supersonic.

(Refer Slide Time: 52:47)



TURBOMACHINERY AERODYNAMICS Lect-21

In the next lecture...

- Axial flow turbine
  - Performance characteristics
  - Exit flow matching with nozzle

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

We will continue our discussion on axial flow turbines in the next lecture, we will basically be talking the performance characteristics of an axial flow turbine, and how one can match the exit flow from a turbine with a downstream component like a nozzle. So these are two aspects that we will be discussing in the next lecture, which would be lecture number 22.

.