**Aerodynamic Design of Axial Flow Compressor & Fans**
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**Lecture 35**
**Design Strategies (Contd.)**

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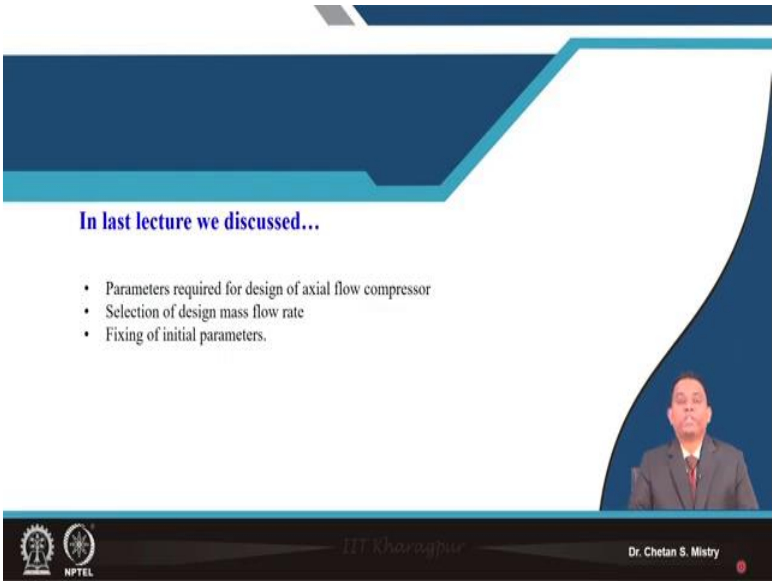


Hello, and welcome to lecture 35. We started discussing about the parameters required for say design of axial flow compressor, we have started with what all parameters which are been required and where we are using or which kind of compressor we are using or we will be designing for particular engine. Then we were discussing about the important parameter, that's what is say mass flow rate; this mass flow rate, we have seen, if we are talking about the commercial aircraft that's what we are deciding based on maximum thrust requirement.

And when we are discussing about say fighter aircraft or supersonic aircraft where my expected thrust that’s what will be different than that of my take-off thrust, under that condition by mass flow rate that will be different for the design. And this is what will be in line to our expected performance for say turbo machinery. So, selection of this design parameter for say supersonic aircraft, that’s what has been done at supersonic cruise condition.

Then we started discussing about the fixing of our initial parameters. So, for initial parameters we have discussed about energy balance, we have discussed about the continuity, we have discussed about the power balance, we have discussed about the speed balance and then we started discussing about very important aspects that’s what is the selection of my pressure ratio for particular stages.

And we have realized when we are discussing for the selection of pressure ratio specially when it is applicable for say our initial stage that’s what is having pressure ratio to be large and my efficiency we are assuming to be lower because my flow will be going transonic in that region.

For middle stages, our expected pressure ratio is moderate but at the same time our efficiency is on higher side that’s what we are talking about the flow uniformity we are achieving in our compressor. Now, for later stages, we have realized my blades are shorter blades and that’s what will be giving all kind of flow three-dimensionality which will lead to increase the losses and reducing the efficiency and our expected pressure ratio for such kind of blades are on the lower side.

We also have discussed when we are talking about say supersonic aircraft or supersonic engine design, say, for military applications may be in middle stages also they are going transonic because there we are not having any concern about the fuel economy. Now, with this background let us move ahead.

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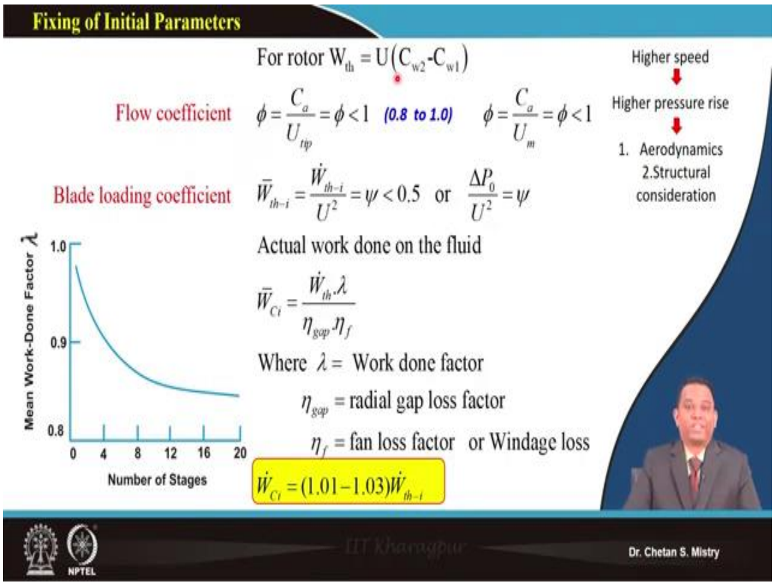


Say, what we know for our rotor, our work done that’s what we are defining based on our fundamental Euler's equation. Today let me introduce very important parameter that’s what is say flow coefficient. Now, this flow coefficient is nothing but it is a velocity ratio that’s what is given by axial velocity divided by peripheral speed at the tip, okay, and it says that need to be less than 1.

$$Flow\ coefficient,$$

$$\phi = \frac{C_a}{U_{tip}} = \phi < 1 \quad (0.8\ to\ 1.0)$$

In some of the open literatures people they are defining this flow coefficient at the mid station also. They say, this is what is given by axial velocity divided by my peripheral speed at the mean station. So, we need to be very careful which parameter that’s what is given. We will see what all are the uses of this flow coefficient. It says that need to be less than 1.

$$\phi = \frac{C_a}{U_m} = \phi < 1\ (\sim 0.5\ or\ 0.55)$$

So, conventionally when we are doing our initial design that time we are assuming this at the tip in the range of 0.8 to 1, when we are talking about the mean station, some of the important designs people they are selecting that to be 0.5 or 0.55, okay; that’s what is based on my mean peripheral speed, okay. So, this is what we can say is one of the important parameter for our design.

Let us talk in a different way. Suppose, if I know what is my axial velocity based on my continuity equation if I know my mass flow rate, and if I am not aware of my peripheral speed by assuming the flow coefficient we can do calculation for that, it is one condition. Secondly, we can say, we are having say our peripheral speed that's what is known to us, we can assume our flow coefficient and based on that we can do our calculation for the mass flow rate.

Now, this peripheral speed, that's what we are defining in sense of $\frac{\pi DN}{60}$ that means this is also deciding your rotational speed and the diameter, okay. So, this one parameter, that's what is very important parameter, we can say, that's what is as a flow coefficient, okay. Let me introduce second parameter, that's what is defined as a blade loading coefficient that is nothing but it is my $\frac{work\ done}{U^2}$, that's what it say it need to be less than 0.5. If you recall, this is what all we have discussed also in the last module it says this is what we also can define in sense of $\frac{\Delta P_0}{U^2}$.

$$Blade\ loading\ coefficient,$$

$$\overline{W}_{th-i} = \frac{\dot{W}_{th-i}}{U^2} = \Psi < 0.5\ \ or\, \frac{\Delta P_0}{U^2} = \Psi$$

In sum of the literature, people they are defining as $\Delta h/U^2$, it is nothing but static enthalpy rise divided by U square. This U here, it may be say Umean or it may be tip. So, based on the designer's choice you need to check with what peripheral speed they are putting in. If you recall, we have plotted the graph for say performance of single stage axial flow compressor, where on x-axis we have defined $\phi = C_a/U_{tip}$ and on y-axis we have defined loading coefficient that's what we have defined as say $\frac{\Delta P_0}{\frac{1}{2}\rho U^2}$.

And for both we are selecting tip, okay. You can select mid also there is nothing wrong for that, okay. So, when you are reading or when you are referring the literature, be careful, which peripheral speed they are talking of. Now, if you are looking for actual work done; so, you know, we have introduced a parameter that's what is called work done factor, okay. And, this work done factor, that's what is giving us idea about when we are having say variation of axial velocity.

So, if you recall, when we are introduced this work done factor, we have initialized the parameter saying which stage you are designing. Suppose say I am designing my stage 4, accordingly I need to introduce the parameter that's what is my work done factor and it says my work done factor it is always less than 1, so here this is what is my case.

$$Actual\ work\ done\ on\ the\ fluid$$

$$\bar{W}_{Ci} = \frac{\dot{W}_{th} \cdot \lambda}{\eta_{gap} \cdot \eta_f}$$

$$where\ \lambda = Work\ done\ factore$$

$$\eta_{gap} = radial\ gap\ loss\ factor$$

$$\eta_f = fan\ loss\ factor\ or\ Windage\ loss$$

$$\dot{W}_{Ci} = (1.01 - 1.03)\dot{W}_{th-i}$$

In denominator we are having say gap efficiency and this is what is called say fan loss factor, okay. Now, this gap, that is nothing but it is a radial gap loss factor. Say, when we are having say our rotor, that's what is rotating at particular speed we are providing certain amount of gap between casing and rotor.

Similarly, there are many engines available in which we are providing gap between hub and stator blade also. So, your hub will not be fixed between say your…your blade will not be fixed between say your casing and hub that's what is called cantilever kind of configuration. And this is what is representing the fan loss factor that is also representing my windage losses.

So, in overall if you look at, my work done or actual work, that's what is required by my compressor that's what would be 1.01 to 1.03 times the theoretical work what we are calculating based on $U(C_{w2} - C_{w1})$. So, you can say approximately 1 to 3% higher work that's what is expected from your axial flow compressor, okay.

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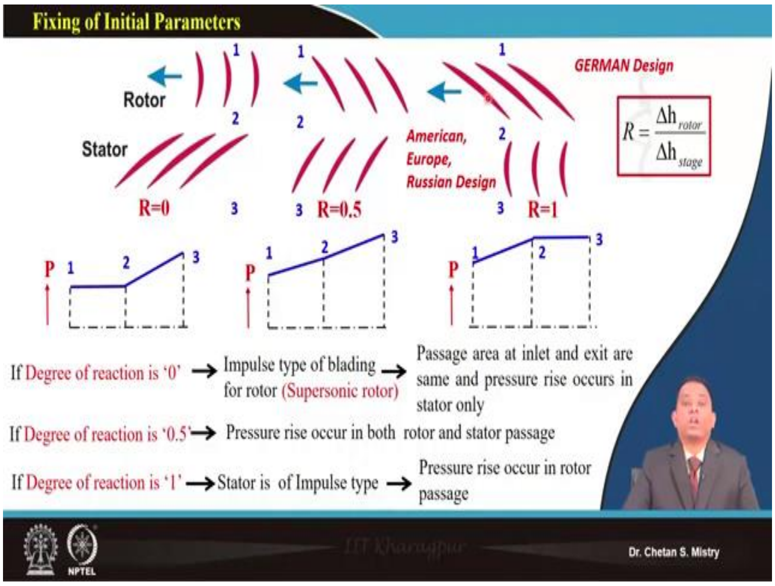


Now, we have learned about the important parameter, that's what is called degree of reaction. This degree of reaction, we have defined as say static enthalpy rise in our rotor divided by say your static enthalpy rise in a stage. We have discussed about when we are having degree of reaction to be 0, degree of reaction to be 50%, degree of reaction to be 100% and what we have realized when we are having our degree of reaction to be 0, whole my work that's what has been done in my stator, rotor is not doing any kind of compression.

When we are having our degree of reaction to be 50% my diffusion work it will be divided between rotor and stator; we can say 50% diffusion it is done in my rotor, 50% reaction or say 50% diffusion it is done in my stator. When we are talking about this 100% reaction, we have realized my whole lot of diffusion that's what is happening only in rotor and the stators are just guiding the flow. So, we should not forget what all fundamentals we have learned up till now.

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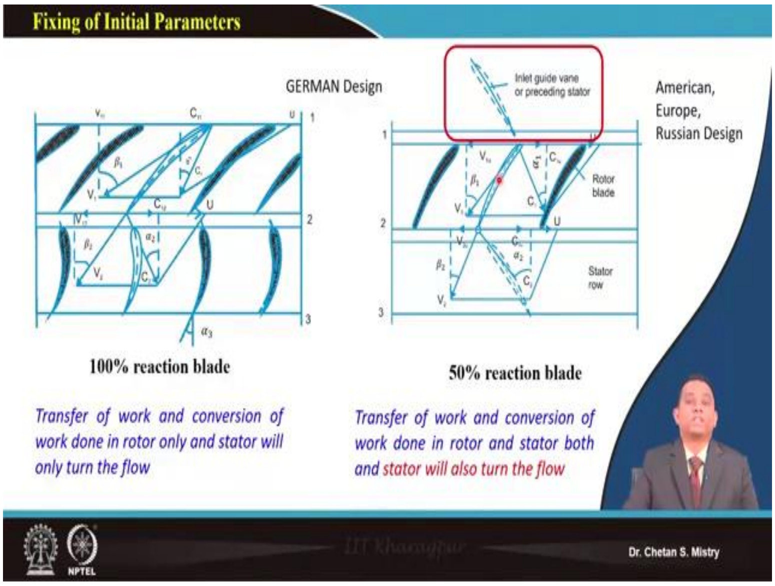


So, in order to have this degree of reaction, if you recall, here we are having two kind of configurations. So, this is what is say 100% reaction configuration and this is what is representing say 50% reaction configuration. And as we have discussed, the whole part or say whole my work, that's what has been done in my rotor when we are talking about 100% reaction configuration.

So, here if you look at, most of the German designs, people they are preferring this kind of configuration. So, during second world war when people they were designing those engines, mainly German engines, they are having high degree of reaction designs and that's what was giving benefit in sense of reducing the number of stages and that's what was led to reduce the overall length and weight of the engine to be reduced, okay.

At the same time, when we are talking about the American designs or say European designs or Russian designs most of them, they are assuming degree of reaction to be 50%. So, here in this case, we can say, my 50% diffusion that's what is happening in my rotor and 50% diffusion that's what is happening in the stator.

Now, when we are talking about say 50% reaction design, we know for our blade, my hub diameter that may be slightly lower and when we are having our hub diameter to be lower, that's what will lead to $\Delta\beta$ to be higher near the hub region, okay, we have realized that part, we have discussed many times this issue.

So, what will happen, if I will be having my $\Delta\beta$ to be large near the hub region, there may be chances of my flow to get separated in that region. And in order to address this issue, it is demanding for inlet guide vanes need to be incorporated, okay. So, when we are discussing about the 50% reaction, many of the engines what you are observing that will be having their inlet guide vanes, that's what has been incorporated.

So, you can say, this is what is giving some other kind of feeling or understanding. So, you know, this is what is giving guidance like when you are doing design for particular kind of stage, be careful, my later stages when we are doing design, say may be third stage or fourth stage, we can move with say 50% reaction design configuration, that's what will be giving this inlet guide vane.

So, initial stages you will not be going with 50% reaction and later stages you will go with say 50% reaction design, okay. So, this is what is a design philosophy and that's what when you are doing your design, you will learn all these aspects.

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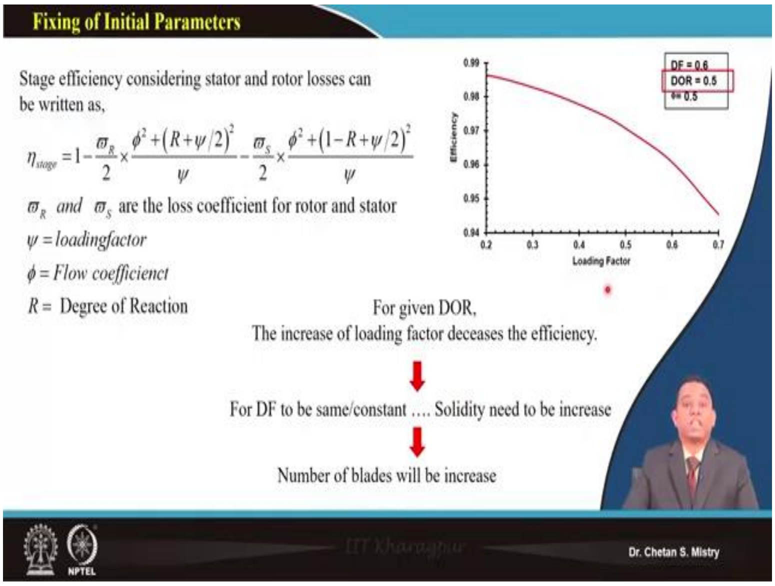


Now, let us try to understand what all parameters we have discussed; say, my loading coefficient, my flow coefficient, my degree of reaction, one more parameter we have discussed that's what is called a diffusion factor, all these parameters we have discussed, they are having certain limits. And, those limits, that's what will be directly related with the efficiency and that is the reason we are focusing more or emphasizing more on those numbers, okay.

So, stage efficiency mainly been defined as 1 minus say this is what is my loss coefficient in rotor, this is what is correlating my flow coefficient degree of reaction and stage loading coefficient, this is what is representing my losses or loss factor that's what is happening in stator and this, okay.

$$Stage\ efficiency\ considering\ stator\ and\ rotor\ losses,$$

$$\eta_{stage} = 1 - \frac{\varpi_R}{2} \times \frac{\phi^2 + \left(R + \frac{\psi}{2}\right)^2}{\psi} - \frac{\varpi_s}{2} \times \frac{\phi^2 + \left(1 - R + \frac{\psi}{2}\right)^2}{\psi}$$

$$\varpi_R\ and\ \varpi_S\ are\ the\ loss\ coefficient\ for\ rotor\ and\ stator$$

$$\psi = loading\ factor$$

$$\phi = Flow\ coefficient$$

$$R = Degree\ of\ Reaction$$

So, when you are doing your simplification of the equation you will be coming with this kind of formula. Now, this is what is giving us idea how all these parameters they are been correlated with. Remember here, this loss factor what we are discussing, that's what is been related with our diffusion factor, okay. So, this is what is coming in relation with the diffusion factor.

So, let us see, suppose say, here if you look at, this is what is a plot for which we have assumed our diffusion factor to be 0.6, degree of reaction to be 50% and flow coefficient to be say 0.5. What we are doing? We are changing our loading factor on x-axis and this is what is representing what will be the change of this loading factor on the efficiency.

What you see? If you look at for particular degree of reaction, say 50% reaction, with increase of loading factor, okay, when we are increasing our loading factor, the efficiency is going to be lower, okay. So, you can say, this is what is interrelating so many parameters. Now the thing is what is the reason, why we are having this efficiency to be lower?

It says for say same diffusion factor of 0.6, the solidity need to be increase. So, for say particular increase of my loading factor, I need to maintain my diffusion factor supposed to be constant then I need to increase my solidity, okay. When we are increasing our solidity, my number of blades will be increasing.

Now, we have realized when we are having our number of blades to be increased, that's what will lead to increase the losses. And that is the reason why it says for particular degree of reaction or fixed degree of reaction and my diffusion factor, you can say, with increase of my loading, efficiency will be decreasing, okay. This loading factor is nothing but per stage loading we are discussing at this moment.

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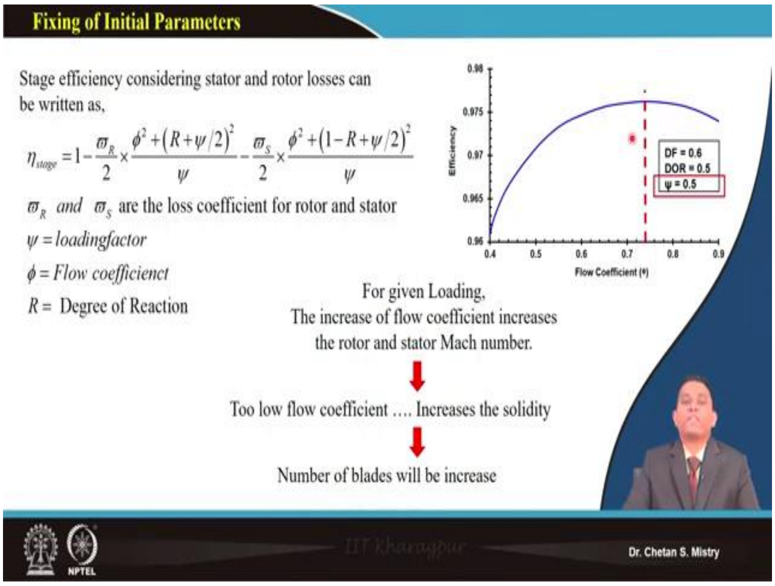


Now, let us take the second case. Suppose say, this is what is representing the variation of flow coefficient along with the efficiency, where we have taken our loading coefficient to be 0.5, okay. If this is what is your case, you can say, with increase of our flow coefficient, you know, my efficiency is going to be increase, okay.

So, the reason here, this is…this increase is by few points. Remember one thing, it says this is what is because of increase of my Mach number, rotor and stator Mach number. If we are considering, we are having low flow coefficient, under that condition, you know, we are having our solidity that's what will be increasing and that's what will lead to increase the number of blades.

So, in order to maintain our diffusion factor to be constant, we need to maintain this number of blades and that's what will lead to give you the variation of efficiency. Suppose if I consider, I am moving for my flow coefficient on the higher side, again, for the same number, my efficiency is going to be decreased, okay. So, somewhere we will be having optimum value.

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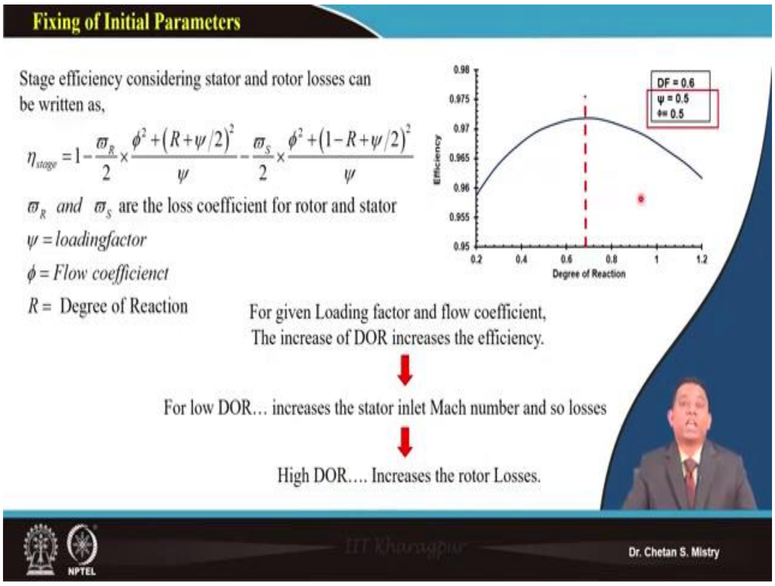


Now, let us take the next case. Say, we are assuming say our loading coefficient and flow coefficient that's what we are fixing with and we are taking the variation of degree of reaction with the efficiency, it says with the degree of reaction to be increased, we will be having efficiency to be rise up to particular extent, okay.

When we say we are having degree of reaction to be lower that's what will be increasing my stator inlet Mach number and that's what lead to increase my losses. So, just realize one thing, here in this case, we are having the flow separation that's what will be coming into the picture, okay. We have realized that part, when we having our degree of reaction to be lower, we will be having issue in sense of aerodynamics.

Suppose, if I consider say high degree of reaction, that's what will be increasing the losses in the rotor. So, here if you look at, this is what is representing that idea. So, now when we say, we are fixing our initial parameters, we need to fix these parameters also, which parameters? Say flow coefficient, my loading coefficient, we need to fix the degree of reaction and the diffusion factor, okay.

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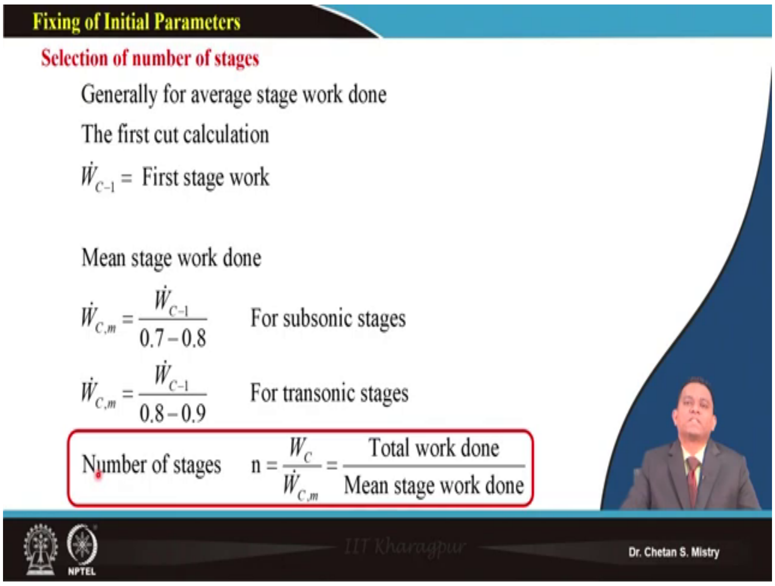


Now, after having all this idea, very important thing that's what we need to decide is say number of stages, because that's what is of major concern these days. Even earlier days also people they are having say major concern but they were not that greedy. The greediness is now with the expectation in sense of performance, okay.

So, conventionally we can say, our first stage work done, that's what we can calculate based on our fundamental Euler's equation and it says after doing that calculation, suppose if I consider all my stages are subsonic stages; so, we can say my later stages of HP we can consider as a subsonic stages for that we can calculate mean stage work done that's what is nothing but my first stage work done divided by 0.7 or say 0.8, okay.

$$Mean\ stage\ work\ done$$

$$\dot{W}_{C,m} = \frac{\dot{W}_{C-1}}{0.7 - 0.8} \quad (For\ subsonic\ stages)$$

Same way, suppose say I am having transonic stages; so, suppose we consider say my LP compressor or initial few stages of say HP compressor for that it says my mean work done that's what can be calculated dividing this by 0.8 or 0.9, okay.

$$\dot{W}_{C,m} = \frac{\dot{W}_{C-1}}{0.7 - 0.8} \ (For\ transonic\ stages)$$

So, once we are calculating what will be our main work done based on what is my total work done; so, we are having our overall pressure ratio known to us and from that overall pressure ratio we can calculate what is our total work done and this is what will be giving me what will be my mean work done and that's what will be deciding how many number of stages we are looking for.

So, this is what is giving you idea about the selection of number of stages, this is what is very important when we are doing our design for LP compressor, when we are doing our design for HP compressor. Let me tell, say HP compressor, that's what is, you know, most important, if you recall in last lectures we were discussing HP compressor that's what is your heart of the engine.

And, you know, few percentage loss in the efficiency that's what will be reflecting in sense of great reduction of fuel economy, at the same time it may be subjected to say formation of stall or failure of the engine because of surge. That is the reason why people they are very careful when they are doing the design for HP compressor. So, let us discuss about how we will be deciding say number of stages.

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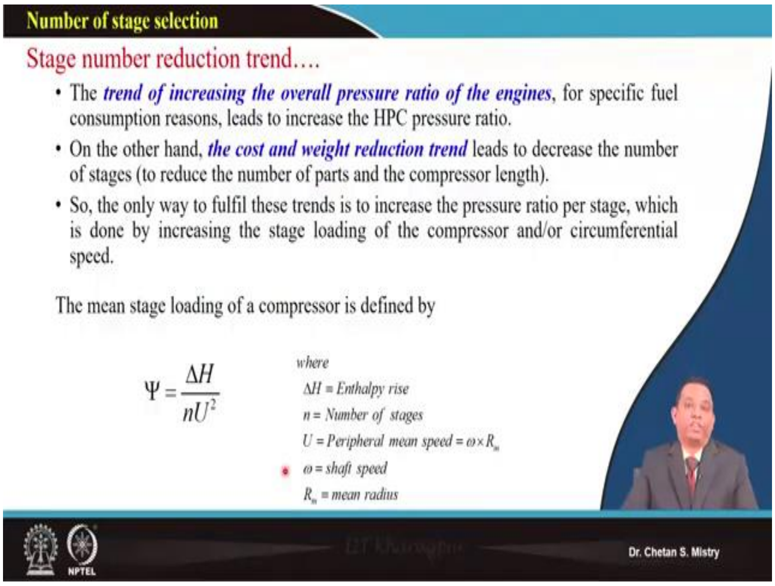


So, you know, this is what is a trend. What is our trend? It says we are looking for overall pressure ratio to be higher because we are looking for reduction in specific fuel consumption and that's what will lead to increase the HP pressure ratio, okay. Now, when we say on the other hand when we are putting cost and weight as a constraint, it says, we need to have number of stages need to be reduced because we are looking for say lightweight engine, we are looking for say compact engine, okay.

So, you know, only way to fulfil this kind of requirement is, you know, per stage pressure ratio requirement that need to be larger. And if you consider, this is what is your requirement we have introduced the parameter that's what is called say mean stage loading for say factor for the compressor. So, here if you look at, this is what is representing our mean stage loading factor, where $\Delta H$ is nothing but it is my enthalpy rise, 'n' is my say number of stages. So, this is what is my overall enthalpy rise, be careful! This is what is representing my peripheral speed and mean radius based on that we are calculating this mean stage loading coefficient.

$$\psi = \frac{\Delta H}{nU^2}$$

$$where$$

$$\Delta H = Enthalpy\ rise$$

$$n = number\ of\ stages$$

$$U = Peripheral\ mean\ speed$$

$$\omega = shaft\ speed$$

$$R_m = mean\ radius$$

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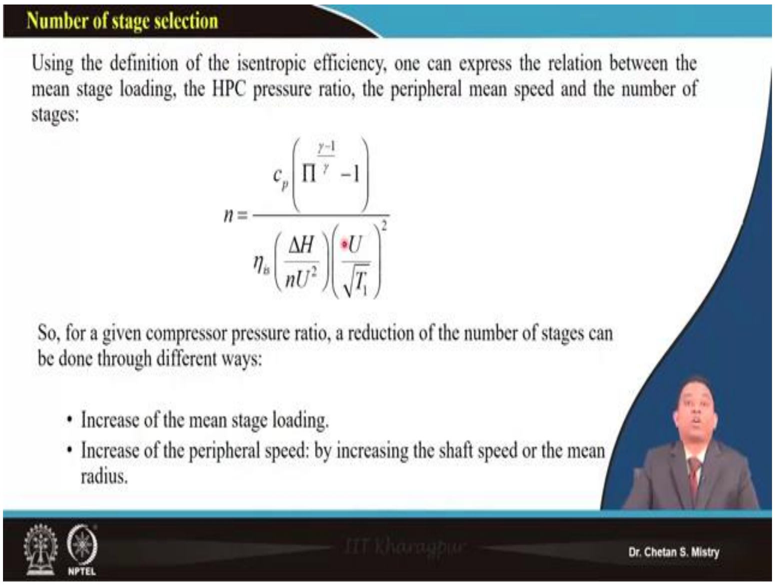


Now, let us see how we will be using this. So, if we consider, say, our HP compressor; so, my overall pressure ratio that's what has been correlated based on my say two parameters; one, it is say stage loading factor and second, that's what is say peripheral speed. So, here if you look at, this is what is representing my number of stages for HP compressor. You can see here, this is nothing but my overall pressure ratio for HP compressor and this is what is my stage loading coefficient and this is what is representing my say peripheral speed parameter.

So, you know, in order to have for particular pressure ratio, if you want to reduce the number of stages, we are having two clues; what it says? Maybe we need to have this to be increased. So, it says you increase the mean state loading coefficient, okay. Second, that's what is say you increase the peripheral speed. Now in order to increase the peripheral speed, we are having two options, maybe we can increase our rotational speed or we can go with increasing the diameter. So, both the parameters they are of great importance to us.

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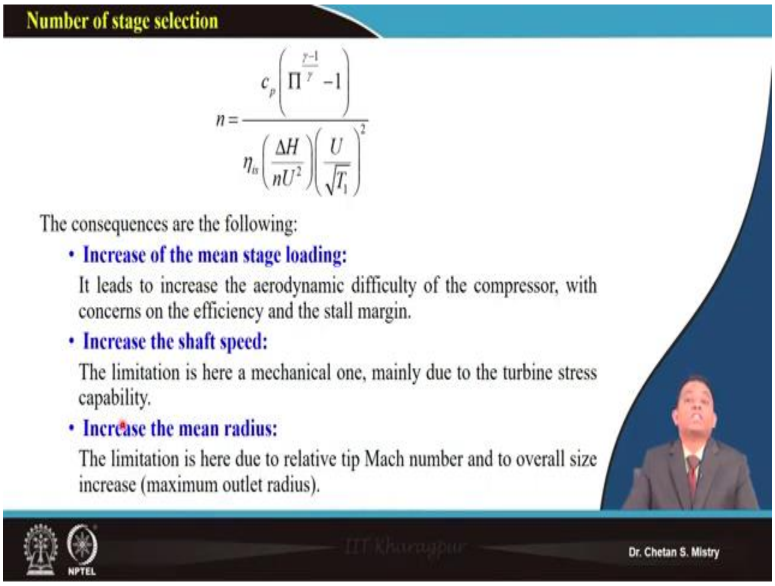


Now, this number of stages as we have discussed, we are having two parameters, that's what need to be increased in order to reduce the number of stages. When we say we are increasing our say mean stage loading, that's what will be creating trouble in sense of aerodynamics, okay; because we are more concerned about our efficiency as well as our stall margin.

So, when we say we are increasing our stage loading, my per stage pressure rise expectation will be very high and that may lead to my $\Delta\beta$ to be large and when this is what is your situation, there are chances for my flow to get separated and that is the reason why this higher loading that's what is one of the major concern.

Second option what we are having is say increasing the rotational speed. This increase of rotational speed, that's what is putting our mechanical constraint because we need to rotate our turbine and that turbine that's what will be having say higher stress and that is the reason why this higher rotational speed also will be the issue with us, okay.

Next option what we have is to increase the mean radius. So, when we say we are increasing our mean radius, it may be possible that near the tip region we will be having our flow to be say supersonic or transonic, okay. So, when we are having constraint with the overall size, we cannot increase this diameter. Suppose if we say, we are applying this design or say this concept for say aero engine for fighter aircraft there my diameter is coming as a constraint, so there we cannot think of changing this parameter, okay.

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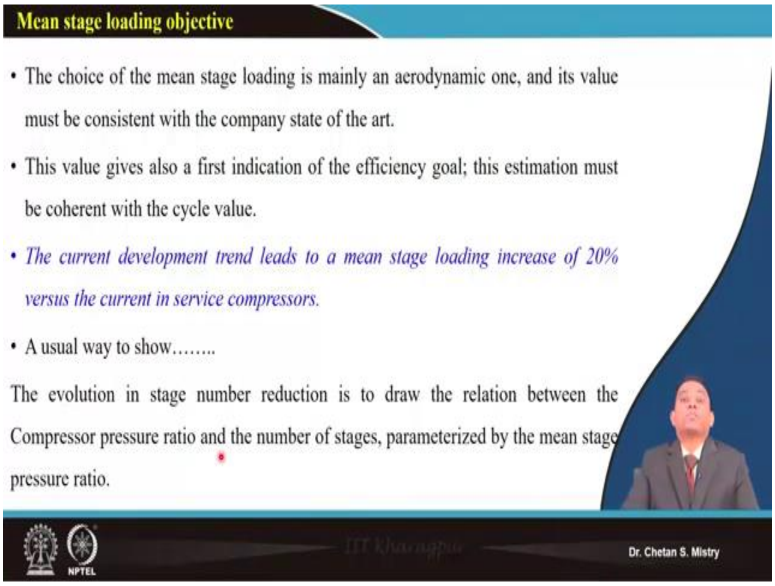


Now, the choice, that's what is mainly based on my aerodynamic requirement and that's what is say engine manufacturing companies, engine designing companies, they are having their own database with them and that's what they are using. So, here our major concern is with the efficiency and at the same time, we need to check with all our cycle parameters also, okay.

So, the current trend it is saying like mean stage loading, that need to be increased by 20% with existing flying engines. You can imagine, that's what is a big number in itself, okay. So, it says, you know, usually we need to play with the number of say…number of stages what we are looking for our design aspects, okay. So, this is what is in relation with what pressure ratio we are expecting, what number of stages we are talking of and what all are the effect of different parameters what we have discussed, that's what is my main loading coefficient and peripheral speed. So, let us try to understand what all are the effects of these parameters.

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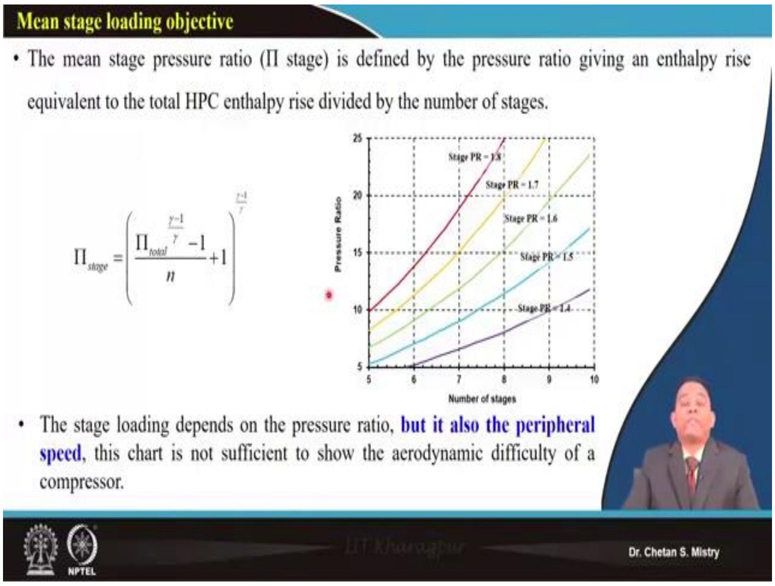


So, here if you go, this is what is correlating my total pressure ratio and stage pressure ratio based on our fundamental equation of the efficiency. And here if you look at, this is what is representing my stage pressure ratio that’s what is varying from 1.4 to 1.8 and this is what is my overall pressure ratio what we are looking for. And it says when we are selecting on the lower side, for particular pressure ratio, suppose say I am expecting my pressure ratio to be 10 and if you are selecting say stage pressure ratio of 1.4 it says we are looking for say 9 number of stages.

If I am increasing that to say 1.6, it says maybe we are looking for 6 number of stages. So, this is what is giving rough estimation but we should not forget this say stage pressure ratio and overall pressure ratio with number of stages is not the only parameter, we are talking about the second parameter also, that’s what is in relation with our peripheral speed, okay. So, let us try to look at what all will be the effect.

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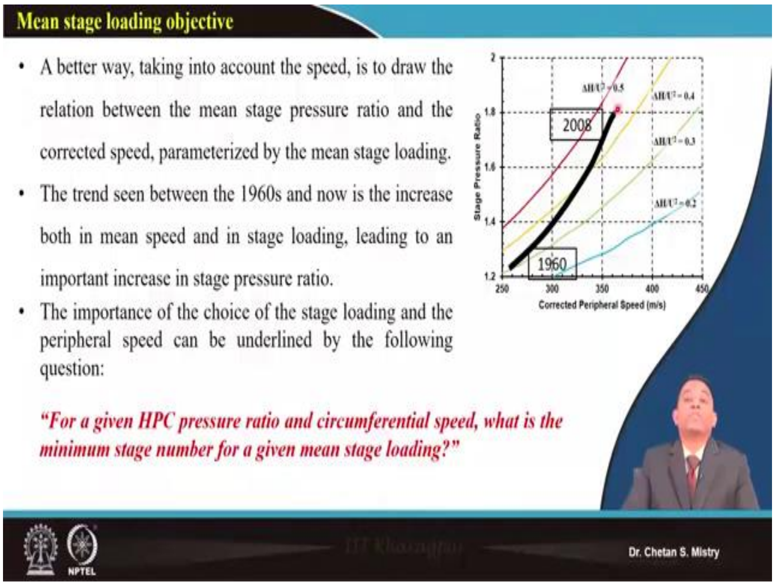


So, here in this case if you look at, this is what is represented my corrected peripheral speed versus my stage pressure ratio and this is what is representing my say stage loading coefficient or mean loading factor, okay. So, this is what is representing the trend from 1960 to 2008; if you look at carefully, its states my mean loading factor or main stage pressure ratio and my peripheral speed they all are increased by some amount, okay, and this is what is a recent trend.

Now, the question that's what will be coming with us is for HPC pressure ratio or for given HPC pressure ratio and circumference speed what will be the minimum number of stages for given mean stage loading. So, we need to decide with the parameter that's what is called mean stage loading coefficient and peripheral speed. And here if you look at, this is what is representing the most recent trend, okay. So, the selection of these two parameters that's what is very important for us.

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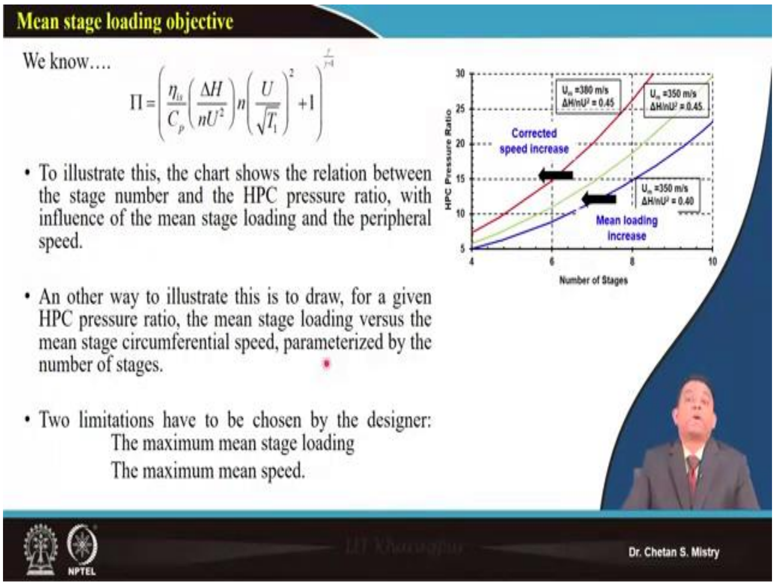


Now, here if you look at, this is what is representing my say overall pressure ratio, that’s what is in sense of say my mean loading coefficient, my peripheral speed, number of stages; and here if you look at, this is what is representing my number of stages versus HP pressure ratio for particular peripheral speed and my mean loading coefficient.

So, here if you try to look at, this is what is representing, when I am saying, mean stage loading if I am increasing, it says I am able to reduce the number of stages, okay. At the same time, you can say, we are able to achieve high pressure ratio. Now, going little greedy, it says, if I will be increasing my peripheral speed and my mean loading coefficient, again I will be able to reduce the number of stages required for particular pressure rise. And this is what is a global trend, that’s what is coming into the picture. And it says, we are having limitations with what need to be the maximum mean loading coefficient and what need to be my mean speed or mean peripheral speed, okay.

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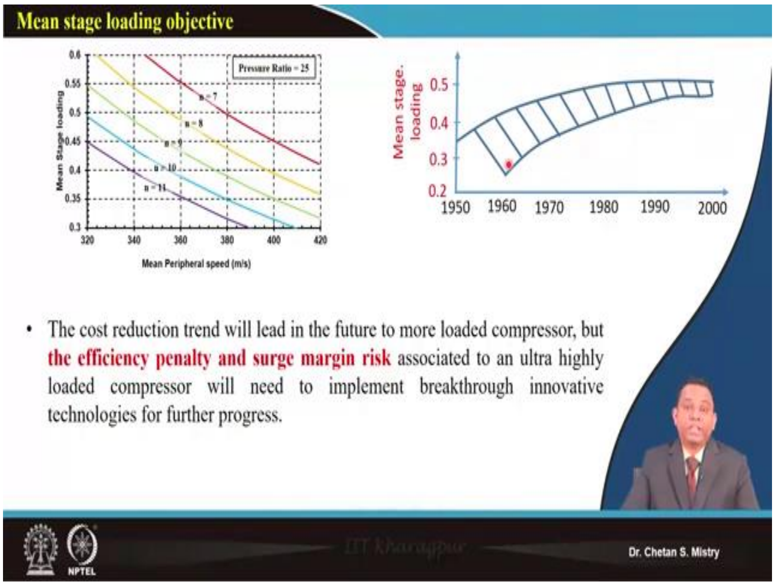


Now, here in this case, if you look at, this is what is representing suppose say if I am assuming my stage or overall pressure ratio is 25. It says, when I am moving with the particular peripheral speed and if I am selecting the number of stages, here if you look at, this is what we are doing, if we are reducing our number of stages then my mean stage loading that's what is going to increase.

So, if you recall, this is what is representing the global trend. What it says? Day by day, our expected overall pressure ratio, that's what is increasing and at the same time, we are moving towards say higher loading, higher mean stage loading that is where we are moving with. And when we are going say on the higher number or higher mean loading, we are going on greedy side and that is where it requires whole lot of new developments to be addressed, the issues related to the efficiency, issues related to say stall or say my operating range.

And that's what it says, we are looking for the new technologies to come in order to address this kind of issues, they are some of them, people they are working at this moment that's what is say aspiration, may be tandem bladed configuration, may be in sense of contra-rotating configuration, all those, that's what will be helping in order to achieve this kind of mean stage loading, okay.

So, you know, day by day, when we are expecting our pressure rise to be very high, we are expecting my number of stages to be lower, we are expecting compactness; so many expectations, that's what is coming for say my axial flow compressor, that's what is demanding more and more work need to be done in sense of research and development, okay.

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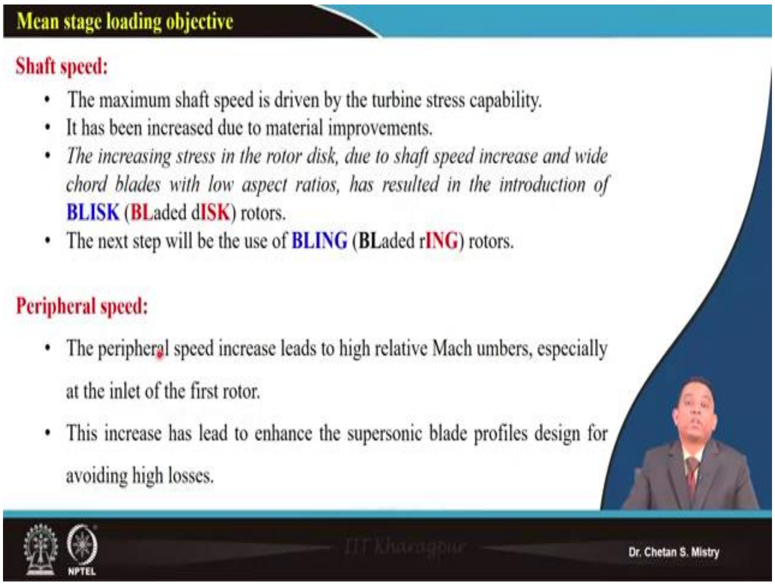


Now, if we discuss about the shaft speed, we have discussed that's what has been limited in sense of my turbine stress limit but with the development of new materials now this issue, that's what is been rectified. What present…present trend is, say with increase of stress on the rotor disc due to higher rotational speed, we are moving towards say low aspect ratio blade means we are having higher chord blade and this is what will be read as resulted into introduction of new kind of configuration that's what is defined as BLISK rotor, okay. So, this is nothing but the bladed disk rotors, okay.

So, the whole rotor that's what has been made along with hub with a single piece, okay, that's what is a recent trend people they started working on. There are many existing engines which are having this kind of configuration. The next step will be to use of bling, that's what is called say bladed ring rotors.

So, this is what will be coming for the near future. So, you can understand, with the requirement of high stage loading, with the requirement of high overall pressure ratio, all these developments, that's what is going on, okay. Second parameter as we have discussed, that's what we say my peripheral speed.

So, when we are increasing our peripheral speed, we will be having higher relative Mach number, okay. And, that's what will be mainly at the entry of my say compressor or say very first stage of my rotor, okay. And, that is where in order to enhance or in order to have performance to be improved, we have introduced new kind of airfoils; those airfoils, they are able to produce very high pressure rise by managing the flow within blade to blade, we will be discussing this aspect for say transonic compressor.

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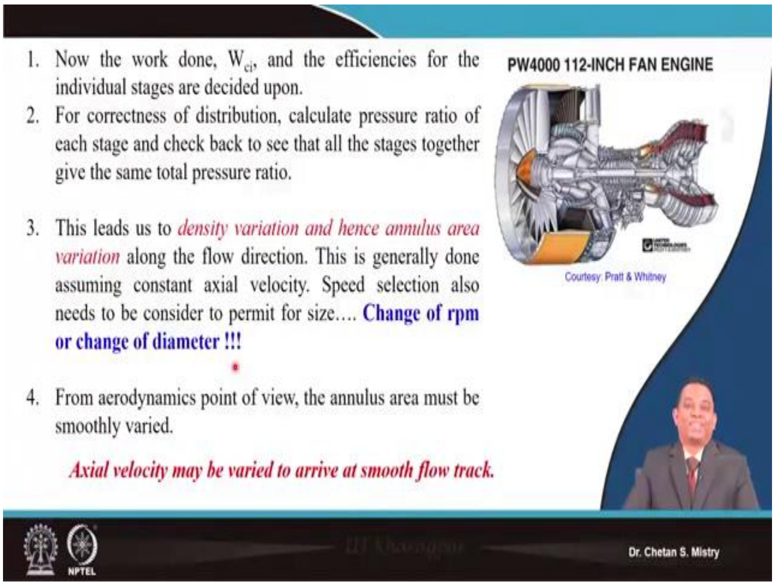


Now, you know, once, we have decided with our number of stages; we have decided with say what will be my stage loading, all these aspects, that's what will be giving us idea what need to be my design, okay and that's what we are fitting with say kind of configuration, we defined that as a track or flow track.

So, here in this case, we will be having say step by step calculation of my pressure ratio. That pressure ratio whether it is meeting with my overall pressure ratio. Then after we will be fixing all these stages, that's what will be giving me my flow track, okay. Now, you know, because of variation of our density and that is the reason we are having say variation of our annulus area, it may be possible that we will be having variation of diameter and that is the reason why we will be having variation of peripheral speed, okay.

So, we need to take care of this change, both the parameter changes, that's what is change in rpm and change in my diameter, okay. And as we have discussed, when we are talking about the aerodynamic aspects, we are looking for our flow track to be smooth flow track and when we say we are looking for smooth flow track, it may be having some compromise.

So, it says when we are doing our design for axial flow compressor it may be possible that in some region our axial velocity will be coming slightly on higher side, it may not remains constant, okay.

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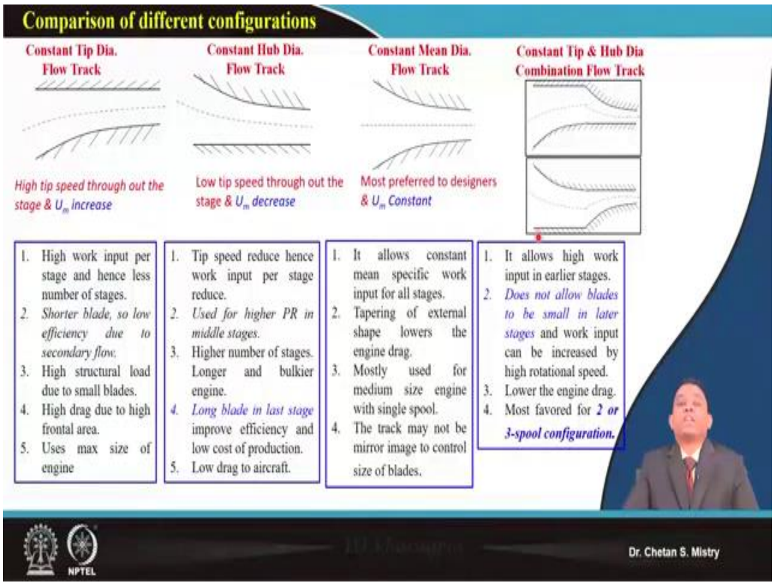


And, if you recall, this is what all we have discussed in sense of different kind of configuration, in sense like constant mean diameter, constant hub diameter, constant tip diameter and combination of flow tracks. Now, suppose we are looking for say number of stages to be reduced, we can say, we will be going with the configuration of constant tip diameter. But at the same time for the later stage, we will be having blade to be very small and that’s what will lead to reduce the efficiency.

Now, if we are having the flexibility that may be one or two stage we can increase and we want to have improvement in the efficiency, we can go with say constant hub diameter kind of configuration. Constant mean kind of diameter or constant mean track, that’s what will be giving us idea or benefit in sense of improvement of efficiency; so, most of the middle stages for our compressor for engines they have been designed based on that.

And in order to have combined benefit of constant tip diameter and constant hub diameter, we will be going with say combination and that’s what we are using at this moment for multi-spool configuration; let it be two-spool configuration or three spool configuration, for all those aspects we are using this combination of these tracks.

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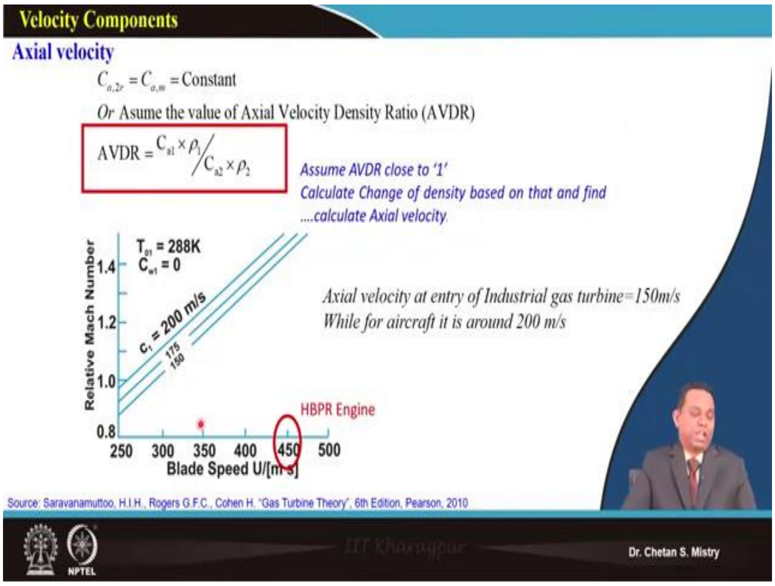


Now, we have next parameter, as we have discussed, we have introduced a parameter called say flow coefficient and that flow coefficient we have correlated with axial velocity and peripheral speed. So, axial velocity, that's what is also equally important parameter that need to be considered, okay. So, we are assuming our axial velocity to be constant. In some of the designs, people rather selecting say axial velocity alone they are selecting axial velocity density ratio, that is nothing but my entry velocity, entry axial velocity and entry density; and you know, it is a ratio of exit…say…axial velocity and exit density.

Now, when initially the cascade study, that's what was going on in different parts of say world, they realized, there is a fluctuation in results, fluctuation in $C_p$ distribution. And, they were unable to initialize at the initial moment. Then later on based on experimentation, they found like because of growth of boundary layer from both the walls for linear cascade, my central portion, that's what will be getting say higher axial velocity and that's what lead to change the $C_p$ distribution and that's what was creating trouble.

And in order to address this issue, they have introduced this axial velocity density ratio parameter. In some of the cascade tunnel, people they have kept some flow control mechanism like flow sucking mechanism, some corrugation, that's what they have kept on say both the walls and that's what was led to reduce this variation, okay.

So, in many designs, people they are using this kind of concept also that's what is called axial velocity density ratio, okay. And if you recall, this is what was a plot we were discussing when we were discussing, when we are looking for higher aerodynamic loading or higher pressure ratio or per stage pressure ratio.

And, here if you look at, this is what is representing my blade speed versus relative Mach number and these are nothing but we can say this is what is say my entry absolute velocity, if I am assuming my entry to be axial, we can say, this is what is representing axial velocity. So, what it says? Thumb rule says, my axial velocity for industrial compressor you can assume at initial guess to be 150 $m/s$ and for aero-engines, you can select that to be say 200 $m/s$, okay, or you can assume your blade peripheral speed, that is also one of the possibility.

So, here if you look at, for most of the high bypass ratio engines, this peripheral speed or this blade speed, that's what they are selecting as say 450 $m/s$ and for many engines they are going on slightly lower side for low bypass ratio that's what is in the range of 350 $m/s$.

So, the selection of parameter called flow coefficient, that's what is coming into the picture when we are deciding this thing. So, when we are not aware of what all parameters are known to me, say my mass flow rate, suppose that's what is unknown, I do not know what is my peripheral speed, if I do not know what is my axial speed under that condition, you can safely assume the flow coefficient as we have discussed in particular range and then after you can start doing your design, okay. So, there are strategies for the selection of this parameter.

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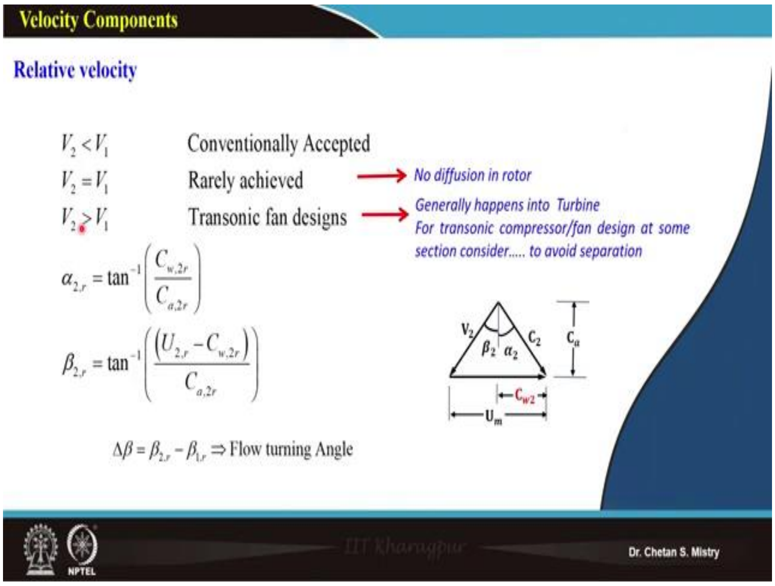


Then we have discussed about very important parameter, that's what is called say relative velocity ratio; we have defined that as say de-Haller's factor, okay. So, here if you look at, this is what is representing my exit relative velocity and on this side, I am having say, entry relative velocity. So, if I will be having my exit relative velocity to be lower, that's what we can say, it is showing the diffusion that's what is happening in my rotor and that's what is conventionally that's what has been accepted.

So, in order to check whether the diffusion has happened or not or my blade or rotor is doing diffusion or not, we can safely calculate base on the relative velocity. There are many designs in which we are having $V_2$ and $V_1$, they both are same. So, when we are talking about this kind of configuration it rarely happens, it says like there is no diffusion that's what is happening in my rotor.

So, you can understand, when we are talking about degree of reaction to be 0, this is what is a kind of configuration that's what will be coming into the picture. And, there are some design in which you will be having your relative velocity to be very large, okay. So, this is what is happening in transonic fan design, okay.

So, you know, conventionally this need to be happened in the turbine. So, many times, when we are doing our design for say transonic compressor or the fan, in some of the sections we are purposefully doing design like that in order to avoid the flow separation. If you recall, near the hub region, this is what is a critical problem and that's what will lead to say, you know, flow separation near the hub region and that's what is called hub stall. So, to avoid that kind of situation, we are using this kind of design configuration, okay.

So, we can understand, today what all we have discussed is in sense of selection of very important parameters, what all we have learned and how we are correlating that, those all parameters in the combination for the design, okay, in order to achieve particular stage efficiency. We also have discussed how do we decide with the number of stages because this is what is very crucial part when we are talking about say HP compressor, okay.

And we also have discussed about how do we decide with our parameter called…say…my flow coefficient, how do we decide with our axial velocity and what is the meaning of having say relative velocity to be different. We will continue our discussion in next session. Thank you very much for your kind attention.