Aerodynamic Design of Axial Flow Compressors and Fans
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Lecture No 63
Design of Industrial Fan (Contd.)

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Hello, and welcome to Lecture 63. So, in last lecture we started discussing the design of wind tunnel fan, that’s what will be developed at IIT, Kharagpur, sponsored by RDSO that’s what is called Centre for Railway Research at IIT, Kharagpur.

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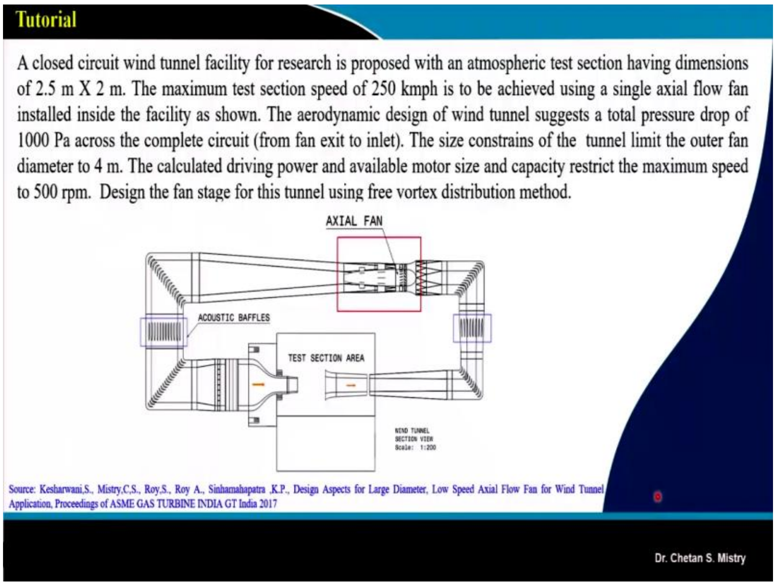

We are having the details, these all details that’s what is available with us in terms of test section, maximum diameter of say fan that’s what is required, we also have some constraints with the motor rating that’s what is available with us.

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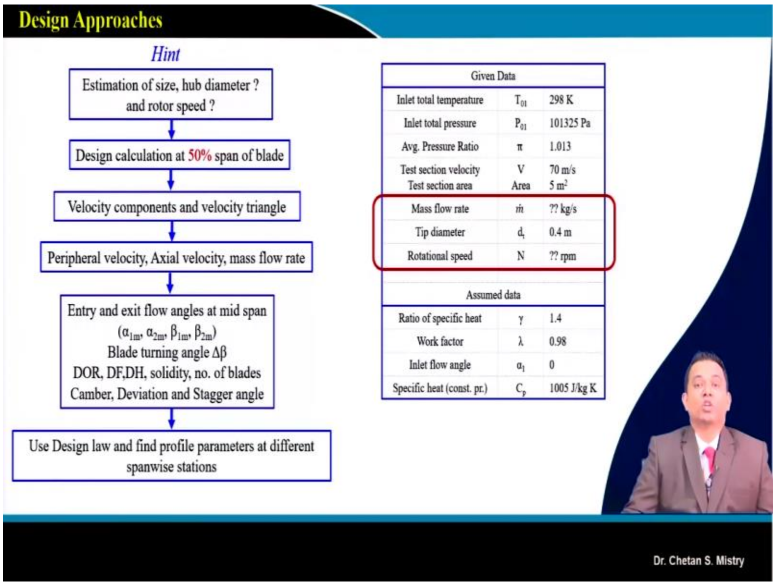

So, if we look at here, this is what we have started discussing about. And, here in this case, we have unknown parameters like mass flow rate, we have constraints with the diameter of the casing, we are not knowing what is the diameter of our hub, we are not knowing what exactly will be the axial velocity and other parameters.

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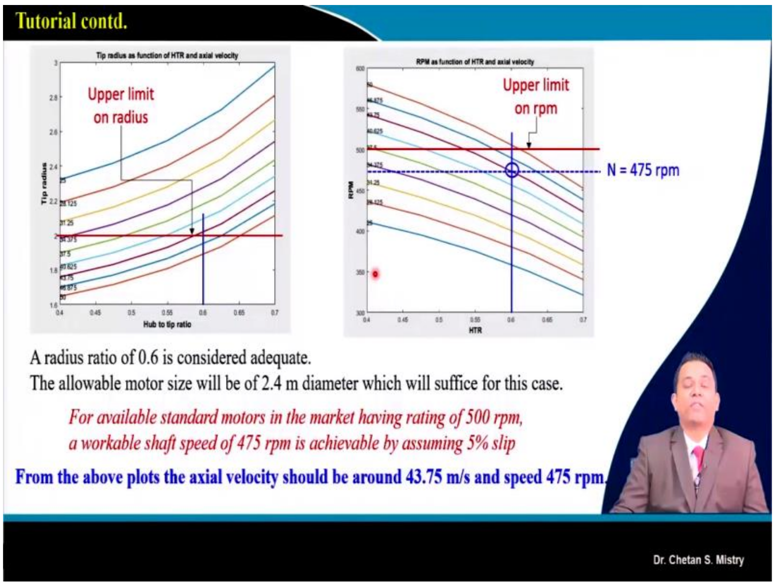

So, we started discussing about the selection of different parameters and we have correlated that with say hub-to-tip radius ratio. So, we have correlated our radius ratio with hub-to-tip ratio and different axial velocity numbers, at the same time we are having constraint with the rotational speed and that's what we have kept as say 500 rpm. Now based on this parametric study we have come up with say radius ratio of 0.6 and that's what is giving us axial velocity in the range of 43.75 m/s.

And, this rotational speed that's what was coming say 475. Based on that we have made assumption of axial velocity to be 44 m/s and we have come up with our rotational speed of 480 rpm and that's what we have decided as our final parameter for doing further calculation.

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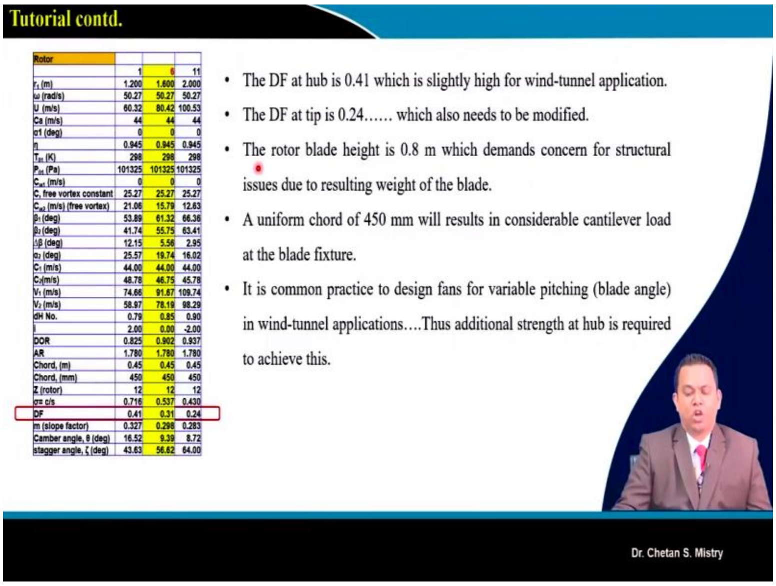

And, in sense of doing the calculation we have done our calculation at the mean line based on our fundamental understanding. The design approach for industrial fan for say industrial compressor or say axial compressor for aero engine that's what is remains same, it is common. Here, in this case this fan is subsonic fan that is the reason we are doing our mean line calculation at 50% span.

Now, this is what all we have discussed about. We have assumed our aspect ratio of the rotor blade as say 1.78. We have assumed our solidity as 0.54 and based on that we have started doing the calculation. We have done our calculation at the hub station as well as tip station because we have adopted our approach of free vortex design. Now, based on this free vortex design methodology we have come up with this number.

So, if you look at these numbers, say my diffusion factor at the hub it is coming 0.41 and diffusion factor at the tip that's what is coming 0.24. Now, here if you look at, this fan what we are planning to design for wind tunnel application that's what is expected to generate certain pressure rise. Now, we are not going aggressively in sense of doing design for such kind of fans.

Like in the case of compressor we are expecting our diffusion factor to be in a large number, say 0.5, 0.55, 0.6 that's what is our expected number. Since this is what is a fan we are not expecting such high diffusion factor near the hub region. At the same time near tip also, this is what is coming slightly on higher side. Now, if we look at our height of the blade, that's what is coming 0.8 m.

And, for that 0.8 m height and chord of 450 mm if we consider the weight of single blade that's what will be coming slightly on a higher side. So, conventionally what people they are doing? Say, this is what will be acting like a cantilever and in order to avoid the structural problem, in order to provide the structural rigidity, people they are adopting different kind of concepts.

At the same time, when we are talking about the wind tunnel fans, this wind tunnels fans they are having provision for changing of pitch angle that's what is basically maintaining the mass flow rate through this fan. And, at the same time it is used to manage the flow velocity that's what is required at the test section and in order to have such kind of mechanism, in order to treat the blade at certain angle we need to have pitching mechanism.

So, my hub or my station of hub for the blade that need to be rigid or that need to be strong. So, in order to address all these aspects, we have done certain modifications in the design. Let us see what modifications we have done.

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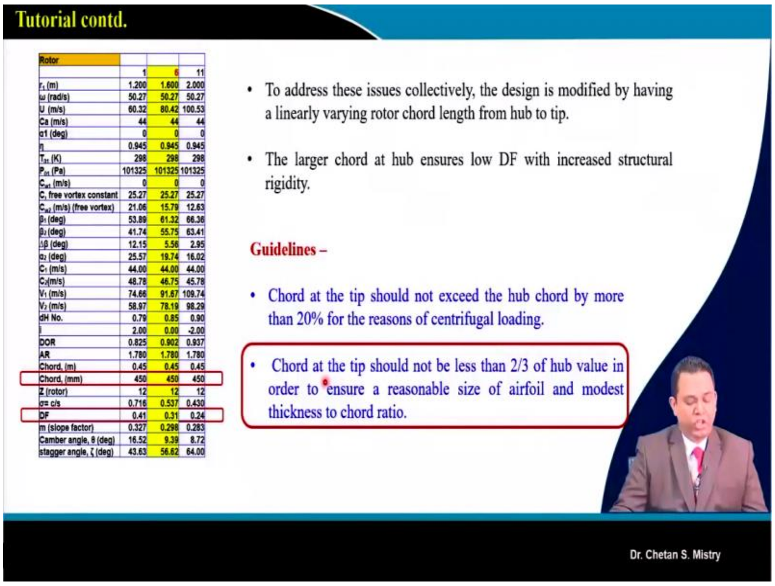

So, here in this case, like in order to address the issue with the structure with the requirement…special requirements and weight, the chord of the blade that's what need to be varied from hub-to-tip. So, there are different methodology, there are different guidelines that's what is available in different handbooks, specially for the fans. What they say? The chord of the tip should not exceed the hub chord by more than 20% because of centrifugal loading action.

Second aspect it says the chord of the tip should not be less than $2/3^{rd}$ of the hub value in order to assume say in order to have reasonable size of the airfoil as well as thickness to chord ratio variation for that airfoil. Now, here if we look at, this is what is a special kind of fan that's what we are using for industrial purpose, that's what we are using for wind tunnel fan.

So, we are adopting second approach in which we will be having chord that's what will be different at hub, my chord at the mid section will be different and chord at the tip section will be different. So, we need to assume systematic distribution of the thickness or we can say we need to assume systematic distribution of chord from hub-to-tip.

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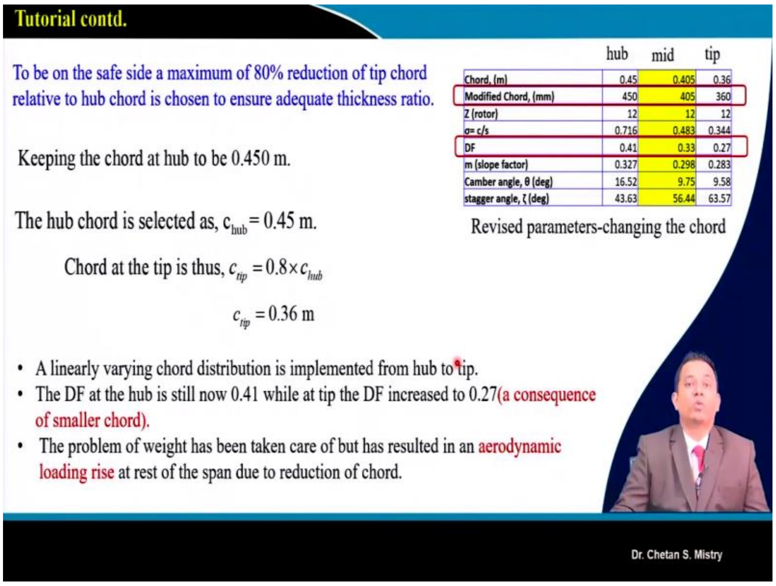

So, in order to address this issue what we need to do is here, we have modified our chord. So, my chord at the hub, that’s what we have kept as say 450 mm and near the tip we have assumed our chord to be 80% chord of hub and that’s what is giving my chord at the tip as 0.36.

$$Keeping\ the\ chord\ at\ hub\ to\ be\ 0.450\ m$$

$$The\ hub\ chord\ is\ selected\ as, c_{hub} = 0.45\ m$$

$$The\ chord\ at\ the\ tip\ is\ thus, c_{tip} = 0.8 \times c_{hub}$$

$$c_{tip} = 0.36\ m$$

Now, here if you look at, this is what is representing a variation of my chord say 450 mm that’s what is at the hub, 405 mm that’s what is at the mid station, and at the tip, that’s what is coming 360 mm.

Now, when we are modifying our chord, what is happening? Our diffusion factor, that’s what is going to change. So, here if you look at, my diffusion factor that’s what is coming 0.41 and at the same time near the tip, that’s what is coming 0.27. So, basically in order to address the issue because of weight what we have done? We have modified our chord.

But at the same time, that’s what is creating trouble in sense of aerodynamic loading. And, that is the reason why we need to address now this particular issue. So, what is happening let us see.

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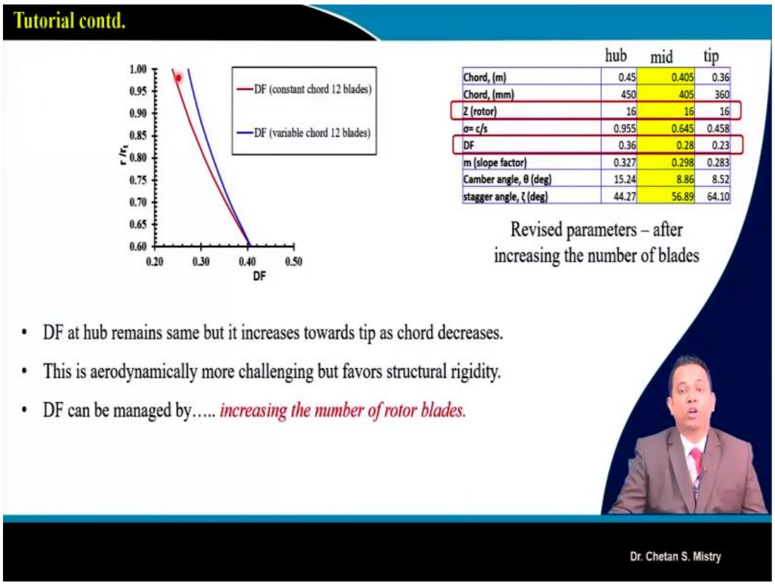

Say, here if you look at, say this red colour one, that's what is representing when I am having constant chord. So, this is what is representing how my diffusion factor that's what is varying from hub-to-tip. So, here in this case, this is what is representing my diffusion factor variation when I am having constant chord. Now, when we have modified our chord, under that condition if we look at near the hub region we have assumed our chord to be same as 450 mm that is the reason why my diffusion factor is same.

But along the span if we look at, the diffusion factor that's what is going to increase, okay. Now in order to address say like as we discussed we are not looking for aggressive design in sense of aerodynamic loading for this particular blade. And, in order to address this problem, now we need to explore some other possibility and that possibility is nothing, but that is to change the number of blades.

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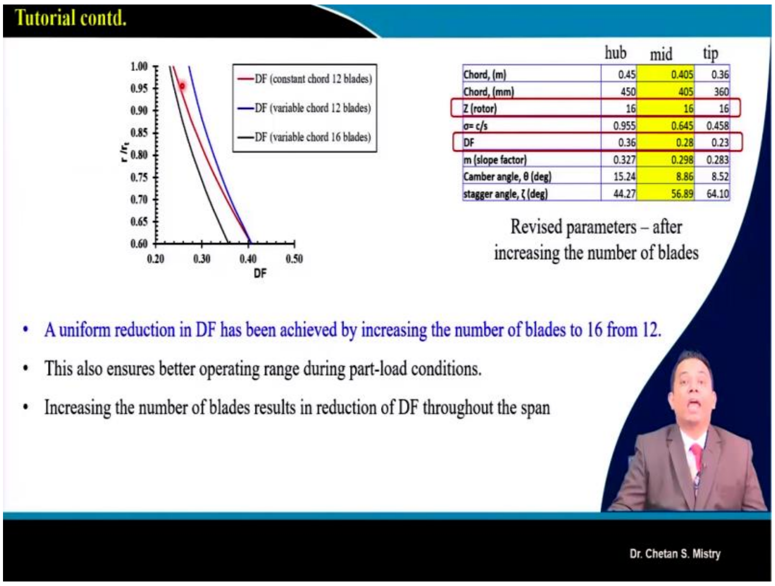

So, here if we look at, this is what is representing when I am having my chord, that's what is varying from 450 mm to 360 mm near the tip region in place of number of blade to be 12; now, we are assuming our number of blades to be 16 and by doing so if we compare here, this is what is representing my variation of diffusion factor along the span. So, if we look at carefully we can see we are able to reduce the loading near the hub as well as near the tip.

And we can say throughout the span we are able to manage our diffusion factor. We are able to manage our loading. Basically, this is what is helping us in sense of operating range when we are working under part load condition and we have seen when we are having our system resistance that's what is changing under that condition also this fan need to work in a systematic way as per our expectation.

And, in order to have that, this is what is a modification that's what we have done. Now, this modification basically we have taken the help of CFD. So, when we will be discussing in next week the use of CFD in one of the case study, we will be discussing this modification of number of blades and how my flow physics that's what is changing and how it is helping, but at this moment we can realize, we can understand this part.

This is what is one of the way of changing the aerodynamic loading for the fan. So, when we are talking about the industrial fan, when we are talking about the wind tunnel fan, we need to be very careful in sense of selection of aerodynamic loading throughout our span, okay.

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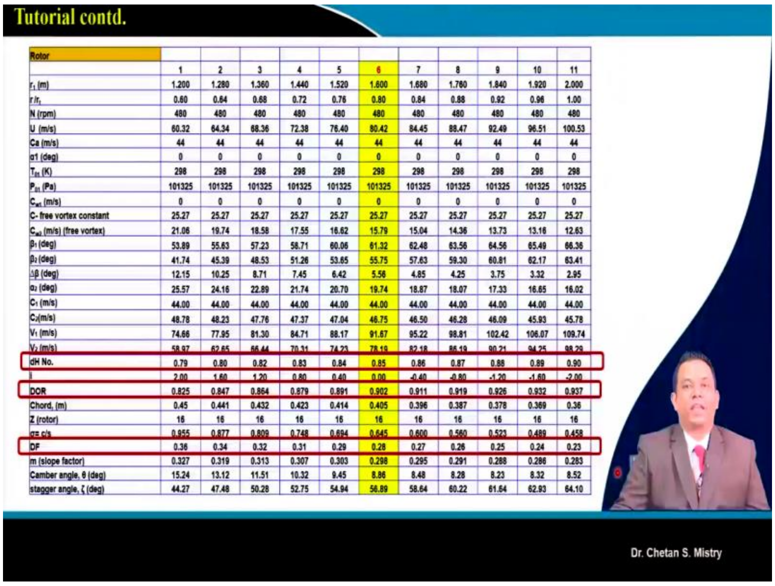

Rotor											
	1	2	3	4	5	6	7	8	9	10	11
r_1 (m)	1.200	1.280	1.360	1.440	1.520	1.600	1.680	1.760	1.840	1.920	2.000
r/r_t	0.60	0.64	0.68	0.72	0.76	0.80	0.84	0.88	0.92	0.96	1.00
N (rpm)	480	480	480	480	480	480	480	480	480	480	480
U (m/s)	60.32	64.34	68.36	72.38	76.40	80.42	84.45	88.47	92.49	96.51	100.53
Ca (m/s)	44	44	44	44	44	44	44	44	44	44	44
α1 (deg)	0	0	0	0	0	0	0	0	0	0	0
T_{01} (K)	298	298	298	298	298	298	298	298	298	298	298
P_{01} (Pa)	101325	101325	101325	101325	101325	101325	101325	101325	101325	101325	101325
C_{w1} (m/s)	0	0	0	0	0	0	0	0	0	0	0
C- free vortex constant	25.27	25.27	25.27	25.27	25.27	25.27	25.27	25.27	25.27	25.27	25.27
C_{w2} (m/s) (free vortex)	21.06	19.74	18.58	17.55	16.62	15.79	15.04	14.36	13.73	13.16	12.63
β_1 (deg)	53.89	55.63	57.23	58.71	60.06	61.32	62.48	63.56	64.56	65.49	66.36
β_2 (deg)	41.74	45.39	48.53	51.26	53.65	55.75	57.63	59.30	60.81	62.17	63.41
Δβ (deg)	12.15	10.25	8.71	7.45	6.42	5.56	4.85	4.25	3.75	3.32	2.95
α_2 (deg)	25.57	24.16	22.89	21.74	20.70	19.74	18.87	18.07	17.33	16.65	16.02
C_1 (m/s)	44.00	44.00	44.00	44.00	44.00	44.00	44.00	44.00	44.00	44.00	44.00
C_2(m/s)	48.78	48.23	47.76	47.37	47.04	46.75	46.50	46.28	46.09	45.93	45.78
V_1 (m/s)	74.66	77.95	81.30	84.71	88.17	91.67	95.22	98.81	102.42	106.07	109.74
V_2 (m/s)	58.97	62.65	66.44	70.31	74.23	78.19	82.18	86.19	90.21	94.25	98.29
dH No.	0.79	0.80	0.82	0.83	0.84	0.85	0.86	0.87	0.88	0.89	0.90
i	2.00	1.60	1.20	0.80	0.40	0.00	-0.40	-0.80	-1.20	-1.60	-2.00
DOR	0.825	0.847	0.864	0.879	0.891	0.902	0.911	0.919	0.926	0.932	0.937
Chord, (m)	0.45	0.441	0.432	0.423	0.414	0.405	0.396	0.387	0.378	0.369	0.36
Z (rotor)	16	16	16	16	16	16	16	16	16	16	16
σ= c/s	0.955	0.877	0.809	0.748	0.694	0.645	0.600	0.560	0.523	0.489	0.458
DF	0.36	0.34	0.32	0.31	0.29	0.28	0.27	0.26	0.25	0.24	0.23
m (slope factor)	0.327	0.319	0.313	0.307	0.303	0.298	0.295	0.291	0.288	0.286	0.283
Camber angle, θ (deg)	15.24	13.12	11.51	10.32	9.45	8.86	8.48	8.28	8.23	8.32	8.52
stagger angle, ζ (deg)	44.27	47.48	50.28	52.75	54.94	56.89	58.64	60.22	61.64	62.93	64.10

Now, once we have decided with this, this is what is a final excel sheet, or this is what is my final design sheet, okay. Now, in final design sheet we know what all methodology we are opting for all the designs, subsonic fan design, say contra rotating fan design, compressor design, transonic compressor design, for all of them this methodology that's what will remain same. Only difference here is in sense of having say constant span kind of configuration because my pressure rise expected that's what is say on a lower side.

So, here if we look at the numbers, it says my de-Haller's factor, that's what is varying from 0.79 to 0.90. At the same time if we look at our degree of reaction, we can say that's what is varying from 0.82 to 0.93. So, the meaning of degree of reaction we must realize here; what it says? Majority of my work that's what will be done only by the rotor, okay, when we are having our degree of reaction to be higher.

So, almost all diffusion that's what we are expecting that need to be done by the rotor, okay. So, this is the kind of design. Now, why we have done this? We will see when we will be discussing design of the stator. Now, here in this case, as we have discussed, we are able to manage our diffusion factor that's what is varying from 0.36 to 0.23, okay. And accordingly, we are having say variation of camber angle and stagger angle.

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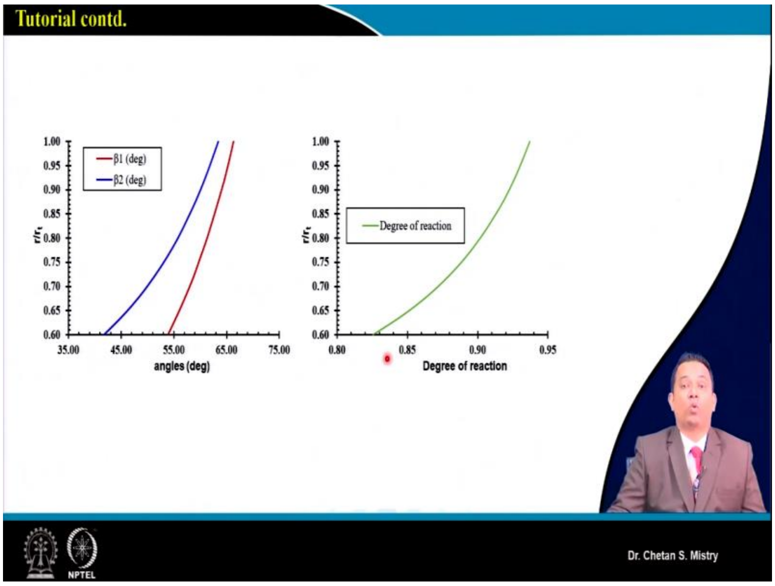

So, let us look at how my $\Delta\beta$, that's what is varying. So, here if we look at my $\Delta\beta$ since my loading is on lower side, my diameter is larger; just understand, just imagine the dimensions we are talking about say dimension of 4 m diameter, we are considering our diameter for the hub that's what is 2.4 m diameter. So, under that condition my $\Delta\beta$ variation if we are looking at this is how $\Delta\beta$ that's what is varying.

At the same time, degree of reaction as we have discussed, this is what is a design where we are expecting majority of our loading or majority of my work done or majority of my pressure rise that's what will be happening only with the rotor. Now, the question is what is about the stator? Let us see.

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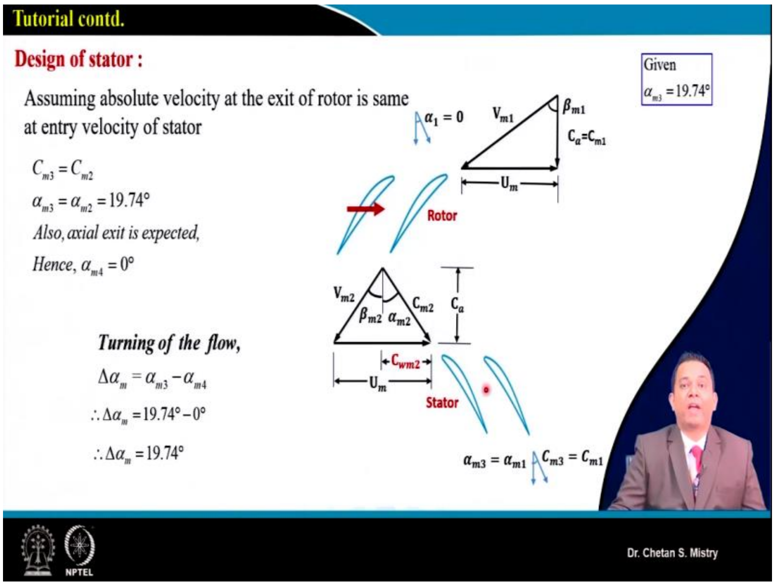

So here, this is what is a design for our stator. If we look at for the stator the assumption that's what is the flow which is coming out from the rotor that's what is coming at absolute velocity C_2 and angle α_2 and as per our conventional design what we are doing? My α_2 *and* α_3, they both are same, and since this is what is a fan in which we are considering our exit to be axial one.

So, we can say my α_4, that's what is 0. So, if we are putting that my $\Delta\alpha$, that's what is coming 19.74.

Assuming absolute velocity at the exit of rotor is same as entry velocity of stator

$$C_{m3} = C_{m2}$$

$$\alpha_{m3} = \alpha_{m2} = 19.74°$$

Also, axial exit is expected,

$$Hence, \alpha_{m4} = 0°$$

Turning of the flow,

$$\Delta\alpha_m = \alpha_{m3} - \alpha_{m4}$$

$$\therefore \Delta\alpha_m = 19.74° - 0° = 19.74°$$

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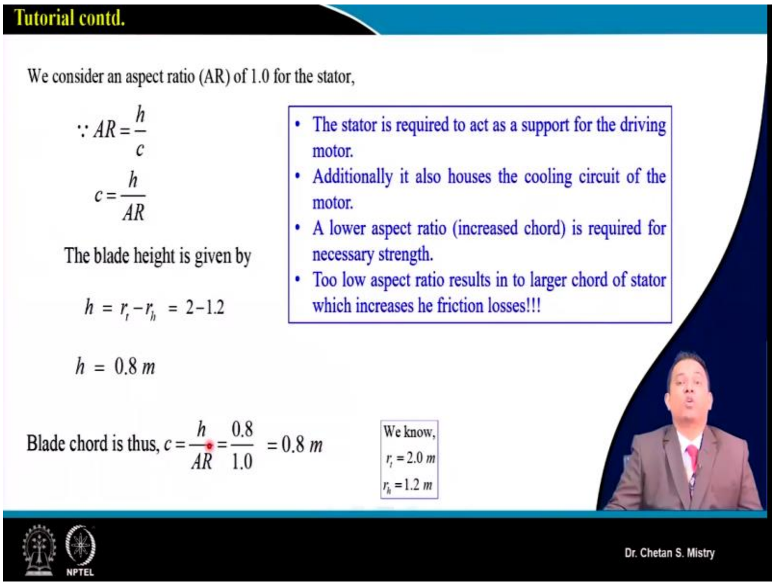

Now, for this stator; now, as we are discussing stator design that is also equally important for such kind of application. Now, as we have discussed in very first lecture and I was saying like purpose of the stator it is to guide the flow then later on we have discussed, we have introduced the parameter that's what is degree of reaction where we were discussing my half diffusion that's what will be done by the rotor, and my half diffusion, that's what will be done by say stator.

So, stator also is contributing in sense of diffusion. Now for this fan design we have understood my degree of reaction that's what is coming on higher side that's what is representing majority of my diffusion that's what is happening with the rotor. Now what is the use of stator then? The stator is required to support the driving motor.

So, we can understand, if we look at the construction it says like I need to accommodate my fan that's what is in a closed circuit wind tunnel. Now, for that close circuit wind tunnel, we need to accommodate our motor that will be on the back side of my rotor and stator combination. So, basically this stator we are using as a supporting structure. Secondly, this motor, that's what is having high power capacity say 750 kW.

So, we can imagine once it is started running with, it will be generating lot of heat and that's what is demanding for the cooling. So, my cooling circuit or cooling pipes that can be accommodated through this stator blades. That is second advantage that we need to take with. If we consider suppose say lower aspect ratio kind of configuration that's what will be giving the necessary strength for such kind of rotating device.

And if we configure two row kind of configuration, that's what will be having say larger chord and when we are having larger chord, that's what will be increasing our frictional loses because my solid surface, that's what will be large and that's what is creating trouble in sense of increasing the loses. So, now here we need to play with the aspect ratio. Basically, for such kind of configuration aspect ratio that's what is roughly been selected as 1.

So, if we are considering my aspect ratio to be 1, that's what is giving the height of my blade it is 0.8 m and my chord of the blade or stator blade that's what is also coming to be 0.8 m, okay.

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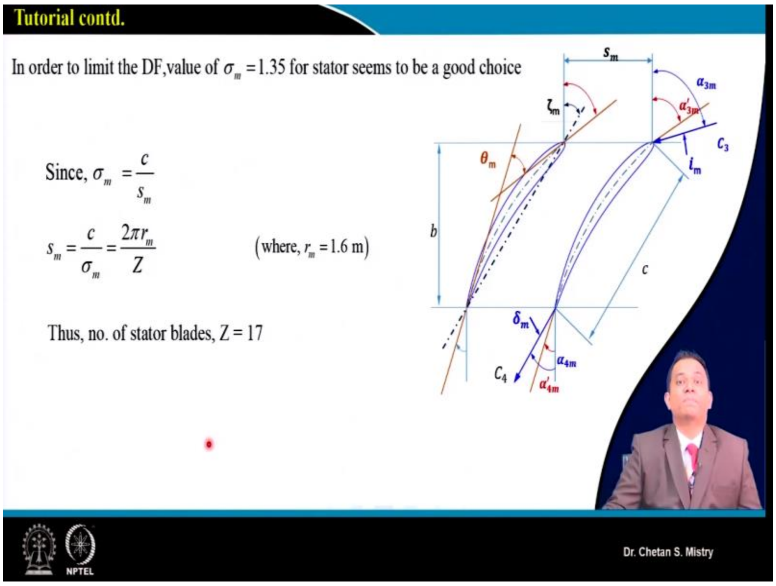

Now, in order to select the number of blades. So, as we have discussed earlier, now here if we look at old tunnels, modern tunnels, most modern tunnels, for all these tunnels the combination of stator and rotor blade that's what is very important. Now, when we are talking about say low acoustic wind tunnel design we know when the blade that's what is rotating, my rotor blade is rotating that's what will be striking on the stator.

Under that configuration there maybe chances of the wake that will be striking on the stator blade and this is what is generating lot of noise. So, in order to avoid that kind of configuration, in order to avoid such kind of situation, it is preferred that maybe one or two blade more we need to select for the stator. If we are considering even kind of configuration that's what is creating trouble in sense of say resonance.

And, that is the reason why one more blade that's what we need to select with. So, we have selected with the combination of 16 and 17 blade. So, in order to have that we are having two different approaches possible. We can assume our mean solidity. So, here in this case in order to limit the diffusion factor, the solidity it was assumed to be 1.35. When we are putting that solidity to be 1.25, we are getting our number of blades to be 17.

$$In\ order\ to\ limit\ the\ DF, value\ of\ \sigma_m = 1.35\ for\ stator\ seems\ to\ be\ a\ good\ choice$$

$$Since, \sigma_m = \frac{c}{s_m}$$

$$s_m = \frac{c}{\sigma_m} = \frac{2\pi r_m}{Z}$$

$$Thus, number\ of\ stator\ blades, Z = 17$$

There is other way as I told maybe you can select the number of stator blades and based on that you can do your calculation for solidity that is also possible. It is your choice you can play with the numbers and accordingly you decide with, but there are certain thumb rules that's what is available in open literature which is suggesting this kind of configuration to be possible.

One more thing is the cost of this fan that is very important. Suppose, if we consider this diameter fan with motor and stator and rotor blade it may cost in terms of crores of rupees. So, reducing the number of blade for stator, reducing the number of blade for rotor, that's what is also one kind of parametric study, people they are doing that study and finally they are coming up with the solution, okay.

So, as per the demand, as I told, as a designer you may be having many constraints, those constraints we need to take care of, okay. Somebody will say I am looking for wind tunnel fan it should not have high cost then it is your choice to decide with. Sometimes the structure engineer will say we are not looking for such kind of large diameter, we are looking for small diameter.

So, if possible just try to accommodate small diameter fan that's what will be giving same performance; yes, that's what is designer's choice. Now designer, he has to play or she has to play with the numbers in order to achieve the expected performance for this fan.

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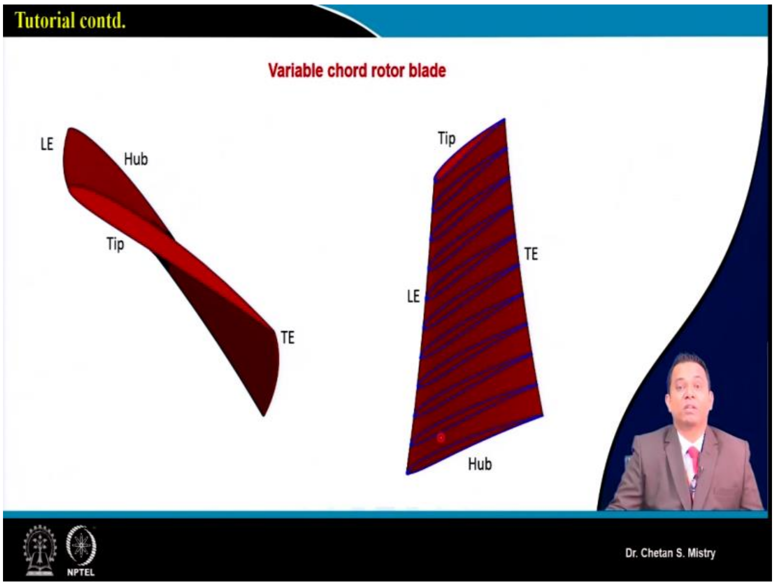

Now, once this is what is done, this is what is representing my rotor blade. If we look at the rotor blade, my camber of this blade that's what is lower because my aerodynamic loading is low. Just understand the thing my $\Delta\beta$, that's what is coming to be lower and that is the reason why my camber at hub, my camber at tip that's what is lower and here we can say this is what is representing the stacking of my blade about the CG.

Be careful, what we are doing here! There are some designs in which people they are doing stacking about leading edge, there are some designs in which people they are doing they are stacking about say trailing edge. Again, this is what is designer choice, but it is most preferred when we are going with say rotating component we need to stack these blades about say CG point only, okay.

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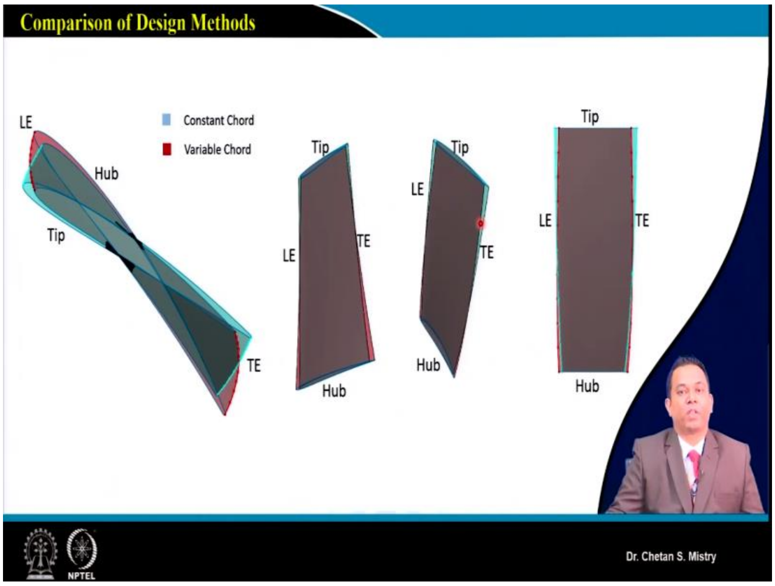

Here, this is what is with the constant chord of 450 mm we can say this is also been stake about the CG point. And, if we compare these two blades, we can easily understand how my twist of the blade, that's what will be coming with. Because we are having change of our chord, all the way from hub to tip and this is what is representing how my dimensions that's what is changing all the way from hub-to-tip, okay.

So, here this is what is very important for all of us to realize how you will be deciding with this number of blades, how do we decide with chords and everything. Now, this is what is the first cut kind of design or we can say it is a preliminary design; later on using computational tool you can do your study and you will come up with nice airflow or flow field study kind of study and based on that you will be finalizing your dimensions.

Once you are finalizing, you make the blade and do have testing for that; but you can understand, for this kind of fans to be tested it required different kind of testing facility 4 m diameter. I was telling like for cooling towers, these fans, they are in sense of 12 feet diameter, 20 feet diameter, just can imagine the dimension what we are talking of. Though, this fans for cooling fan, they are rotating at low speed maybe 80 RPM or 100 rpm.

Same here also, we can see though this diameter that's what is 4 m, my rotational speed is in the range of 400 to 500 rpm, okay. So, realize all these dimensions, realize this understanding for design.

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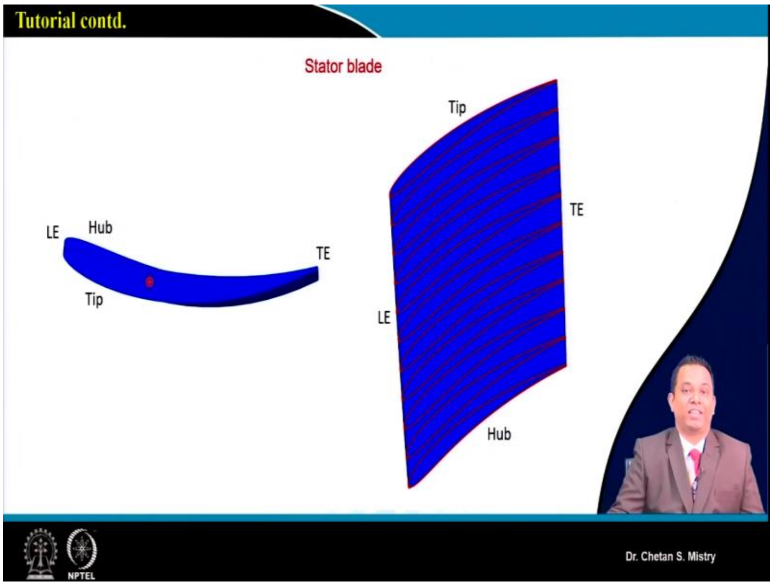

Now, this is what is representing the stator blade, as we have discussed, since this is what is having say larger chord. So, my thickness of this blade, that’s what will be coming to be large. So here, this is what can be used in order to accommodate maybe cables, my cooling circuit, this is what will be acting like a supporting structure. So, this is what is all about what we say of design for wind tunnel fan, okay.

So, this is what is one kind of industrial fan, that’s what is challenging in these aspects; later on people, they are asking for performance map with change of different pitch angles based on that they are doing their parametric study, all those stuff, that’s what will be coming. But, initially we must realize we are having one design point that means one mass flow rate and one pressure rise, that’s what is called design point.

We cannot have more than one design point, just keep this in mind, okay! Now, this is what is representing the design of say wind tunnel fan.

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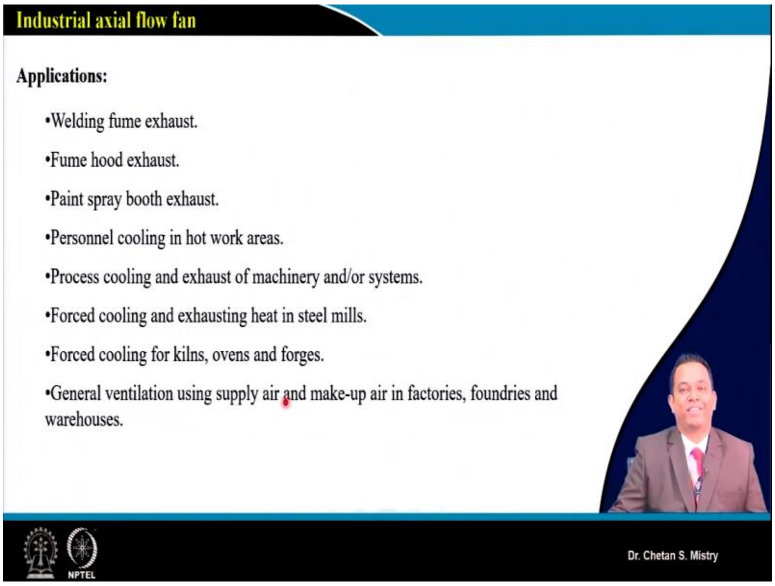

Now, there are certain different applications of this industrial fans other than what all we have discussed. What are they? Say, welding fume exhaust, fume hood exhaust, paint spray booth exhaust, personnel cooling in hot work area, process cooling or the exhaust of machinery and or the system, forced cooling and exhausting the heat in steel mills, forced cooling in the kiln, ovens and forges, general ventilation using the supply of air and make the air in factories, foundries and warehouses.

So, you know, like applications for this axial flow fan, that's what is not restricted with what all we have discussed up till now. There are so many applications also possible; people, they are using this axial flow fan we can say it is a part of industry wherever you visit the industry, maybe process industry or say maybe plant or maybe you are going for say computational center there also you will be finding such kind of axial flow fans!

So, realize the importance of this, okay. Now, when we are talking about the industrial fan, their specification that's what will be somewhat different.

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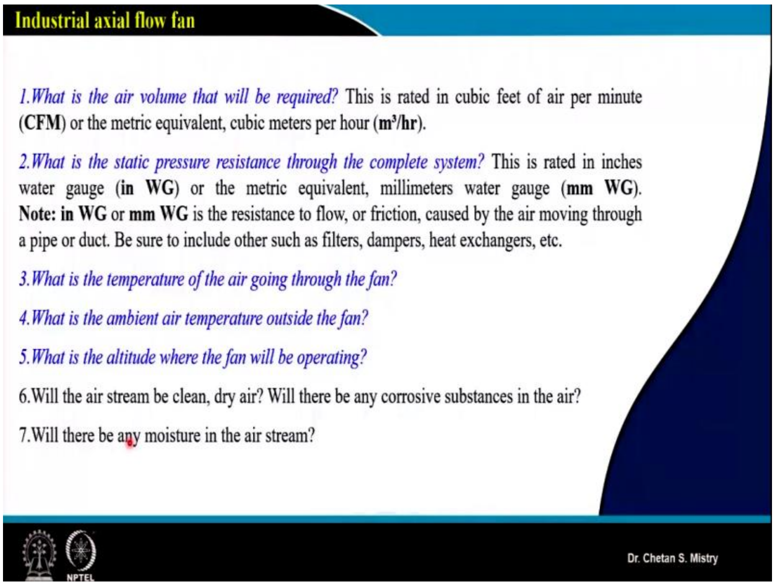

What they are doing? Say, the mass flow rate what we are discussing for axial flow compressor or for say fan; now for industrial fan, this people, they are talking the flow rate in sense of CFM, that is cubic feet per minute, that's what is rated mass flow rate they are discussing with. Same way, we are talking in sense of total pressure rise. Here, for industrial fan, they people, they are talking in sense of static pressure rise for the particular system.

Now, for this system, that's what has been represented in sense of say mm of water gauge or we can say this is what is representing in sense of inch of water gauge. So, we can say this pressure or your fan that need to generate sufficient amount of pressure to override the problem in sense of frictional losses. Basically, when the fluid is flowing through the duct, that's what will be having loss of pressure and that's what we are recovering using these fans.

At the same time, what is the temperature of air going through this fan that is also equally important because we can understand we are defining certain parameters, we are calculating our design parameters say mass flow rate, axial velocity, density, area that's what is a function of this temperature, okay. Same way, the exhaust maybe going to ambient condition that temperature also is equally important.

We know that's what is varying, but still we need to have certain reference temperature where we are exhausting our air. At what altitude these fans are operating, that is also important. You can realize what we are discussing is mainly the effect of pressure, effect of density, effect of temperature those all parameters need to be considered, when we are talking say design of our industrial fan.

It says will the air stream be clean and dry air? or it may be having some substances that’s what is moving with the air? Now, we can understand when we are designing the fan for say ventilation application for mines, there, this configuration also is equally important, okay. Then it says will there be any moisture in the air stream? Suppose, we are talking about say some application where we are using cooling, okay.

Suppose, we are considering say cooling tower fan, that fan also we need to have our configuration in sense of what is the moisture content in the air stream. So, now if we look at in overall sense, these industrial fans seems to be little tricky and different than what all understanding we have. Now, these fans need to be designed and that design that need to be done by people like you and me.

But the design methodology what all we have discussed for last 10 weeks, the same design methodology we need to opt for. Only thing is few parameters we need to realize few parameters, few numbers we must understand. Now, when we are talking about say HVAC like heating, ventilation and air conditioning, for those kinds of applications all these terminologies, they are very important, okay.

So, you cannot say no I have done design for axial flow compressor for aero engines. I have done design for axial flow compressor for industrial application, I have design for wind tunnel fans, but I have never done the design for industrial fans. So, I cannot do this design; that no should not come in your discussion and that is the reason why now in next lecture we will be discussing the design of industrial fan for particular application.

So, in overall if you look at, this course it has been designed in such a way that you will be having all exposure for all kind of fans that’s what need to be designed with, okay. So, here we are stopping with our discussion. In next lecture, we will be discussing about the design of industrial fan for special application. So, thank you very much and being with us enjoy this course!