Turbomachinery Aerodynamics

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Lecture No. # 37
Radial Turbine Characteristics And
Design of Radial Turbines

We are talking about radial flow turbines. And, in today's lecture, we will be looking at some of the issues related to the overall characteristics of radial flow turbine, and how, one goes about designing a radial flow turbine. Now, radial flow turbines, as you have done in the last few lectures and we have solved some problems also. It has given you an idea that radial flow turbine is a robust machine like centrifugal compressor, but it has a few limitations of its own.

And, one of the things is that, its ability to produce work is not substantially more than axial flow turbine, as it was; for example, in case of centrifugal compressor, which had an ability to produce work per unit mass flow is substantially more than axial flow compressors. So, the difference between radial flow turbine and axial flow turbine is not as much as, it was between axial flow turbine and centrifugal compressor.

Now, radial flow turbine as you have seen is somewhat, you know, it look like and its flow is inverse that of a centrifugal flow compressor. And, in some books indeed, it is also referred to as centrifugal turbine. But, most people prefer to call it radial turbine. And, the one that we are looking at very closely is radial inflow turbine because there have been few radial outflow turbines that have been designed and have been worked really speaking. But, radial inflow turbine is, as been done in the last lectures is a substantially superior machine, it has ability to produce more work per unit mass flow. And, of course it lends itself to very high temperature and very fast motion or movement of flow of gas through the machine, as it is normally done in gas turbine engines that are used in land based or aeronautical applications. So, many of these issues put together for most practical applications; both aeronautical as well as non-aeronautical. The radial flow in flow turbine is the more preferred form of machine.

Now, we will look at some of the characteristic features of this radial inflow turbine. And, those characteristic features will also leads us towards how one goes about designing a radial inflow turbine, and what are the primary design considerations that govern the design of a radial inflow turbine right from the beginning, right from scratch, where you have really nothing. And then, we will indicate that under certain circumstances when a design is first cut, good design has been made. One can go to CFD to get a fine tuning of the design.

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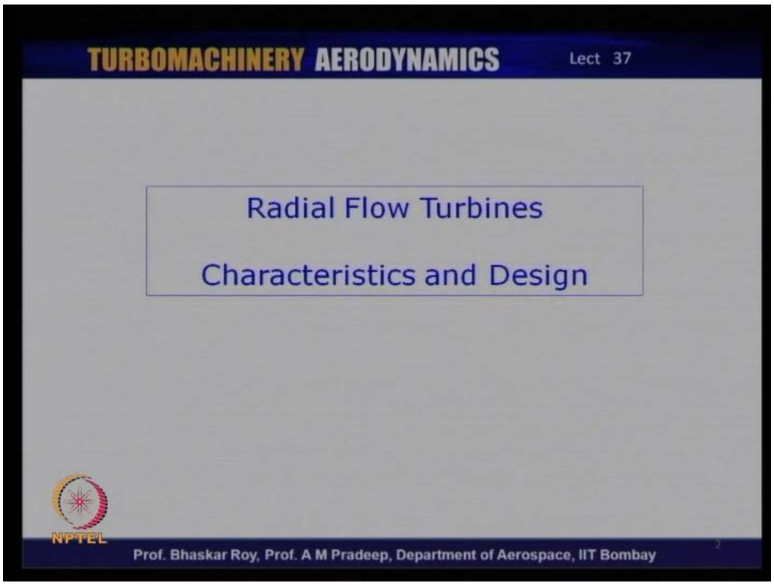

So, let us first take a look at what is a radial flow turbine, which you have done in the last few lectures and then from there, we will look at the basic characteristics of radial flow turbine. So, in today's class we are doing radial flow turbines, its overall characteristics, and how that leads us towards its design features.

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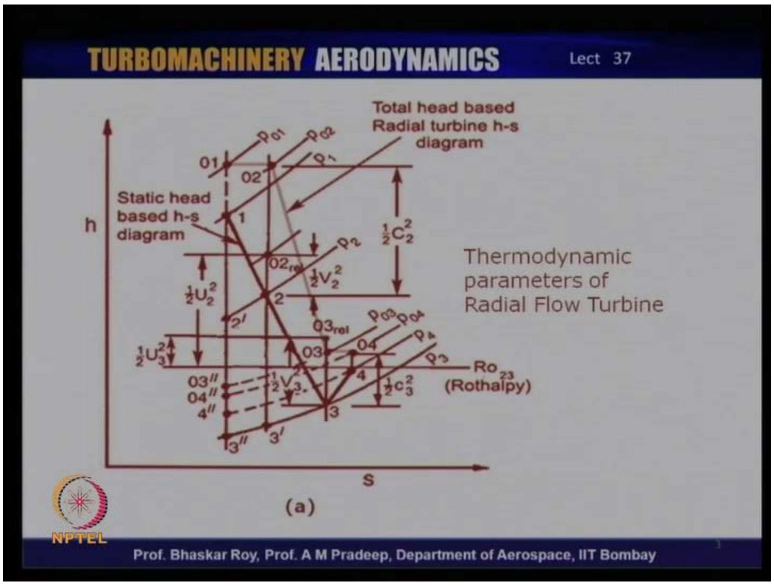

Now, let us take a quick look at what you have done already in the last couple of lectures. The h-s diagram, you may have done t-s diagram, but it quickly captures all the things that are happening inside. The flow is coming in at 0 1 and then going through the nozzle from 01 to 02 and then it produces work, which brings the enthalpy each down from 02 to 03. And then, of course you may have a small bit of diffusion from 0 3 to 0 4 essentially, aerodynamic method to conserve and make use of the available energy level.

So, at the exit, the flow from the rotor is going out with a velocity C 3 squared. And, this is something, which one has to decide because the incoming energy into the rotor is C 2 or half C 2 square, is the energy level from which it comes down to of C3 square. And, this drop in kinetic energy level accompanied with this drop in overall total enthalpy from 0 2 to 0 3 signifies the amount of work that is produced by the radial flow inflow turbine. And, of course this graph here shows the real flow as you have done before. The straight graph of course, signifies the isentropic flow as it would have been if the entire process was totally isentropic.

So, all the parameters that you have done are sort of captured over here. And, one can probably relate to the some of the things that you have done in the earlier lectures. And, the flow, the radial turbine actually moves with a speed of U 2 at the tip of impeller and U 3 at the exit face of the impeller.

So, these are the parameters, which we would have to deal with during the design process and that is why, we are having a quick recap of what has already being done in the earlier lectures.

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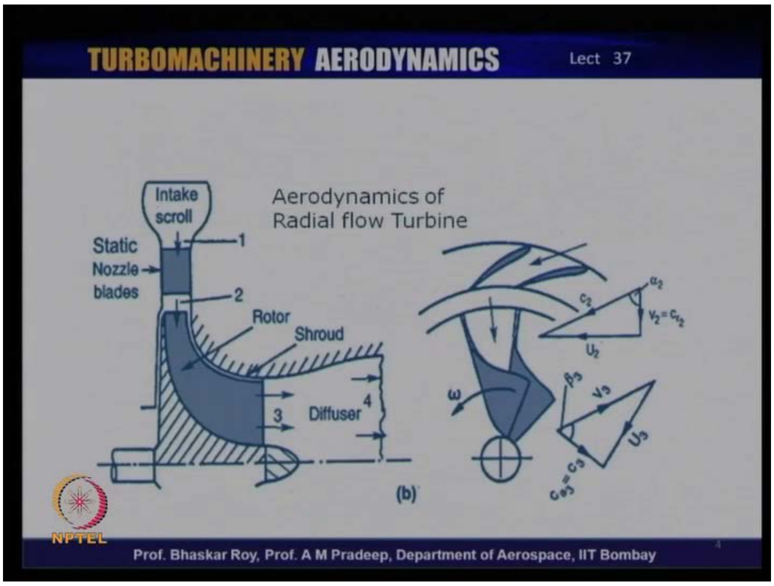

Now, this is of course, the picture that you are familiar with; that the flow comes in from the tip over here. So, first we have a stator nozzle, and then through the stator nozzle, flow gets accelerated hugely and is fed into this rotor, which has a shape like this; and that is why, it is called a radial inflow turbine. So, the flow comes in radially and then of course, exits axially or more or less axially and gets fed into quite often a small diffuser. So, the flow has been accelerating all the way. And, after it has left the machine, quite often a small bit of diffusion is done, essentially to ensure that the pressure at the end of the diffuser meets the destination pressure. And, if that is a little on the higher sides it allows the pressure at 3 to be lower. If the pressure at 3 is lower than the pressure drop between 2 to 3, can be a little more. So, this little more pressure drop allows more work to be done. So, allowing a diffuser to be stationed here or placed here, allows P 3 to go lower and that allows the turbine to do a little more work.

Now, this is what, has been done in the earlier lectures. These are, of course velocity diagrams. This is at the entry to impeller and this is at the exit of the impeller. So, you have to create this jet C 2 through this stator nozzle. Stator nozzle is essentially positioned there, to create this jet and then of course, it comes out with an angle with a relative velocity V 3 and absolute velocity axial. So, it is sort of coming in radially in terms of axial velocity and then going out actually again in terms of absolute velocity.

So, some of these things are normally used in most radial turbine design. This is kind of an ideal velocity diagram. And, this is ideal velocity diagram at the exit. The real thing could be a little different. And, of course in off-design, they would be different. But, this is what normally most people are doing in terms of radial inflow turbines.

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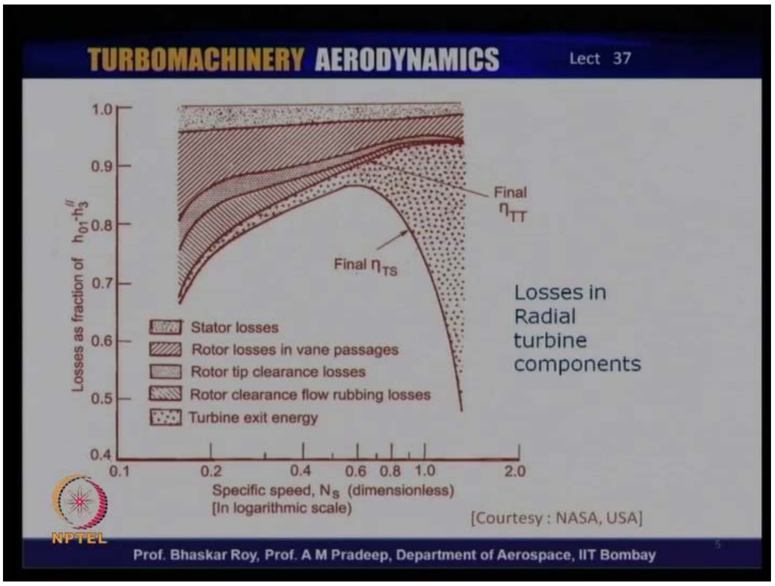

Now, let us take a look at some of the issues that are involved, when you move towards characterizing the radial inflow turbine and its design. Now, this particular up lot for example, tries to capture what are the losses in a radial turbine and its various components.

Now you see, ideally as we have seen in the h-s diagram if the flow is isentropic, then you know there are sort of no losses. So, you know this efficiency ratio that we see over here, is the work done difference between ideal and real that is been captured over here. And, this actually gives a flat characteristic. And then, of course we have the losses. Now the first loss, of course is the stator. And, that in the stator, you can see the loss actually increases with the specific speed, which is a dimensional; a specific speed that has been defined essentially for all kinds of Turbomachinery. And, this of course, reduces with the increase of specific speed. So, let us say that if you increase the speed, the stator losses actually come down. On the other hand, the next shaded area is a rotor loss in the rotating vane passages and that also comes down with the increase of the speed or specific speed as it is plotted here.

Now, this is because once the speed is increased in both the places, the local Reynolds number actually goes up. And, when the Reynolds number goes up, the boundary layer growth actually is reduced substantially as the flow in turbine is accelerating flow. And, when you have a higher Reynolds number, the boundary layer is substantially reduced and hence you have a reduction, essentially in the losses due to reduction in the boundary layer growth. Towards the end, towards a very high specific speed the losses again go up because of the friction losses that go up with very high specific speeds.

So, this slight increase is mainly due to the high speed of the flow, which results in higher friction losses. Then, we have the rotor tip clearance losses. As you know the impeller positioning of the impeller leaves a little clearance at the tip of the impeller between the stator nozzle and the impeller. And, this of course, has a loss penalty that has to be bounded by the machine and comes out in the process of efficiency; however, as you can see the tip losses also go down with the specific speed and it becomes very low at high speeds.

The next is the rotor clearance flow, due to the rubbing of the losses. As the rotor is rotating, the flow that is captured between the rotor and the stator, and the rotor and the body outside the impeller, that is, the shroud, and the back plate; that fluid is captured over there and is continuously being rubbed. It is actually being carried by the impeller. On the other hand, one surface of it is sticking to the shroud body or the shroud surface. So, as a result of this there is a bit of rubbing; that means, the fluid that has been captured there, experiences a shared traction, a share between the layer that is sticking to the surface of the fluid of the shroud or the back plate and the other layer, which is being intended or being carried or being pulled by the rotating impeller.

So, this being captured on one side and being pulled from the other side creates traction in that fluid, which creates large amount of rubbing losses. And then, of course you have a very large amount of turbine exit energy, which always increases with the specific speed or the speed. And, as a result of this you can see towards the end, there is a large amount of exit energy, which is not utilized by the turbine.

So, if you take out all the actual losses over the vanes, then your total-to-total efficiency would have been something like this, and would have continued to increase with the specific speed.

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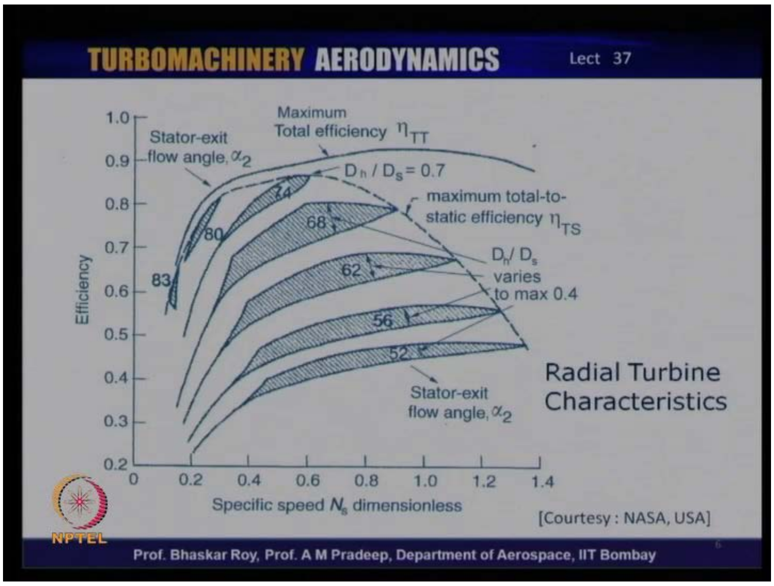

So, total-to-total efficiency, which includes the kinetic energy content of the outgoing gas, actually increases with the specific speed. On the other hand, the total-to-static efficiency starts dropping after a certain time and as a result of which, as you have done in the earlier lectures, in many turbine applications the total-to-static efficiency becomes an important consideration both for design as well as for operation. And, as a result of this, one can see that one may need to peak total-to-static efficiency as operating point, which is not the peak total-to-total efficiency, which is somewhere over here.

So, the differences in the two efficiencies, actually are also figuring in the design selection and in the design choices because they have borne out of the losses and the kinetic energy content of the outgoing gas.

Now, let us take a look at another radial turbine characteristic, which is efficiency verses speed or specific speed. Now, the maximum total-to-static efficiency as you have seen starts falling. As we have seen in the last diagram, it starts falling here and it peaks somewhere over here. And, the maximum total-to-total efficiency as we saw in the last slide keeps going up like that. The stator exit flow angle alpha 2, which as we all know is a very important parameter for turbine design and also radial inflow turbine design, actually it has a high impact on everything that is happening. And, here that angle has been factored in as one of the primary parameters for design considerations.

So, it starts off with the higher angle of 83, 80 and then 74 and 68 and 62 and 56 and 52. So, these are the angles. Quite often, the choice is somewhere between 62 and 74. And in this particular case, for example, it shows that somewhere around 74 degree is alpha 2 and somewhere over here you have the peak of the maximum static total-to-static efficiency, eta T S. And, that could be a good design choice at which the dimensionless specific speed is something like 0.58 little less than 0.60 and that, and then becomes your design choice.

Now, at that design choice, the other thing that needs to be looked into is the diameter ratio; the hub to shroud diameter ratio at the exit face of the impeller, which as we have just seen that at the exit phase over here, this is D H and this is D shroud. This ratio is an important parameter. The other important parameter, which we look at just now is, the the diameter ratio between D shroud to D 2, that is, the tip of the impeller. So, these two diameter ratio between this point and the shroud of the exit phase, and the diameter ratio between shroud and hub at the exit phase itself, actually are important design considerations. And, alpha 2 as we just saw is the important consideration because that creates the jet and that jet goes into the radial impeller because the relative velocity there has to be radial. So, the flow is going into the radial impeller completely radially. So, relative velocity has to be radial, but the absolute velocity there is very high. It is a jet that is being created by the stator nozzle.

So, if we look at all these characteristics put into this diagram, we can see that at the peak over here, which we have identified as the probable design point, the ratio of D 2 to D S, that is, the tip of the impeller to the shroud is point… D hub to D 2 is 0.70. So, this is something which has been created by number of design people, who have looked into various aspects of the design and have inferred that if you put together some of these numbers in terms of diameter ratio, in terms of alpha 2, then you can arrive at a peak efficiency in terms of eta T S. And, the efficiency of the total-to-total is still very good; it is not really that bad. So, it is somewhere near the peak of total-to-total efficiency. So, you get a good efficient turbine design. So, these parameters have been put together by the designer over the years. And, this kind of plot is a generalized plot. It is available for selection of your turbine fundamental parameters.

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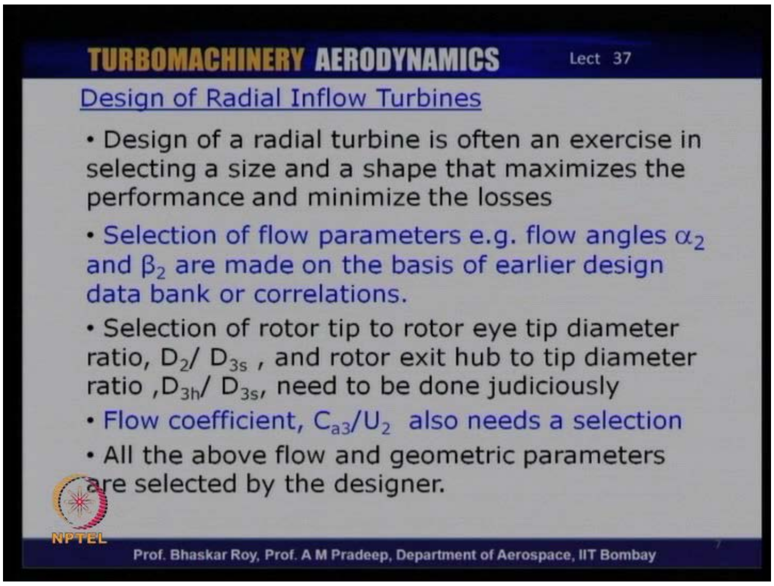

So, if we put together many of these things that we have just shown, we can start our discussion on the design of radial inflow turbines. Now, design of a radial turbine is often an exercise in selection of the size and shape of the vanes, both the stator nozzle as well as the complicated shape of the rotating impeller. And, the shapes put together should maximize the performance and minimize the losses. So, we had a look at how the losses vary with dimensionless speed and we have to ensure that it produces the work. The work that runs a compressor or any other load that needs to be maximized. So, that is the purpose of the turbine. And, for it to be competitive in the market, for it to compete with the axial flow turbines, which of course as we know are producing, very high work these days due to the cooling technology. And, we have seen that the radial inflow turbine has to be competitive with those technologies to hold its own. So, you have to maximize the work done and somewhere along the way, we have to ensure as we have just seen that you are somewhere near the peak of the efficiency.

If you remember the efficiency parameters that we have done in case of actual flow turbine, the efficiencies were those axial flow turbines where actually higher. The efficiencies of the radial flow turbines are a few points less than that of axial flow turbines. Now, this is in evitable because we have a flow that is coming in radially and then going out axially. This, huge 90 degree turn and over a larger surface of the rotor or impeller produces certain amount of inevitable friction losses at high velocity jet;

because the flow is continuously accelerating. And, as a result that kind of a loss through the impeller vane as we have just seen in the couple of slides back is inevitable.

So, the efficiency would always be few points less in radial turbine than in case of axial flow turbine. This is one of the reasons, why the radial inflow turbine has not been the most popular choice of turbines even for small gas turbines. People often choose axial flow turbines simply because it is that 2 or 3 percentage more efficient in terms of its working capability. However, radial turbine is a good machine. There is no question about that. It is a robust machine. That is also accepted. It normally does not have cooling, but it produces reasonably good amount of work with reasonably good efficiencies and it has its uses. Towards the end of today's lecture, I will be able to show you a very special use of radial flow turbine concept in very special applications.

So, the design of radial inflow turbine starts with the selection of flow parameters. You have to select the flow angle alpha 2, that is, exit angle from the stator nozzle, which produces jet at the velocity C 2. So, choice of the angle alpha 2 we had seen in case of axial flow turbines. Also, it is an important design driver. So, here also alpha 2 is indeed a strong design driver because it creates a jet and then finally, ensures that the flow going into the turbine rotor is indeed radial. Then, of course beta 3, which is made on the basis of earlier design data bank; beta 3 is the exit angle which goes out of the impeller. And, this angle is important because the absolute velocity here going out should be axial.

So, the relative flow angle beta 2 has to be of such an order that the absolute flow angle is 0. Now, this is again you need to ensure by design. It is not going to happen by itself. So, designer has to sit down and make sure that under design conditions, these things are properly done. So, the flow in the relative frame is going in radially; flow in the absolute frame is going out at the exit phase in the absolute frame actually. So, these are some of the issues that need to be looked into right in the beginning of the design.

Then we will look at the geometrical parameters. The geometrical parameters here are the diameter ratio as we just saw, D 2 by D 3 S, which is the shroud tip diameter, shroud I tip diameter or the exit phase shroud diameter. So, this ratio we just saw has a value close to something like 0.70 or inverse of that, and this about 1.3 or so. And, that gives rise to a selection criterion for the diameter ratio. The other one is, of course as we saw the exit hub tip to diameter ratio D 3 H to D 3 shroud. And, these two need to be decided because that fixes the size of the machine. So, the size of the machine is fixed with the help of these two diameter ratios. Now, unless you have some other restriction for restricting the size of the impeller, these two figures need to be chosen as early as possible; even, if it other restrictions apply. You have to choose them with reference to those other restrictions where it is to be applied.

Now, quite often radial turbines are indeed used, where restrictions of size actually been applied. The utility of radial turbine is that if you make a radial turbine that is a restricted size, let us say a very small one, it produces still very high efficiency machine.

On the other hand, as we have discussed before if you make the axial machines smaller and smaller, the efficiency starts dropping. So, axial compressor and axial turbine if they are very small, the three dimensional flow inside those aerofoil shaped blades actually bring down the efficiency of those things and the aerofoil shape, which is a two dimensional entity, fundamentally loses its efficiency. And as a result, the efficiency of the entire machine in axial flow starts following quite fast, when the size of the machine starts becoming smaller and smaller.

So, when you have a small engine or a small machine to be designed for a special application, quite often people would go for radial turbine or even centrifugal compressor; because they are as I mentioned, robust machines, they hold their efficiency values even when they are very small in size. One of the reasons of course, is that neither of them deploys aerofoils in the rotating vanes. So, rotating vanes are not made of aerofoils, which as we have commented number of times are aerodynamically fragile shapes. So, the robust shapes are the non-aerofoil shapes and the centrifugal machines, the compressor and the turbine have that robustness, which the axial flow machines sometimes are lacking in, especially when they are small in size. So, radial flow turbines often, in a restricted space, again in space craft applications or any other land based applications or in special utility application, even on board an aircraft, a radial flow machines, often have very strong utility value because they occupy less space and produce a lot of work done per unit mass flow. And then, of course the efficiency still holds good. They do not drop so fast. So, these are the reasons because of which the centrifugal and the radial flow machines are still preferred in many applications. In those cases, these parameters need to be chosen as early as possible.

The next parameter that we are looking at is the flow coefficient. Now, flow coefficient as defined here is axial flow at station three; that is, at the exit to the U tip of the impeller U 2. And, this is the flow coefficient, which requires to be selected as early as possible along with the work done or the pressure raise or the pressure raise coefficient or as we call the blade loading coefficient. So, those things need to be chosen together. Now, flow coefficient we have seen in case of earlier machines, axial compressor, axial turbine, centrifugal compressor is an important design driver. So, flow coefficient again like alpha 2 and the diameter ratios are a design driver. Quite often, you choose your, many of the design parameters in conjunction with the flow coefficient. So, the flow coefficient as defined here, as you can see it is slightly different than in axial flow machine, but that is expected.

This flow coefficient is an important design parameter. And then, of course putting all of them together you have a set of flow parameters, you have a set of geometrical parameters, which fixes the side size and the shape of the machine. All of them together constitute the design of your radial turbine.

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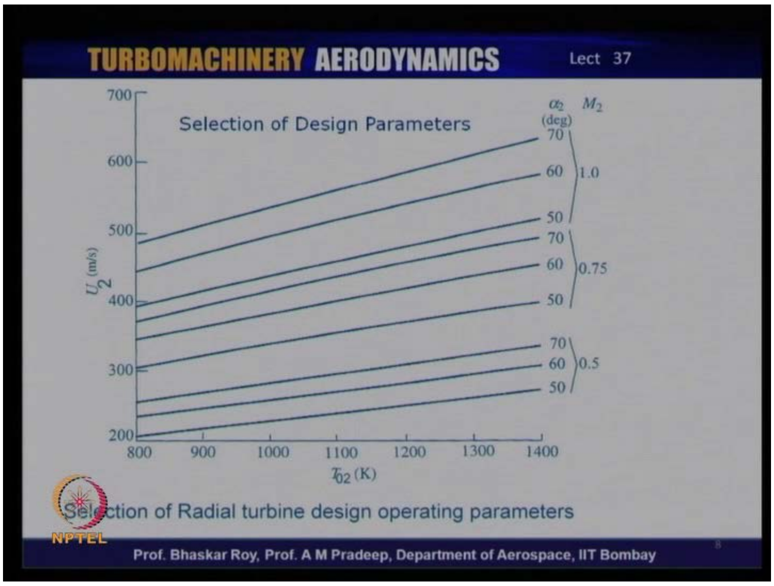

.So, let us take a look at some of the issues that are involved here. Now, in this figure for example, what has been captured is the tip speed U 2 of the impeller, and then the inlet temperature T 0 2 which is same as T 0 1, coming into the radial turbine. And then, of course the various parameters; alpha 2 is one parameter and then M 2 corresponding to C

2, which could indeed go pretty close to sonic mach number. And. So, at various mach numbers of M 2 were, at various values of alpha 2 specifically, this is been plotted and as you can see if the inlet temperature is going up, one can go up to something like 1400 k, the tip speed necessarily needs to be raised to get the work actually to be done properly; correspondingly, the values of alpha can be selected from this particular graph.

Now, this graph is borne out of certain fundamental theories. This is not an experimentally obtained graph. So, it is borne out of fundamental theories. So, this is a kind of graph that allows you to make selection of the design parameters. We have seen you can select certain design parameters at an efficiency of let us say point 87; that gives us a certain values of a diameter ratio that we have seen before. And, this diameter ratio, then leads us to value of U 2. T 0 1 or T 0 2 of course, is a design input from engine thermodynamic cycle. Calculations and fixations of the design point on that cycle, and then together we can now, we should start selecting what will be the value of alpha 2, which is the exit from stator nozzle. So, as we have seen, the alphas can be high of the order of 60 or 70. And, some of these are 50, 60, 70 when mach number is 1; 50, 60, 70 when Mach number is point 75 and 50, 60, 70, alpha 2 when mach number is point 50.

These are the constant alpha lines. So, at any constant alpha line, as temperature goes up your U 2 has to go up. As we can see finally, with high Mach number flow, the value of U 2 could be as high as 500 meters per second tip speed. Now, this tells us, what the design parameters are; in terms of the flow speed, in terms of the rotational speed of the impeller. Because U 2 would immediately fix the revolutions per minute, since we have already tried to fix the diameters through the diameter ratios.

So, now, we are going into fixing the rotational speeds. So, this kind of selection process and this as I mentioned is actually a theoretical graph; not an empirically or experimentally produced graph. So, this directly allows you a design selection in terms of the fundamental design drivers alpha 2, T 0 2. So, you are now in in a position to fix the rotating speed of the impeller.

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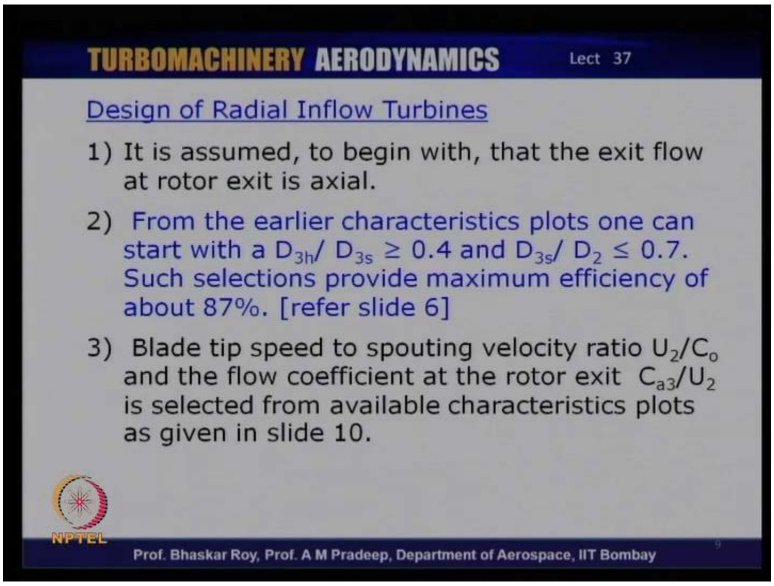

.The next thing that we can summarize is that the exit flow at the rotor exit is axial. Now, as we have mentioned number of times, it is an ideal design condition. So that, the flow goes out actually, any world component there, that means, a non-axial component of the flow is going to be wastage of energy. And, that energy will not be diffused through the diffuser. The diffuser diffuses the actual component. It will not diffuse the peripheral or old component or tangential component. And as a result, the turbine performance would suffer through wastage of energy in old component. One simple design that one can proceed with, as we have mentioned is that from the earlier characteristics plots, the diameter ratio D 3 h by D 3 shroud is normally of the order of 0.40 near about or a little higher than that. And, on the other hand, D 3 shroud to D 2, that is, the tip diameter of the impeller is of the order of 0.70, the inverse of which was around 1.3 or there about.

Now, these are numbers that people have been using for a long time. And, have found that you can get efficiency of the order of 87 percentages using some of these standard design features. The other parameter that one can look at is the blade tip speed to spouting velocity ratio U 2 to C o. C o you have done in the earlier lectures. And, the flow coefficient at the rotor exit which is C a 3 by U 2, which we introduced also in the last slide.

So, this tells us that you can have a selection of these flow parameters. The earlier point was about the geometrical parameters. Now, we can select the flow parameters, using the parameters that have been introduced before including the spouting velocity.

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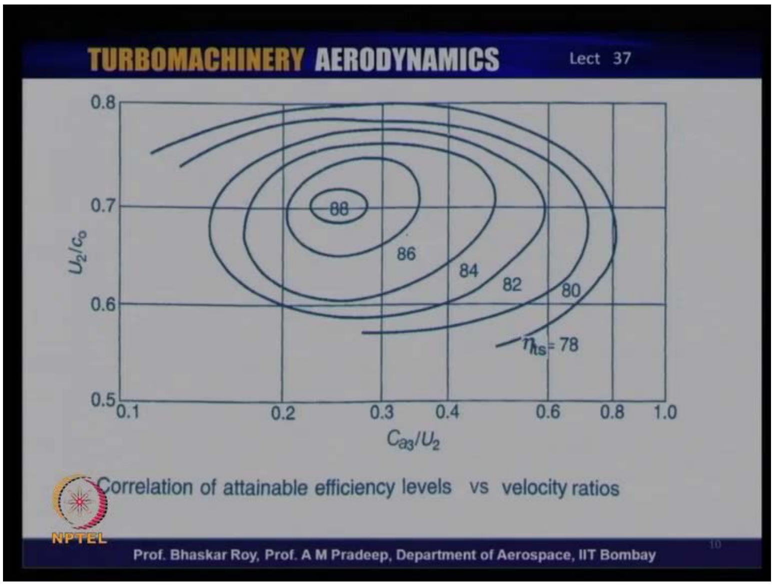

And, we get a graph something like this. Now, this allows us that U 2 by C o is plotted over here, the flow coefficient is plotted over here, and these are the efficiencies, which are the total-to-static efficiencies. So, as you can see these are curvilinear elliptical kinds of plots. So, as you go inwards, the efficiencies goes higher and higher. And, quite often as we have seen a good 87 percentage efficiency design can be achieved, if you choose certain parameters as per some of the specifications or prescriptions that we have been talking about.

So, the prescriptions that we have been talking about do produce reasonably efficient machines. And from, which you can now choose your U 2 by C o and C a 3 by U 2, so very high flow coefficient for example, actually produces low efficiency turbine. Similarly, very low flow coefficient will also produce low efficiency turbine; very high U 2 by C o will again produce low efficiency turbine; and very low values of U2 by C o will also produce low efficiency turbine. So, one needs to have a good kind of a mean optimized value of both these flow parameters, to arrive at a good efficient turbine design.

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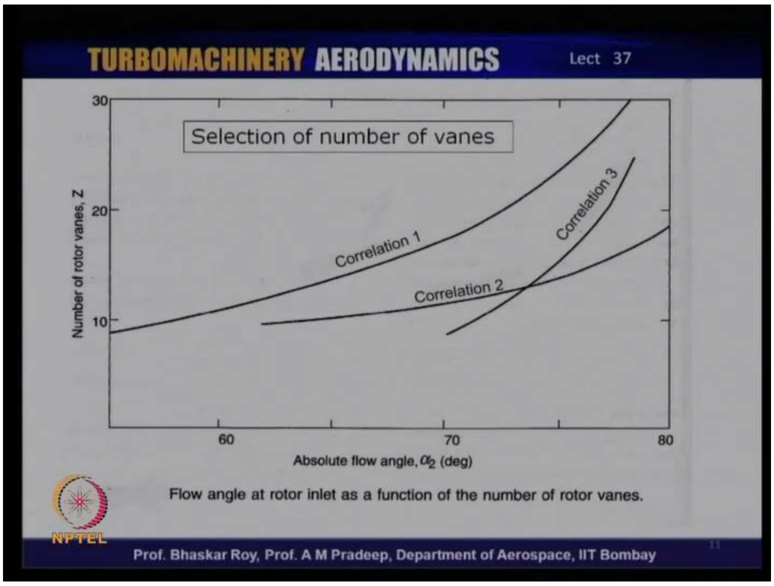

We can take a look at some of the issues related to selection of the number of vanes in an impeller. Finally, you have to do that. There are two, three, correlation that people have been using over the years. One is correlation; in which you can see the number of vanes keep going up with the increase of absolute flow angle. So, when the flow angle goes above 70, the number of vanes becomes very high. Now, up to 20 also it is ok.

Absolute low angle of the order of 74, 75 is used indeed quite often, but after that, as per this correlation your number of vanes would indeed go very high and that may not be a good idea. On the other hand, the other correlation which is available, keeps the number of vanes not very high. So, towards the lower values of alpha 2 below70, the number of vanes is modest. And, you do not need a large number of vanes. A correlation three agrees with a correlation two over some of the flow angles, but later on, it also prescribes very high number of vanes. So, very high number of vanes has a number of issues that needs to be looked into.

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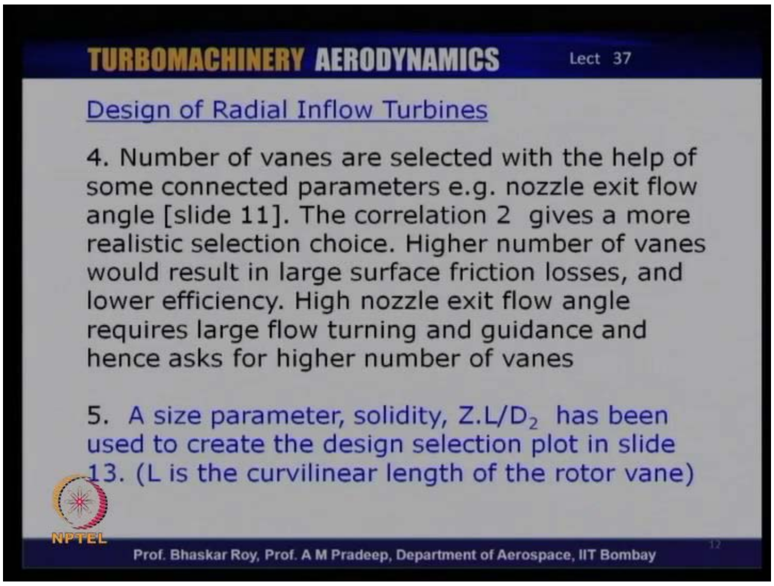

So, what happens is if you have very high number of vanes, you have very large surface friction losses. Now, very large surface friction losses are not a good idea because it is going to give you low efficiency. On the other hand, a certain number of vanes are required to turn the flow from; you know whatever angle is coming in beta 2 to beta 3. And, this large flow turning is indeed required. And, it is also required for good flow guidance through the rotating vanes, before it is exiting from the turbine. This guidance is required for extraction of work or energy for producing work. So, the numbers of vanes needs to be optimized between large surface friction loss and a good guidance and turning, that is required in the vanes. So, the earlier parameter in earlier selection criterion that we are looking at tells us that correlation two is often a good prescription because it gives a modest number of vanes, even with raising absolute flow angle which is a primary design driver. So, correlation two is most used correlation for radial flow turbine design; because it prescribes a reasonable number of vanes, even with raising flow exit flow angle from the stator nozzle.

The other parameter, which of course, is borne out of the number of vanes, is of course, the solidity which is given as, Z into L by D 2 whereas; one is the curvilinear length of the rotor vane. Remember, the rotor vane has a long curvilinear path. Now, this long curvilinear path has to be decided how long it should be? It depends on the… as we have just seen; depends on the number of vanes and it depends on the angle, through which the flow would be turning. And, of course the flow would be guided through those passages. And, that passage if you remember, this is a turbine. So, the passage is going to be a converging passage. So, it will be a continuously converging passage, through which the flow would be also turning in a curvilinear path; so, it is a curvilinear converging passage, through which the flow will have to be accelerated in a guided manner and if you can do that in a rotating frame, you get work extraction.

So, solidity is a parameter that captures all these geometrical features into one single number. And, as we have seen in axial flow machines, also solidity is an important design parameter that needs to be decided. Some are during the design. To ensure that, you have sufficient number of vanes or blades to do the work, but not too many to create flow abstraction, flow blockage and high surface friction.

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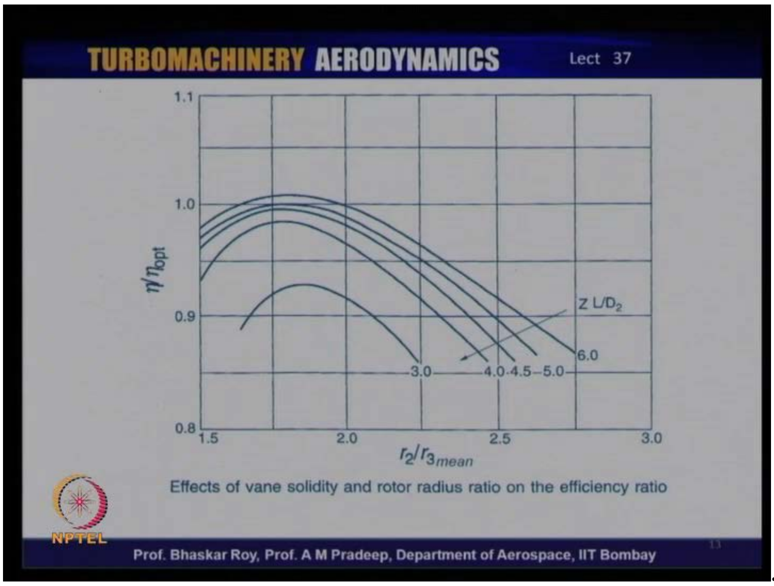

.So, we will look at the selection of these solidity parameters through another plot, which is again plotted with the help of various theories and these tell us that, if you optimize the efficiency with the real efficiency, and then you select the solidity parameter as one can see here. The ratio of the radius of the impeller r 2 to r 3 mean. Of course, it is the mean radius at the exit of the rotor or impeller. And, this radius ratio is similar to the diameter ratio that we have done earlier; borne out of that. It tells us that, you need to select this in conjunction with the solidity and then in conjunction with the efficiency, which is related to the optimized efficiency.

So, this allows us to select the solidity. So, you can see the radius ratio. If it is somewhat lower, your solidity parameter will have to select to get a high efficiency to go for a high solidity to get a reasonable efficiency. On the other hand, at high values of r 2 by r 3, if though that is very high, then even with lower solidity your efficiency starts coming down. So, if with high or 2.0 or 3.0, the general tendency is the efficiency is going to come out to be lower value. This is where, you get high efficiencies. And, depending on what solidity you have, you get a reasonable efficiency figure as a part of your design exploration to begin with. Of course, you have to find the efficiency later on through CFD and through Rig testing. So, this plot essentially gives you a good idea about what you are. Solidity of the vane should be with reference to selection of efficiency and the radius ratio or the diameter ratio that we have done before.

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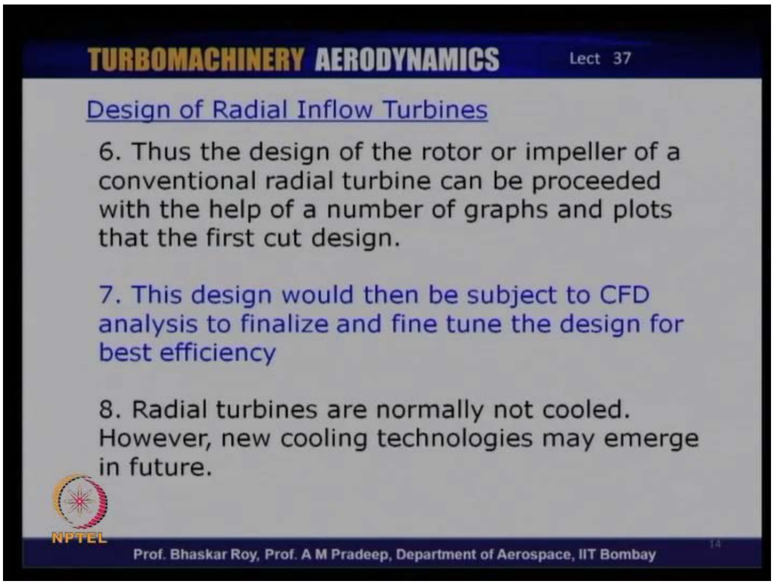

.Now, with the help of these geometrical and other parameters, we can complete the go towards completion of the design process of radial in flow turbine. Now, you can use all the graphs and plots, which if you have more data bank available with you. You can get a good first cut design. You can improve your design with the help of these graph, immensely to get efficiencies easily of the order of 84, 85 percentage. And then, if you have to proceed towards higher values, you can use CFD, which normally gives you fine tuning of the efficiency and other geometrical parameters, vane shapes. You can fine tune them, but normally that is fine tuning. If you want a lot of improvement that has to be done at the design stage itself through the design procedure that we were talking about. CFD gives fine improvement. It does not give a very large improvement. And, CFD of course, cannot be used for basic design. CFD is, when you have a design and the geometry is available and it lends itself to CFD analysis.

The other parameter, the other point that you need to keep in mind, is what is mentioned here that radial turbines are normally not cool turbines. The cooling technology has not been deployed in radial turbines. It is possible that in future, we will have cooled radial turbines. And as a result, the work capability of the radial turbines will go up, but the tip of the radial turbine rotor, for example, vane is rather thin and does not have any provision for cooling. The stator nozzle of course, can be thick and that can be cooled and that cooling technology is now being explored. And, if cooling can be deployed in the stator nozzles vanes, then the radial turbine working capability, its inlet temperature can indeed be increased further, to get more work done out of radial turbine.

So, cooling technology is something, which is in the offing. And, if it is available, radial turbines would be more competitive, especially in the small sized machines compared to axial flow turbines.

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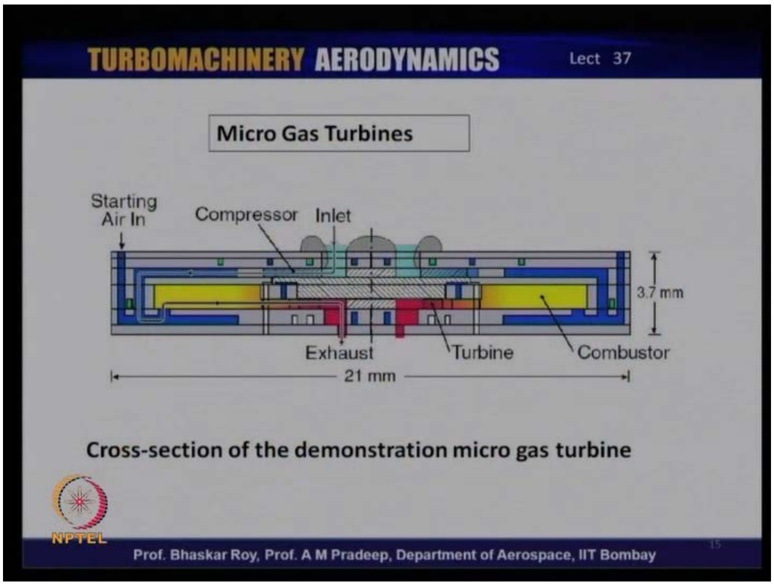

Now, these are the basic design features of radial inflow turbine. Let us, take a look at a very special case of radial inflow turbine that has been used very successfully in creation of micro gas turbines. In micro gas turbine, the size of the gas turbine as you can see here is 21 millimeters. It is a very small machine. It is 21 millimeters, that is, 2.1 centimeter and it is only 3.7 millimeter thick. So, it is like a button of your blazer or a coat and it is as small as a button. It is a button sized gas turbine engine. What it is doing is the flow is coming in, here through this inlet system, and then you have a compressor which is typically a centrifugal compressor. We will have a look at it right in a few minutes. It is basically a centrifugal compressor, but it is very thin. As you can see, it is less than 1 millimeter thin and that drives a flow through this blue line and it comes in.

In this zone, yellow zone, so the blue line is of course, the flow coming in and it goes into the combustion chamber. So, in the yellow zone, the flow is indeed mixed with a fuel and combusted, and then the combusted fuel is then taken through the turbine. So, this is the turbine and then this red is the combusted flow that is, coming through the turbine and finally, exhausted.

So, it comes from all sides. So, yellow zone is shown in both sides. It is an annular configuration; both the compressor as well as the combustion chamber as well as the turbine. So, compressor combustion chamber and turbine are all housed within 3.7 millimeter thickness and 21 millimeter diameter machine.

The compressor turbine as you can see is essentially, back to back. So, turbine directly runs the compressor because they are back to back attached to each other. There was a little problem in the design, regarding the turbine being hot and the compressor being cold; however, little insulation here probably, solved that problem.

So, this is a kind of a real micro machine that people have already invented and has been found to be working with a reasonable working capacity. This is a kind of replacement of small energy producing or work producing machine.

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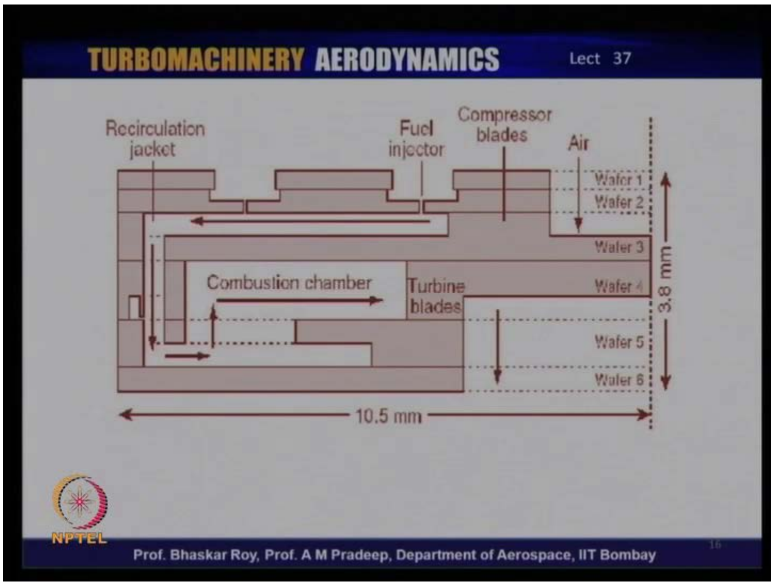

Let us, take a look at a little more detail of this machine. You have the compressor blades over here. This is one half. So, this is 10.5 millimeter. So, you have one half of the machine. So, it is just a little more than 1 centimeter, this whole thing. And, each of them is made of wafer. So, they are very thin. So, you have the fuel injector here, you have the compressor blade and the air is coming in, so the air fuel is mixed over here. And, this air fuel mixer goes in, it goes into the combustion chamber, then it is delivered through the stator nozzles into the turbine and finally, it gets ejected. So, these are wafer thin. So, that is why, they are called wafer one, two, three, four, five, six. Six Wafers are essentially pasted on top of each other to create a 3.7 or a 3.8 millimeter thick micro gas turbine. So, this is a kind of micro gas turbine that has been created and is found to be working.

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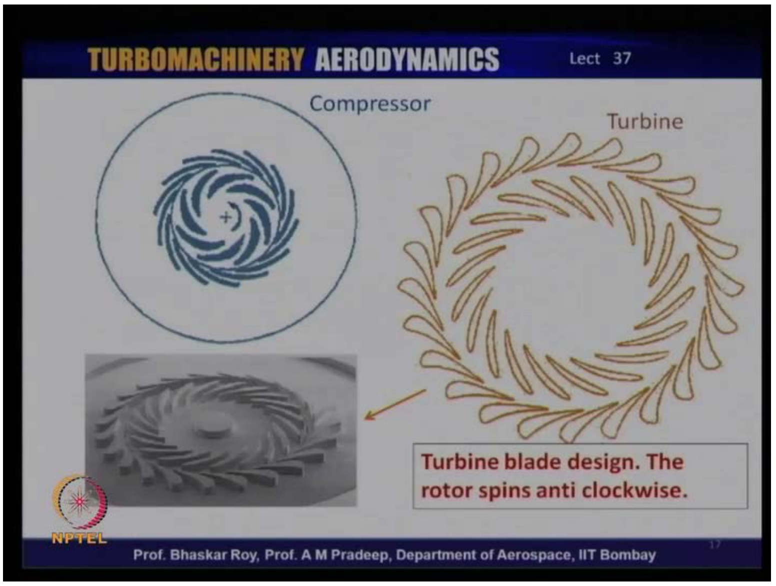

This is the picture of the compressor and the turbine. This is how the compressor works. So, the compressor essentially is centrifugal compressor. It rotates this way and throws the flow out as you can pretty well see here. The flow is diffusing through this and it is a rotational mode, the rotor is rotating. And then, when it is rotating, it ejects a flow out and then this is a straighter way through which the flow gets further diffused. That diffused flow or compressed flow is delivered into the combustion chamber and then it comes to the turbine which, as we have seen are back to back through the turbine. This is the stator nozzle through which the flow gets hugely accelerated. So, this acceleration occurs over here.

Clearly aerofoils have been deployed both in compressor as well as in turbines. In normal radial turbines and centrifugal compressors, we have seen aerofoils are not deployed. But, this is a very special machine in which aerofoils have been deployed. And, flow coming in, be the huge jet and then that creates the motion of the turbine.

So, this rotation of the turbine rotor then rotates the compressor itself. So, the rotor spins in anti-clockwise. This is rotating in this direction and rotates a compressor along with it. So, typical aerofoil that we have seen in case of axial flow turbines are actually deployed over here in micro sizes. You can well imagine how small these individual aerofoils are because the whole thing is only about 2.1 centimeter are thereabout. So, they are extremely small sized entities and these entities are put together to what is called a micro gas turbine. They are very small, but they produce power to the tune of few watts, the order of 10, 20 watts. That is good enough to run a few appliance likes electronic machines, communication systems, essentially as a replacement of battery.

So, it is a very special application of radial flow turbine. And, so radial flow turbine has lot of potential in terms of it; it is the way its principles and the way it works and is a robust machine and creates good efficient machines. So, we had a good look at the various kinds of machines over the last thirty five, thirty six lectures through axial compressors, axial turbines, centrifugal compressor and then finally, radial turbines. And, we had a look at how some of these entities could be designed. The first cut design features have been discussed in our lecture series and we are in a position now to create these machines for usage.

In the next few lectures, we will be looking at usage of CFD in fine tuning these designs. How computational fluid dynamics is indeed brought into the modern design, how the design finally, becomes more efficient and definitely more work producing power producing machine. So, in the next few lectures, we will be looking at CFD of Turbomachinery that is, something we will be doing over the next two or three lectures, which are the final lectures in our lecture series.

So, in the next lecture we are starting with CFD of turbo machines.