# Aerodynamic Design of Axial Flow Compressors and Fans

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## Lecture No 64

## Design of Industrial Fan (Contd.)

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Concepts Covered

**In last lecture we discussed…**

- Design of wind tunnel fan
- Industrial fans and their application

Hello, and welcome to Lecture 64. We are discussing about the Design of Industrial Fans. In last lecture, we were discussing about design of wind tunnel fan; we have discussed different approaches which are being adopted in order to finalize the design of wind tunnel fan. We were discussing about the aerodynamic loading, we were discussing about the structural requirement, we were discussing about say different requirements for such kind of fans. And, finally we have come up with the strong design for that wind tunnel.

Now, later on we started discussing about say different other applications of industrial fans and there we were discussing like they are being rated differently compared to what all we have realized up till now in sense of axial flow compressor or axial flow fan. These fans, they are being rated in a different way as we have discussed it has been rated in terms of say CFM, in terms of say pressure rise as say inch of water column or meter of water column.

Then we realized, they are being operating in the different operating configurations where temperature, pressure, altitude all those terminologies they are of great importance. So, let us take one design for such kind of application.

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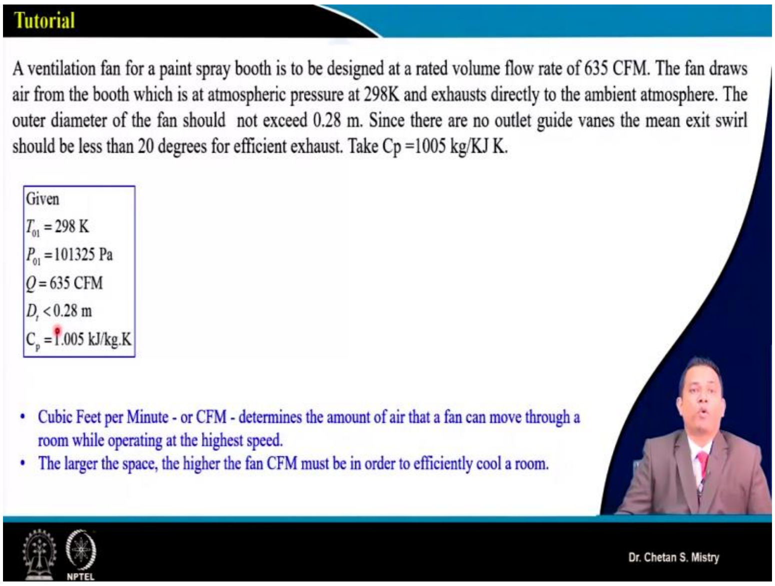

**Tutorial**

A ventilation fan for a paint spray booth is to be designed at a rated volume flow rate of 635 CFM. The fan draws air from the booth which is at atmospheric pressure at 298K and exhausts directly to the ambient atmosphere. The outer diameter of the fan should not exceed 0.28 m. Since there are no outlet guide vanes the mean exit swirl should be less than 20 degrees for efficient exhaust. Take Cp =1005 kg/KJ K.

Given
$T_{01} = 298$ K
$P_{01} = 101325$ Pa
$Q = 635$ CFM
$D_t < 0.28$ m
$C_p = 1.005$ kJ/kg.K

- Cubic Feet per Minute - or CFM - determines the amount of air that a fan can move through a room while operating at the highest speed.
- The larger the space, the higher the fan CFM must be in order to efficiently cool a room.

So, let us see. We are looking for designing a ventilation fan for paint spray booth with design rated flow rate of 635 CFM. The fan draws the air from the booth which is at atmospheric pressure and temperature of 298 K and that is exhaust into open atmosphere. The outer diameter of the fan should not exceed by 0.28 m. Since, there are no outlet guide vanes the mean exit swirl should be less than 20° for efficient exhaust.

Take $C_p$ to be 1005. So, my exit swirl that need to be less than 20°. So, here in this case, this is what is a ventilation fan and for that ventilation fan we are having data like temperature and pressure and my exit condition that's what is atmospheric condition; my volumetric flow rate that is given in sense of CFM. So, just realize this CFM is nothing, but it determines the amount of air that the fan can move through the room while operating at the highest possible speed.

For larger speed, highest rating of CFM that's what is required, that's what will be helping us in sense of efficient cooling of that room. Now, here in this case my tip diameter should not exceed by say 0.28 meter. So, let us try to explore the design possibilities for this.

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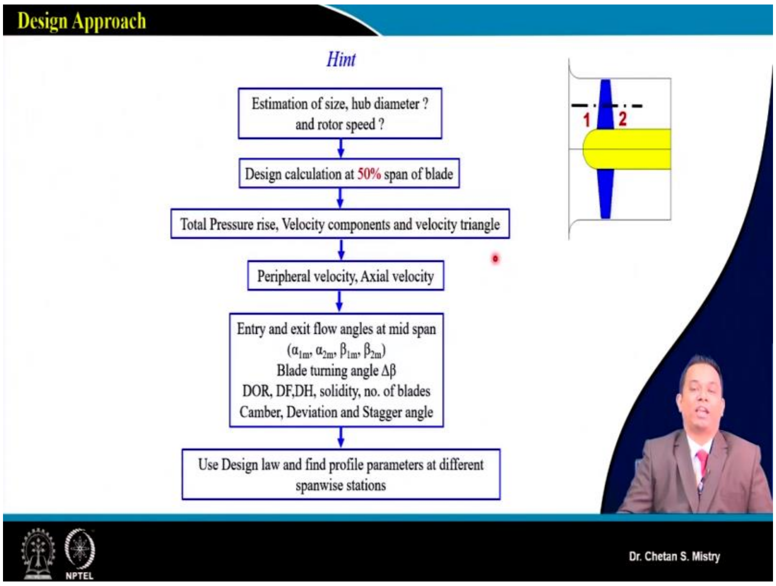

Design Approach

*Hint*

Estimation of size, hub diameter ? and rotor speed ?

Design calculation at 50% span of blade

Total Pressure rise, Velocity components and velocity triangle

Peripheral velocity, Axial velocity

Entry and exit flow angles at mid span ($\alpha_{1m}$, $\alpha_{2m}$, $\beta_{1m}$, $\beta_{2m}$)
Blade turning angle $\Delta\beta$
DOR, DF,DH, solidity, no. of blades
Camber, Deviation and Stagger angle

Use Design law and find profile parameters at different spanwise stations

So, here in this case it says it is not having exit swirl. So, my fan will be looking like this. So, I will be having only rotor. Now, in order to do the design, we need to have certain parameters. Now, my casing diameter that's what is one of the constraints that is given, but nothing it is mentioned in sense of what need to be my pressure rise. My flow rate, that's what is given in CFM.

So, now the thing is here we need to have different velocity components to be known. Once we know our velocity components, we can calculate our flow angle. We can calculate different velocity component then we can check with our parameters like diffusion factor, degree of reaction, De-Haller's number, all those that's what will be common for all kind of axial fan. So, that's what we will be taking as a reference.

Now, once we are doing our calculation at one of the station. Here, in this case we can say, this is what is only rotor and that too it is just small diameter. This maybe in a subsonic region, that's what will be decided based on what pressure rise we are expecting. Now, here it is a tricky and we need to understand my exhaust pressure that's what is say atmospheric pressure.

So, we can say my pressure rise expected that will not be coming in the large number that means this fan is a subsonic fan. So, we will be doing all our calculation at 50% span. Later on, we will be applying our whirl distribution, we will be going with say free vortex kind of design in order to simplify the design methodology and we will come up with what all will be the dimensions, what all will be the angles and how my blade will be looking like. So, this is what all we will be doing in this lecture.

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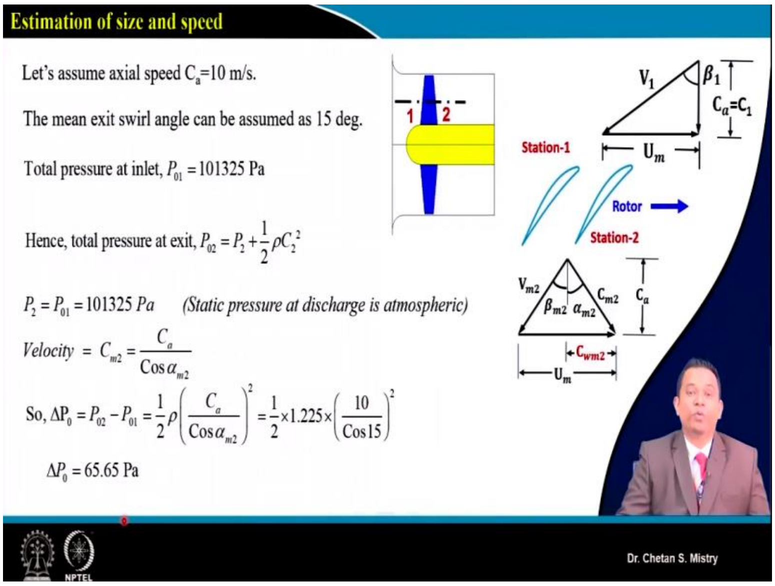

## Estimation of size and speed

Let's assume axial speed $C_a$=10 m/s.

The mean exit swirl angle can be assumed as 15 deg.

Total pressure at inlet, $P_{01} = 101325$ Pa

Hence, total pressure at exit, $P_{02} = P_2 + \frac{1}{2}\rho C_2^2$

$P_2 = P_{01} = 101325\ Pa$ (Static pressure at discharge is atmospheric)

$$Velocity\ = C_{m2} = \frac{C_a}{\cos\alpha_{m2}}$$

$$\text{So, } \Delta P_0 = P_{02} - P_{01} = \frac{1}{2}\rho\left(\frac{C_a}{\cos\alpha_{m2}}\right)^2 = \frac{1}{2}\times 1.225\times\left(\frac{10}{\cos 15}\right)^2$$

$$\Delta P_0 = 65.65\ \text{Pa}$$

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Now, here in this case nothing it has been mentioned in sense of velocities. So, what we will be doing? We will be assuming certain axial velocity. So, let us see, we will assume axial velocity to be 10 $m/s$. Just realize one thing, this 10 $m/s$ that can be 40 or 50 $m/s$, but we need to understand we are not handling large mass flow rate, the volumetric flow rate is not that much. So, we need to assume smaller number.

$$Let's\ assume\ axial\ speed\ C_a = 10\frac{m}{s}$$

So, let us see, we are taking say 10 $m/s$ and it says like my exit swirl angle that's what suppose at this moment for mid station we will be assuming say 15°.

$$The\ mean\ exit\ swirl\ angle\ can\ be\ assumed\ as\ 15°$$

Now, my entry pressure, that's what is say atmospheric pressure or say it is 101325 Pa. Now what we know? My exit pressure…exit total pressure, that's what we can represent in sense of my $P_2 + \frac{1}{2}\rho C_2^2$.

$$Hence, total\ pressure\ at\ exit, P_{02} = P_2 + \frac{1}{2}\rho C_2^2$$

This is what is my exit absolute pressure what we are discussing about. Now, for this case what is given? It says my exit pressure is atmospheric pressure. So, we can say my static pressure $P_2$, that's what is equal to $P_{01}$, they both are same, okay.

$$P_2 = P_{01} = 101325\ Pa$$

So, if this is what is your case, then we need to calculate what will be our $\Delta P_0$ that $\Delta P_0$, that's what we are representing here in sense of static pressure and absolute velocity term.

So, here in this case, my $P_2$ and $P_{01}$, they both are same. So, we will be writing $\Delta P_0$ as

$$So, \Delta P_0 = P_{02} - P_{01} = \frac{1}{2}\rho C_2^2$$

Now, this $C_2$, that is nothing, but the absolute velocity with which by flow that's what is coming out. In this case we have assume our angle of swirl or say my absolute flow angle to be 15°. So, if we are writing that in terms of say axial velocity then we can write down my absolute velocity it is $C_a/\cos\alpha_2$.

$$So, \Delta P_0 = P_{02} - P_{01} = \frac{1}{2}\rho\left(\frac{C_a}{\cos\alpha_{m2}}\right)^2$$

Now, if we are putting this number, my $\Delta P_0$ is coming 65.65 Pa, you can imagine, this is what is a small pressure rise we are expecting.

$$= \frac{1}{2} 1.225 \left(\frac{10}{\cos 15}\right)^2$$

$$\Delta P_0 = 65.65\ Pa$$

This is what is a different kind of fan that's what we are designing at this moment, okay. We have designed for pressure ratio of 1.2, we have designed the compressor for pressure ratio of 2. Now, we are talking about small pressure rise of 65 Pa. Let us see how do we proceed further with.

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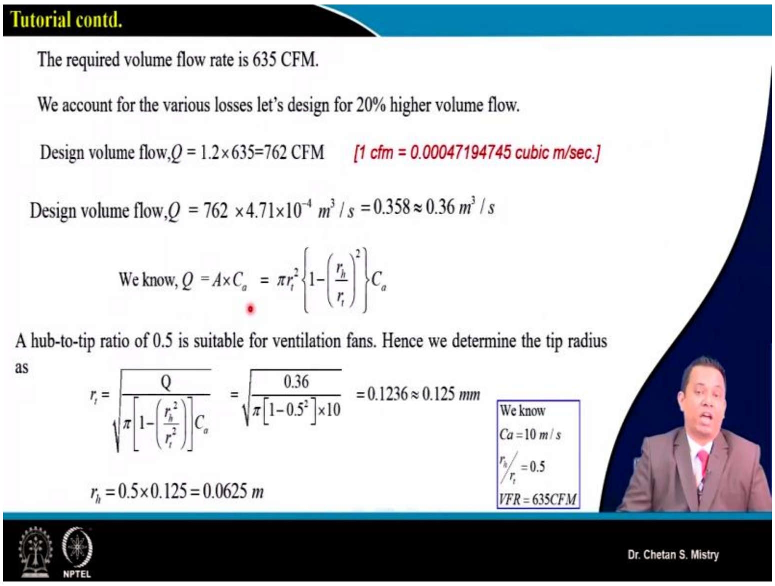

## Tutorial contd.

The required volume flow rate is 635 CFM.

We account for the various losses let's design for 20% higher volume flow.

Design volume flow, $Q = 1.2\times 635 = 762$ CFM [1 cfm = 0.00047194745 cubic m/sec.]

Design volume flow, $Q = 762 \times 4.71\times 10^{-4}\ m^3/s = 0.358 \approx 0.36\ m^3/s$

We know, $Q = A\times C_a = \pi r_t^2 \left\{1-\left(\frac{r_h}{r_t}\right)^2\right\} C_a$

A hub-to-tip ratio of 0.5 is suitable for ventilation fans. Hence we determine the tip radius as

$r_t = \sqrt{\frac{Q}{\pi\left[1-\left(\frac{r_h^2}{r_t^2}\right)\right]C_a}} = \sqrt{\frac{0.36}{\pi\left[1-0.5^2\right]\times 10}} = 0.1236 \approx 0.125\ mm$

$r_h = 0.5\times 0.125 = 0.0625\ m$

We know
$Ca = 10\ m/s$
$r_h/r_t = 0.5$
$VFR = 635CFM$

So, that is given? The required volumetric flow rate it is given 635 CFM. Now if we are accounting for some kind of losses let us say we will be taking design for 20% higher CFM value. So, we will be taking our volumetric flow rate as say

$$Design\ volume\ flow, Q = 1.2 \times 635 = 762\ CFM$$

So, we will be designing our fan for 762 CFM. Now, the conversion for CFM to meter cube per second that's what is given.

$$[1\ CFM = 0.00047194745\ cubic\ m/sec]$$

$$Design\ volume\ flow, Q = 762 \times 4.71 \times 10^{-4}\, {}^{m^3}\!/_{s} = 0.358 \approx 0.36\ {}^{m^3}\!/_{s}$$

So, that's what is giving me my volumetric flow rate to be say 0.36 $m^3/s$. If I will be multiplying that with density, that's what will be giving me kg per second. So, you can imagine this mass flow that's what is coming on a lower side, okay. Now, this volumetric flow rate we are writing in sense of say area into axial velocity. This area we are representing as say $\pi r^2$ and this is what we are writing in sense of hub-to-tip ratio.

$$We\ know, Q = A \times C_a = \pi r_t^2 \left\{1 - \left(\frac{r_h}{r_t}\right)^2\right\} C_a$$

Now, hub-to-tip ratio for such kind of configuration we can say roughly we can assume that to be 0.5. Now, here also, we need to accommodate our motor in hub region. So, sometimes if the dimension for that motor is known to us, so based on that we can decide with our hub diameter. Here, it is nothing mentioned in that specific way. So, we will be considering this hub-to-tip ratio as say 0.5.

And if we are putting that it says my hub diameter is coming 0.0625 m. We are talking about small dimensions, okay.

$$A\ hub-to-tip\ ratio\ of\ 0.5\ is\ suitable\ for\ ventilation\ fans.$$

$$Hence, we\ determine\ the\ tip\ radius\ as$$

$$r_t = \sqrt{\frac{Q}{\pi\left[1-\left(\frac{r_h^2}{r_t^2}\right)\right]C_a}}$$

$$= \sqrt{\frac{0.36}{\pi[1-0.5^2]\times 10}}$$

$$= 0.1236 \approx 0.125\ m$$

$$r_h = 0.5 \times 0.125 = 0.0625\ m$$

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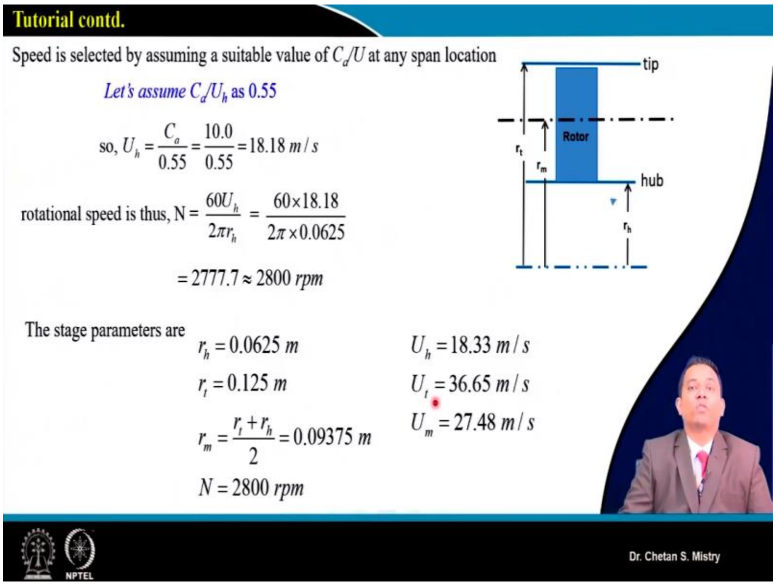

**Tutorial contd.**

Speed is selected by assuming a suitable value of $C_a/U$ at any span location

*Let's assume $C_a/U_h$ as 0.55*

$$\text{so, } U_h = \frac{C_a}{0.55} = \frac{10.0}{0.55} = 18.18\ m/s$$

$$\text{rotational speed is thus, } N = \frac{60U_h}{2\pi r_h} = \frac{60\times 18.18}{2\pi\times 0.0625}$$

$$= 2777.7 \approx 2800\ rpm$$

The stage parameters are

$$r_h = 0.0625\ m \qquad U_h = 18.33\ m/s$$

$$r_t = 0.125\ m \qquad U_t = 36.65\ m/s$$

$$r_m = \frac{r_t + r_h}{2} = 0.09375\ m \qquad U_m = 27.48\ m/s$$

$$N = 2800\ rpm$$

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Now, once this hub diameter, that's what is known to us; our next calculation, our next requirement that's what is to check with our peripheral speed or we need to have what should be the rotational speed. Now, here also we are having number of options that's what is possible; maybe if the requirement says may be those end users, they will say I am having motor that's what is having rotational speed of 3000 RPM. So, you can straight way take that as a RPM.

Now, we have discussed for the design of say wind tunnel fan, we will be having certain amount of slip. So, rated speed, that's what will be say 1440 RPM, 2400 RPM, 3000 RPM. So, we will not be getting exactly that number maybe slightly on a lower side, okay. So, one way is you can assume your rotational speed and based on that we can calculate what need to our peripheral speed, but here in this case let us take a different approach.

Let us assume $C_a/U_{hub}$ that's what is equal to 0.55, you can take it, okay.

$$Let's\ assume\ {}^{C_a}\!/_{U_h}\ as\ 0.55$$

Since my axial velocity we have assumed, it is 10 and my $C_a/U$ value, it is 0.55. It says peripheral speed at the hub it is coming 18.18 $m/s$.

$$So, U_h = \frac{C_a}{0.55} = \frac{10.0}{0.55} = 18.18\ m/s$$

Now, based on that we will be checking with the rotational speed, it says this is what is coming say 2777.7 RPM. So, roughly we can say this is what is in the range of say 2800 RPM.

$$Rotational\ speed\ is\ thus, N = \frac{60U_h}{2\pi r_h} = \frac{(60 \times 18.18)}{2\pi \times 0.0625}$$

$$= 2777.7 \approx 2800\ rpm$$

So, now what we have? We are having our hub radius, we are having our tip radius. We can do our calculation for the mean radius and our peripheral speed that's what we are taking 2800 RPM. So, based on that we are able to calculate what will be the peripheral speed at different locations, okay.

$$The\ stage\ parameters\ are$$

$$r_h = 0.0625\ m$$

$$r_t = 0.125\ m$$

$$r_m = \frac{r_t + r_h}{2} = 0.09375\ m$$

$$N = 2800\ rpm$$

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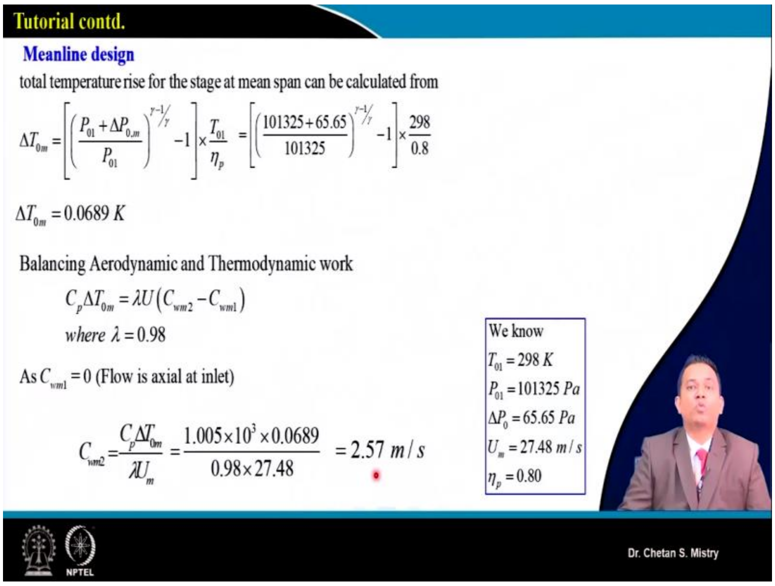

## Tutorial contd.

**Meanline design**

total temperature rise for the stage at mean span can be calculated from

$$\Delta T_{0m} = \left[\left(\frac{P_{01}+\Delta P_{0,m}}{P_{01}}\right)^{\gamma-1/\gamma} - 1\right] \times \frac{T_{01}}{\eta_p} = \left[\left(\frac{101325+65.65}{101325}\right)^{\gamma-1/\gamma} - 1\right] \times \frac{298}{0.8}$$

$$\Delta T_{0m} = 0.0689\ K$$

Balancing Aerodynamic and Thermodynamic work

$$C_p \Delta T_{0m} = \lambda U (C_{wm2} - C_{wm1})$$

$$where\ \lambda = 0.98$$

As $C_{wm1} = 0$ (Flow is axial at inlet)

$$C_{wm2} = \frac{C_p \Delta T_{0m}}{\lambda U_m} = \frac{1.005 \times 10^3 \times 0.0689}{0.98 \times 27.48} = 2.57\ m/s$$

We know
$T_{01} = 298\ K$
$P_{01} = 101325\ Pa$
$\Delta P_0 = 65.65\ Pa$
$U_m = 27.48\ m/s$
$\eta_p = 0.80$

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Now, once this C$_a$ value, peripheral speed value, those numbers are known to us. We are looking for the design of the fan. So, we will do our design at a mid station. So, similar approach what we have opted earlier we will be going with. It says at mid station we can calculate what will be the total temperature rise that's what is given in sense of $P_{01} + \Delta P_0$ what we are expecting.

And, it is in sense of say Polytropic efficiency and entry temperature. So, here we are assuming our efficiency to be 80%. So, if we are taking this as 80% my $\Delta T_0$, you can see, this is what is coming 0.0689 K, that's what is a small pressure rise…total pressure rise what we are expecting.

$$Total\ temperature\ rise\ for\ the\ stage\ at\ mean\ span\ can\ be\ calculated\ from$$

$$\Delta T_{0m} = \left[\left(\frac{P_{01} + \Delta P_{0,m}}{P_{01}}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] \times \frac{T_{01}}{\eta_p}$$

$$= \left[\left(\frac{101325 + 65.65}{101325}\right)^{\frac{1.4-1}{1.4}} - 1\right] \times \frac{298}{0.8}$$

$$\Delta T_{0m} = 0.0689\ K$$

Because my pressure rise, what we are expecting that is also low, okay. So, once this is what is known to us we can calculate, we are comparing our aerodynamic work and thermodynamic work to be same.

So, we can write down,

$$C_p \Delta T_{0m} = \lambda U (C_{wm2} - C_{wm1})$$

$$where\ \lambda = 0.98$$

Now, this $C_{w1}$, that's what we are taking that to be say 0, we are assuming our entry to be axial one. So, under that configuration we can calculate what will be our whirl component at the exit and that's what is coming 2.57 $m/s$.

$$As\ C_{wm1} = 0\ (Flow\ is\ axial\ at\ inlet)$$

$$C_{wm2} = \frac{C_p \Delta T_{0m}}{\lambda U_m}$$

$$= \frac{1.005 \times 10^3 \times 0.0689}{0.98 \times 27.48}$$

$$= 2.57\ m/s$$

Now, this whirl component, once this is what is known to us we know our next step.

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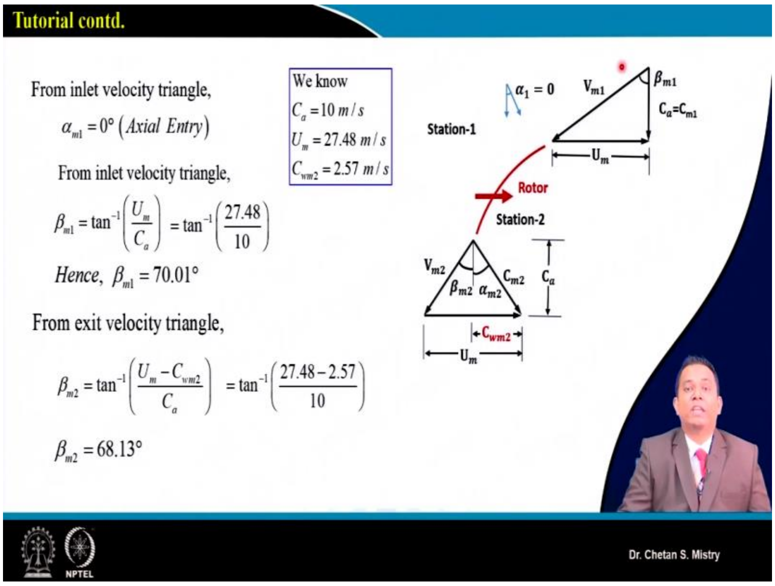

**Tutorial contd.**

From inlet velocity triangle,

$\alpha_{m1} = 0° \ (Axial\ Entry)$

From inlet velocity triangle,

$\beta_{m1} = \tan^{-1}\left(\frac{U_m}{C_a}\right) = \tan^{-1}\left(\frac{27.48}{10}\right)$

$Hence,\ \beta_{m1} = 70.01°$

From exit velocity triangle,

$\beta_{m2} = \tan^{-1}\left(\frac{U_m - C_{wm2}}{C_a}\right) = \tan^{-1}\left(\frac{27.48 - 2.57}{10}\right)$

$\beta_{m2} = 68.13°$

We know

$C_a = 10\ m/s$

$U_m = 27.48\ m/s$

$C_{wm2} = 2.57\ m/s$

We will be calculating our other parameters; like we are looking for our blade angles. So, $\beta_1$ or we can say tan $\beta_1$, it is given by $U/C_a$ and that is coming 70.01°.

$$From\ inlet\ velocity\ triangle,$$

$$\alpha_{m1} = 0° \ (Axial\ entry)$$

$$From\ inlet\ velocity\ triangle,$$

$$\beta_{m1} = \tan^{-1}\left(\frac{U_m}{C_a}\right)$$

$$= \tan^{-1}\left(\frac{27.48}{10}\right)$$

$$Hence, \beta_{m1} = 70.01°$$

Same way, my exit flow angle we can say this is what is coming 68.13°.

$$From\ exit\ velocity\ triangle,$$

$$\beta_{m2} = \tan^{-1}\left(\frac{U_m - C_{wm2}}{C_a}\right)$$

$$= \tan^{-1}\left(\frac{27.48 - 2.57}{10}\right)$$

$$\beta_{m2} = 68.13°$$

Now, this $\Delta\beta$, that's what we can calculate based on our $\beta_1 and\ \beta_2$. Please be careful whenever you are doing your calculation at mid station, do not forget to plot velocity triangle, that's what will give you idea and understanding.

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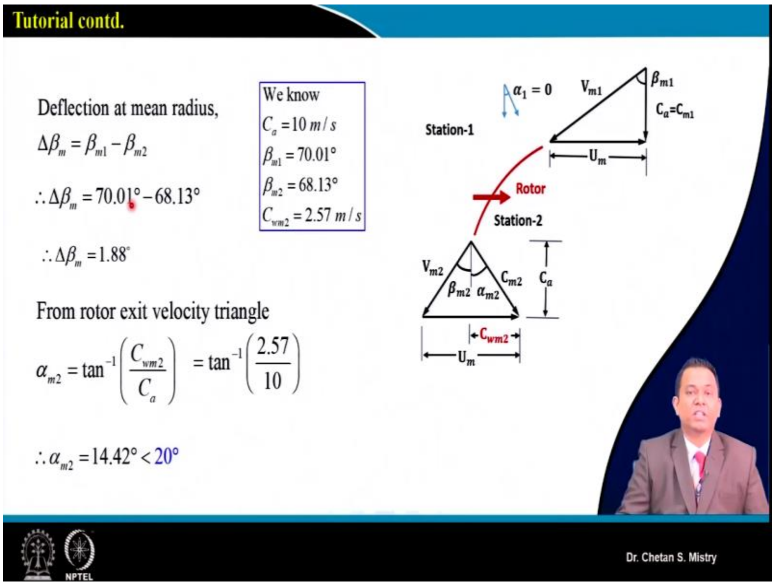

**Tutorial contd.**

Deflection at mean radius,

$\Delta\beta_m = \beta_{m1} - \beta_{m2}$

$\therefore \Delta\beta_m = 70.01° - 68.13°$

$\therefore \Delta\beta_m = 1.88°$

We know

$C_a = 10\ m/s$

$\beta_{m1} = 70.01°$

$\beta_{m2} = 68.13°$

$C_{wm2} = 2.57\ m/s$

From rotor exit velocity triangle

$\alpha_{m2} = \tan^{-1}\left(\frac{C_{wm2}}{C_a}\right) = \tan^{-1}\left(\frac{2.57}{10}\right)$

$\therefore \alpha_{m2} = 14.42° < 20°$

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Now, this is what it says my $\Delta\beta$ is coming 1.88, you can imagine my deflection angle that is also coming to be lower.

$$Deflection\ at\ mean\ radius,$$

$$\Delta\beta_m = \beta_{m1} - \beta_{m2}$$

$$\therefore \Delta\beta_m = 70.01° - 68.13°$$

$$\therefore \Delta\beta_m = 1.88°$$

This is what is a different kind of, you know, design, okay. Now, once this is what is known to us, our whirl angle it says that should not be more than 20°, so let us calculate, it is coming 14.42°, okay.

$$From\ rotor\ exit\ velocity\ triangle,$$

$$\alpha_{m2} = \tan^{-1}\left(\frac{C_{wm2}}{C_a}\right)$$

$$= \tan^{-1}\left(\frac{2.57}{10}\right)$$

$$\therefore \alpha_{m2} = 14.42° < 20°$$

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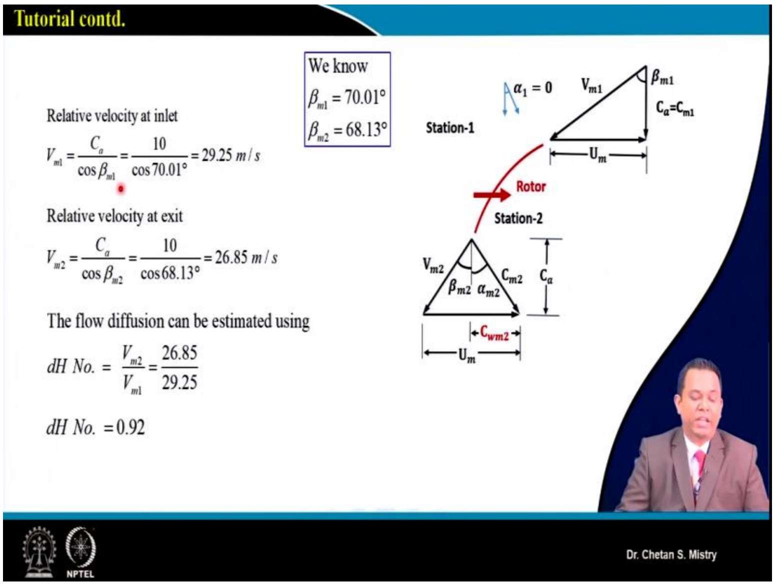

**Tutorial contd.**

We know

$\beta_{m1} = 70.01°$

$\beta_{m2} = 68.13°$

Relative velocity at inlet

$V_{m1} = \frac{C_a}{\cos\beta_{m1}} = \frac{10}{\cos 70.01°} = 29.25\ m/s$

Relative velocity at exit

$V_{m2} = \frac{C_a}{\cos\beta_{m2}} = \frac{10}{\cos 68.13°} = 26.85\ m/s$

The flow diffusion can be estimated using

$dH\ No. = \frac{V_{m2}}{V_{m1}} = \frac{26.85}{29.25}$

$dH\ No. = 0.92$

Now, once this is what is known, we can calculate what will be our speed…relative velocity. So, relative velocity we are writing in sense of cos component. So, cos $\beta_1$, that's what is $C_a/V_1$ based on this velocity triangle. So, my $V_1$ is coming 29.25 $m/s$, $V_2$ that's what is coming 26.85 $m/s$ and De-Hallers factor, that's what is coming it is say 0.92.

$$Relative\ velocity\ at\ inlet,$$

$$V_{m1} = \frac{C_a}{\cos\beta_{m1}} = \frac{10}{\cos 70.01°} = 29.25\ m/s$$

$$Relative\ velocity\ at\ exit,$$

$$V_{m2} = \frac{C_a}{\cos\beta_{m2}} = \frac{10}{\cos 68.13°} = 26.85\ m/s$$

$$The\ flow\ diffusion\ can\ be\ estimated\ using$$

$$dH\ No. = \frac{V_{m2}}{V_{m1}} = \frac{26.85}{29.25}$$

$$dH\ No. = 0.92$$

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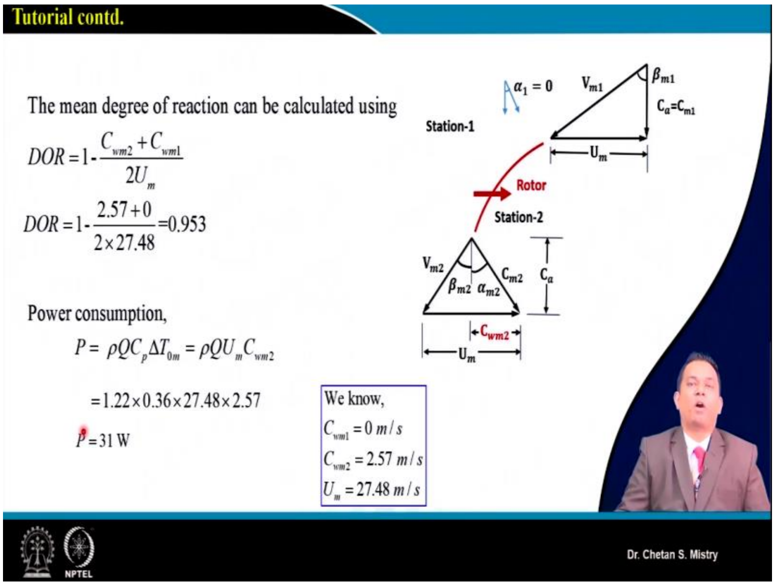

**Tutorial contd.**

The mean degree of reaction can be calculated using

$$DOR = 1 - \frac{C_{wm2} + C_{wm1}}{2U_m}$$

$$DOR = 1 - \frac{2.57 + 0}{2 \times 27.48} = 0.953$$

Power consumption,

$$P = \rho Q C_p \Delta T_{0m} = \rho Q U_m C_{wm2}$$

$$= 1.22 \times 0.36 \times 27.48 \times 2.57$$

$$P = 31\ \text{W}$$

We know,
$C_{wm1} = 0\ m/s$
$C_{wm2} = 2.57\ m/s$
$U_m = 27.48\ m/s$

Now, the next calculation, that’s what will be with a degree of reaction. So, degree of reaction we are putting in sense of whirl component as well as in terms of my mean peripheral speed. So, at mid station this is what is coming 0.953, okay.

$$The\ mean\ degree\ of\ reaction\ can\ be\ calculated\ using$$

$$DOR = 1 - \frac{C_{wm2} + C_{wm1}}{2U_m}$$

$$DOR = 1 - \frac{2.57 + 0}{2 \times 27.48}$$

$$= 0.953$$

It is a cruel way of doing, because this is what is not a stage understand one thing. Stage means I will be having rotor as well as stator, okay. Here, in this case we are having only rotor.

But in order to show like whole diffusion or whole pressure rise, that’s what we are expecting from the rotor and that is the reason why this degree of reaction number, that’s what is coming on a higher side. Now, next calculation, that’s what will be what will be the consumption of power. So, that’s what we are writing here in sense of $mC_p\Delta T$ that $\dot{m}$ or mass flow rate we are writing in terms of $density \times volumetric\ flow\ rate$. And, this is what is coming 31 W.

$$Power\ consumption,$$

$$P = \rho Q C_p \Delta T_{0m} = \rho Q U_m C_{wm2}$$

$$= 1.22 \times 0.36 \times 27.48 \times 2.57$$

$$P = 31\ W$$

If we are considering different loses, barring loses, mechanical loses, that's what will say, say need to select this power rating that's what will be slightly on the higher side, okay. So, you can see, we are looking for the design of small fan; that small fan, that's what is required to give small pressure rise. In order to achieve that small pressure rise, this is what is a power it is reasonable in the range.

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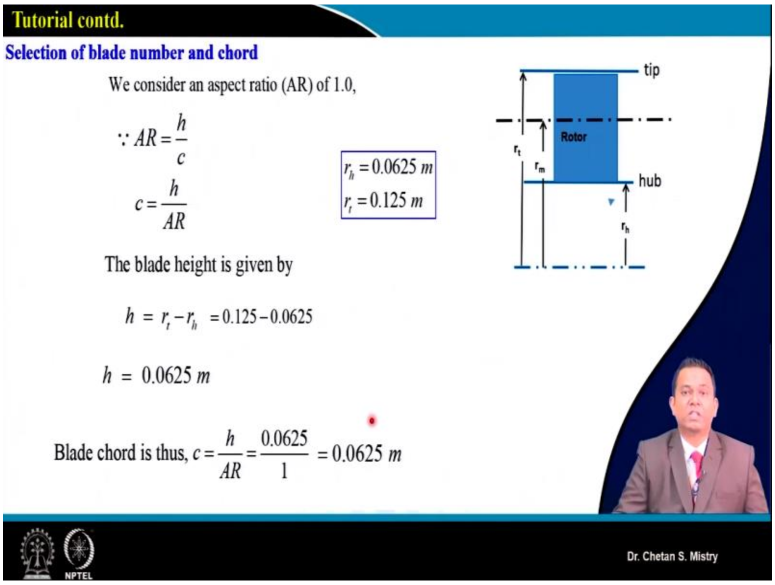

**Tutorial contd.**

**Selection of blade number and chord**

We consider an aspect ratio (AR) of 1.0,

$$\because AR = \frac{h}{c}$$

$$c = \frac{h}{AR}$$

$r_h = 0.0625\ m$
$r_t = 0.125\ m$

The blade height is given by

$$h = r_t - r_h = 0.125 - 0.0625$$

$$h = 0.0625\ m$$

Blade chord is thus, $c = \frac{h}{AR} = \frac{0.0625}{1} = 0.0625\ m$

The next calculation, that's what will be what will be my chord or what need to be my number of blade. So, in order to do that we will be assuming our aspect ratio. Conventionally, for this ventilation fans the aspect ratio is roughly in the range of 1, okay. Because it is not handling large mass flow rate and that is the reason why we are looking for aspect ratio in the range of 1. We are also looking in terms of say structure, structural consideration, okay.

So, let us assume the aspect ratio to be 1. If we are taking our aspect ratio to be 1, it says my height of the blade that is coming 0.0625 m and the chord of the blade it is 0.0625 m, okay.

$$We\ consider\ an\ aspect\ ratio\ (AR)\ of\ 1.0,$$

$$\because AR = \frac{h}{c}$$

$$c = \frac{h}{AR}$$

$$The\ blade\ height\ is\ given\ by,$$

$$h = r_t - r_h = 0.125 - 0.0625$$

$$h = 0.0625\ m$$

$$Blade\ chord\ is\ thus, c = \frac{h}{AR} = \frac{0.0625}{1} = 0.0625\ m$$

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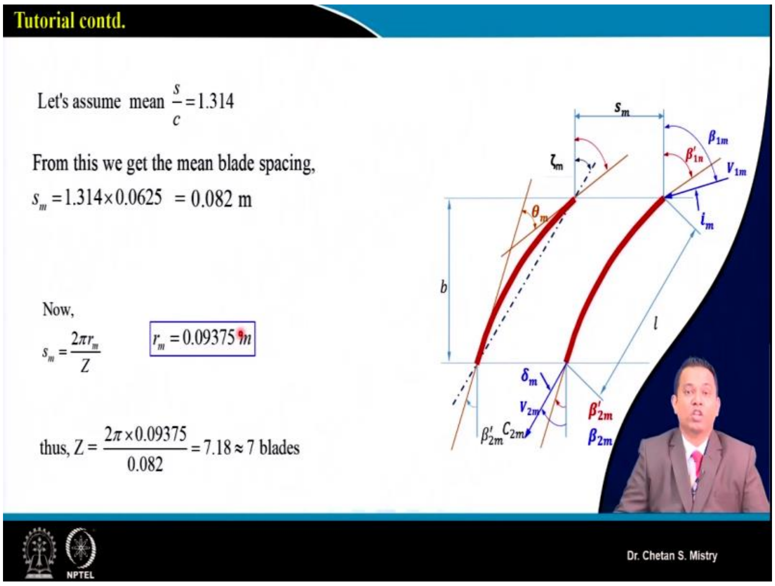

**Tutorial contd.**

Let's assume mean $\frac{s}{c} = 1.314$

From this we get the mean blade spacing,

$s_m = 1.314 \times 0.0625 = 0.082$ m

Now,

$s_m = \frac{2\pi r_m}{Z}$ $\boxed{r_m = 0.09375\ m}$

thus, $Z = \frac{2\pi \times 0.09375}{0.082} = 7.18 \approx 7$ blades

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Now, once this is what is known to us, we can do our calculation for the number of blades. Again, here in this case, the selection of number of blade that is always a challenging part. We are designing the ventilation fan at this moment and for that ventilation fan the cost will be one of the criteria. And, that is the reason why this number of blades selection that is also very important consideration. So, here in order to have the calculation we are assuming our mean $s/c$ - mean solidity number, that's what is say $s/c$ as 1.314.

$$Let's\ assume\ mean \frac{s}{c} = 1.314$$

And, we are calculating our number of blade based on mean radius, that’s what is coming as say 7.18, roughly we can say that’s what is 7 blades.

$$\textit{From this we get the mean blade spacing,}$$

$$s_m = 1.314 \times 0.0625 = 0.082\ m$$

$$Now, s_m = \frac{2\pi r_m}{Z}$$

$$Thus, Z = \frac{2\pi \times 0.09375}{0.082} = 7.14 \approx 7\ blades$$

So, for ventilation fans, the number of blades will be in the range of 3, 5, 7; sometimes they are taking or going for 9, okay. You can understand, this is what we need to put in mind. So, here you can assume number of blade to be 5.

You can do your calculation for say your pitch and accordingly you can go ahead that is also one of the possibility; no one will stop you. But, you know, when you are taking this numbers that time you need to have proper justification. It is not like I will be taking say 1 number of blade, that’s what is next to impossible, just realize that part, okay. So, understand these are what we are looking for in terms of doing the design. So, now we are having number of blades to be 7.

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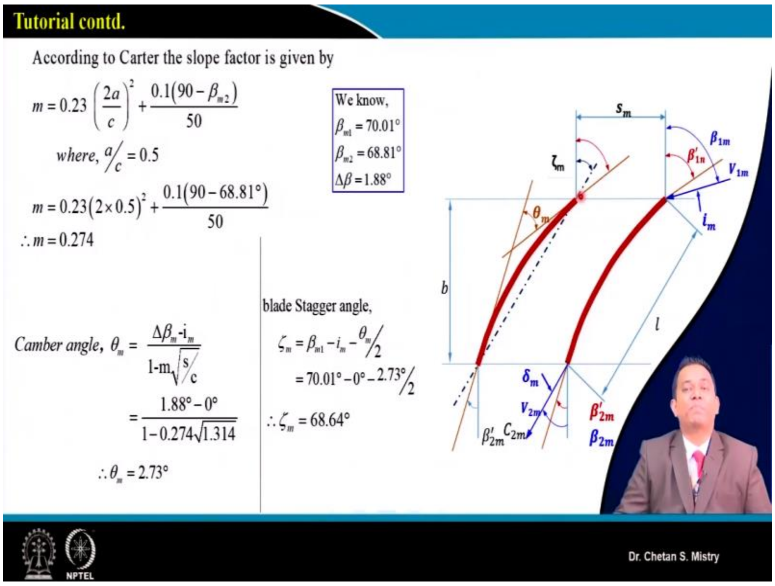

Tutorial contd.

According to Carter the slope factor is given by

$$m = 0.23\left(\frac{2a}{c}\right)^2 + \frac{0.1(90-\beta_{m2})}{50}$$

$$where,\ a/c = 0.5$$

$$m = 0.23(2\times0.5)^2 + \frac{0.1(90-68.81^\circ)}{50}$$

$$\therefore m = 0.274$$

We know,
$\beta_{m1} = 70.01^\circ$
$\beta_{m2} = 68.81^\circ$
$\Delta\beta = 1.88^\circ$

$$Camber\ angle,\ \theta_m = \frac{\Delta\beta_m - i_m}{1 - m\sqrt{s/c}} = \frac{1.88^\circ - 0^\circ}{1 - 0.274\sqrt{1.314}}$$

$$\therefore \theta_m = 2.73^\circ$$

blade Stagger angle,

$$\zeta_m = \beta_{m1} - i_m - \theta_m/2 = 70.01^\circ - 0^\circ - 2.73^\circ/2$$

$$\therefore \zeta_m = 68.64^\circ$$

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Now, once we have decided with that this fan we are talking that’s what is say low pressure rise fan and we are not expecting that to be expensive one and we are not looking for running that fan at variable speed configuration. Maybe, rarely we will be having that kind of; it will be rotating at a constant speed and that is the reason if you look at carefully this blade what we are making that will be made by bending of the plate, so this is what we can say.

This is what will be the blade looking like. It is not having airfoil shape. And, as we have discussed earlier, maybe you bend the plate and if it is rotating, that also we will be generating the pressure rise. There is a special requirement of airfoil when we are expecting our pressure rise in a systematic way because we are having pressure surface and suction surface.

We are having flow acceleration and de-acceleration on my pressure surface as well as on the suction surface and that’s what we will be deciding my pressure rising capacity. Here in this case, our pressure rise expected is low and that is the reason we will be taking bend of this plate. Now, this bending also that is important. So, this curvature, here in this case we have taken as a circular camber line.

So, we will be calculating our carter slope factor and this is what is coming 0.274.

$$m = 0.23\left(\frac{2a}{c}\right)^2 + \frac{0.1(90 - \beta_{m2})}{50}$$

$$where, a/c = 0.5$$

$$m = 0.23(2 \times 0.5)^2 + \frac{0.1(90 - 68.81°)}{50}$$

$$\therefore m = 0.274$$

Once we have calculated that we can calculate our deviation angle, we can calculate our camber angle and stagger angle. So, here in this case, this camber angle is coming 2.73° and the stagger angle, that’s what is coming 68.64°.

$$Camber\ angle, \theta_m = \frac{\Delta\beta_m - i_m}{1 - m\sqrt{\frac{s}{c}}} = \frac{1.88° - 0°}{1 - 0.274\sqrt{1.314}}$$

$$\therefore \theta_m = 2.73°$$

$$Blade\ stagger\ angle,$$

$$\zeta_m = \beta_{m1} - i_m - {}^{\theta_m}/_{2}$$

$$= 70.01° - 0° - {}^{2.73°}/_{2}$$

$$\therefore \zeta_m = 68.64°$$

Since, my $\Delta\beta$ is coming to be low or lower side, and that is the reason why my camber angle also is not coming in large side.

But at the same time, if we look at my blade is too staggered. Let us see what all are the dimensions we are getting with.

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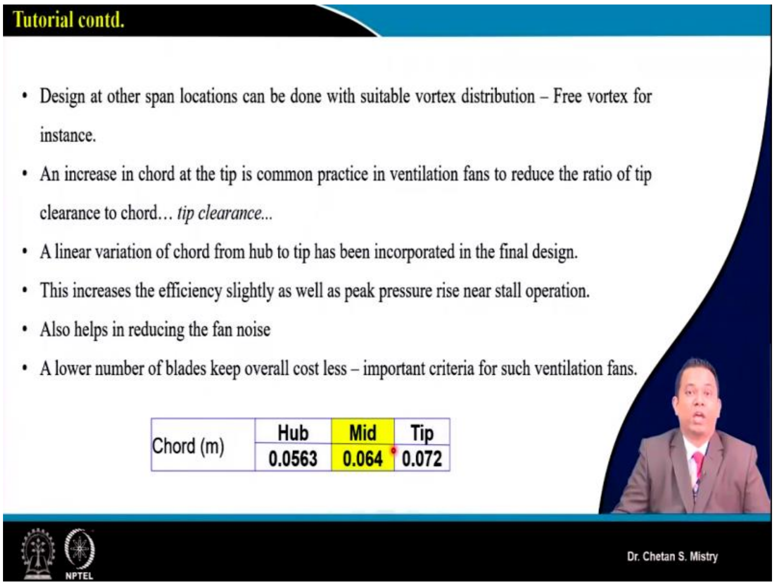

**Tutorial contd.**

- Design at other span locations can be done with suitable vortex distribution – Free vortex for instance.
- An increase in chord at the tip is common practice in ventilation fans to reduce the ratio of tip clearance to chord… *tip clearance...*
- A linear variation of chord from hub to tip has been incorporated in the final design.
- This increases the efficiency slightly as well as peak pressure rise near stall operation.
- Also helps in reducing the fan noise
- A lower number of blades keep overall cost less – important criteria for such ventilation fans.

| Chord (m) | Hub | Mid | Tip |
|---|---|---|---|
| | 0.0563 | 0.064 | 0.072 |

Now, once we have done our calculation at the mid station, very next step, that's what will be we will be assuming our span wise distribution, that's what we have done for almost all designs what we have discussed. So, we will not be repeating same thing here. Say for this design, we will be opting with say free vortex concept. Now, once we are doing this calculation for ventilation fan it says the selection of chord that's what is very important.

So, conventionally if you look at your ventilation fans available at home or maybe at industry or surrounding. If we look at carefully, my chord near the tip region that's what is larger compared to hub. Now, this is what has to do with the tip clearance because mainly this tip clearance what we are defining that’s what in sense of percentage chord, okay. So, that is the reason why this is what is one of the configuration.

So, for this design we have taken say linear variation of chord from hub-to-tip region in final design. This will give good efficiency as well as peak pressure rise near the stall operation. This also will be helping us in sense of reducing the noise, that’s what is of main need. So, if you look at carefully, say the fans what we are using for air conditioning system, the fans what we are using for say exhaust, those fans are of special kind.

They are having different kind of shape that’s what has been done by using CFD tool. But at this moment, we are considering say we are taking our variation of chord from hub-to-tip. So, here if you look at, at hub say at mid station we have done our calculation for the chord that’s what is coming 0.064 and we will be varying linearly from hub-to-tip that’s what is representing the variation of this chord length from hub-to-tip region, okay.

Now, here in this case, in order to reduce the cost as we have discussed, number of blades, that’s what is very important. Now, those number of blades that’s what will be deciding the cost, okay. So, when you are asked to do the design for the ventilation fan, all these criteria need to be considered with. Because we are having great competition amongst different distributors, amongst different manufacturers.

And, that is the reason why when you want to stay in competition, your product need to be of cost effective. And, that is where this design, that’s what is coming into the picture. Many times, the cost may not be the only criteria; people, they are talking about say having say noiseless or energy efficient fan under that configuration you need to go with the efficient design and that efficient design only you need to do it, okay.

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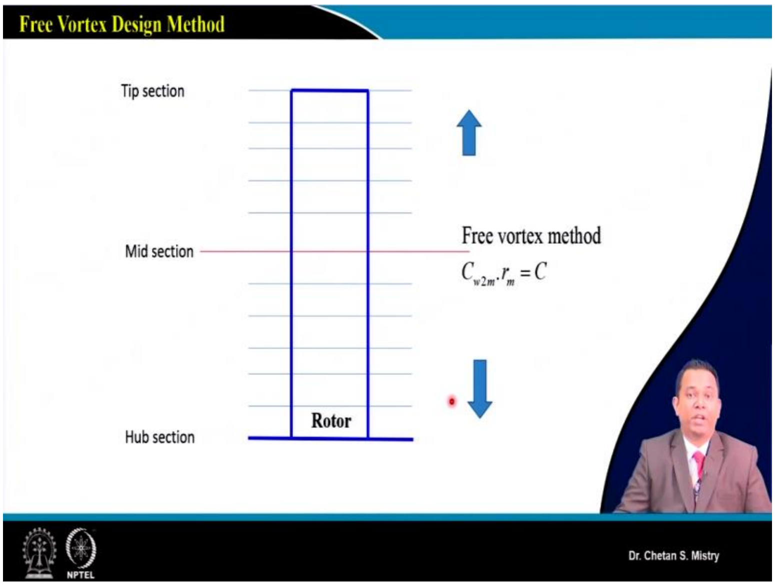

**Free Vortex Design Method**

Free vortex method

$C_{w2m}.r_m = C$

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Now, once we are going with this, what we know as per our understanding, if we are opting with the free vortex, we will be selecting $C_w \cdot r = constant$, that's what we are calculating at the mid station. This constant we will be putting from say mid section to tip section, from mid section to hub section, and based on that we will be calculating what will be our $C_{w2}$. And, based on that we will be doing all our calculation as we have done for almost all cases.

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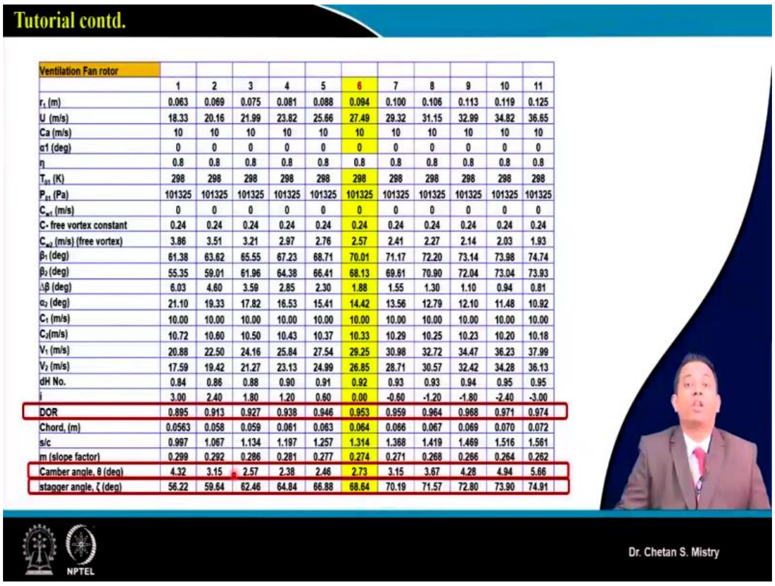

**Tutorial contd.**

| Ventilation Fan rotor | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| $r_1$ (m) | 0.063 | 0.069 | 0.075 | 0.081 | 0.088 | 0.094 | 0.100 | 0.106 | 0.113 | 0.119 | 0.125 |
| U (m/s) | 18.33 | 20.16 | 21.99 | 23.82 | 25.66 | 27.49 | 29.32 | 31.15 | 32.99 | 34.82 | 36.65 |
| Ca (m/s) | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| α1 (deg) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| η | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| $T_{01}$ (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 | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 |
| $C_{w2}$ (m/s) (free vortex) | 3.86 | 3.51 | 3.21 | 2.97 | 2.76 | 2.57 | 2.41 | 2.27 | 2.14 | 2.03 | 1.93 |
| $\beta_1$ (deg) | 61.38 | 63.62 | 65.55 | 67.23 | 68.71 | 70.01 | 71.17 | 72.20 | 73.14 | 73.98 | 74.74 |
| $\beta_2$ (deg) | 55.35 | 59.01 | 61.96 | 64.38 | 66.41 | 68.13 | 69.61 | 70.90 | 72.04 | 73.04 | 73.93 |
| Δβ (deg) | 6.03 | 4.60 | 3.59 | 2.85 | 2.30 | 1.88 | 1.55 | 1.30 | 1.10 | 0.94 | 0.81 |
| $\alpha_2$ (deg) | 21.10 | 19.33 | 17.82 | 16.53 | 15.41 | 14.42 | 13.56 | 12.79 | 12.10 | 11.48 | 10.92 |
| $C_1$ (m/s) | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 |
| $C_2$(m/s) | 10.72 | 10.60 | 10.50 | 10.43 | 10.37 | 10.33 | 10.29 | 10.25 | 10.23 | 10.20 | 10.18 |
| $V_1$ (m/s) | 20.88 | 22.50 | 24.16 | 25.84 | 27.54 | 29.25 | 30.98 | 32.72 | 34.47 | 36.23 | 37.99 |
| $V_2$ (m/s) | 17.59 | 19.42 | 21.27 | 23.13 | 24.99 | 26.85 | 28.71 | 30.57 | 32.42 | 34.28 | 36.13 |
| dH No. | 0.84 | 0.86 | 0.88 | 0.90 | 0.91 | 0.92 | 0.93 | 0.93 | 0.94 | 0.95 | 0.95 |
| i | 3.00 | 2.40 | 1.80 | 1.20 | 0.60 | 0.00 | -0.60 | -1.20 | -1.80 | -2.40 | -3.00 |
| DOR | 0.895 | 0.913 | 0.927 | 0.938 | 0.946 | 0.953 | 0.959 | 0.964 | 0.968 | 0.971 | 0.974 |
| Chord, (m) | 0.0563 | 0.058 | 0.059 | 0.061 | 0.063 | 0.064 | 0.066 | 0.067 | 0.069 | 0.070 | 0.072 |
| s/c | 0.997 | 1.067 | 1.134 | 1.197 | 1.257 | 1.314 | 1.368 | 1.419 | 1.469 | 1.516 | 1.561 |
| m (slope factor) | 0.299 | 0.292 | 0.286 | 0.281 | 0.277 | 0.274 | 0.271 | 0.268 | 0.266 | 0.264 | 0.262 |
| Camber angle, θ (deg) | 4.32 | 3.15 | 2.57 | 2.38 | 2.46 | 2.73 | 3.15 | 3.67 | 4.28 | 4.94 | 5.66 |
| stagger angle, ζ (deg) | 56.22 | 59.64 | 62.46 | 64.84 | 66.88 | 68.64 | 70.19 | 71.57 | 72.80 | 73.90 | 74.91 |

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So, once we are doing that calculation, this is what is a final design sheet. We can look at, here in this case, we are doing our $C_w \cdot r = constant$ that constant we are calculating here. And that constant, that's what will be helping us in order to calculate the $C_{w2}$ value. Based on that we can calculate our $\Delta\beta$. So here, as we have discussed, $\Delta\beta$ that's what is coming on a lower numbers.

So, you can see, this is a 6° and here almost it is 1°, okay. Now, if you look at the degree of reaction, that's what is coming on a higher side. Just understand, do not say like sir, this is not a stage, but we can say, we are doing whole our diffusion using the rotor. So, this definition can be applicable for; in order to understand, in order to realize how we are doing our diffusion with rotor, okay.

Now, here in this case my camber angle, that's what is varying all the way from 4° to almost 5.66°. At the same time, the stagger angle that's what is coming to be on a large side.

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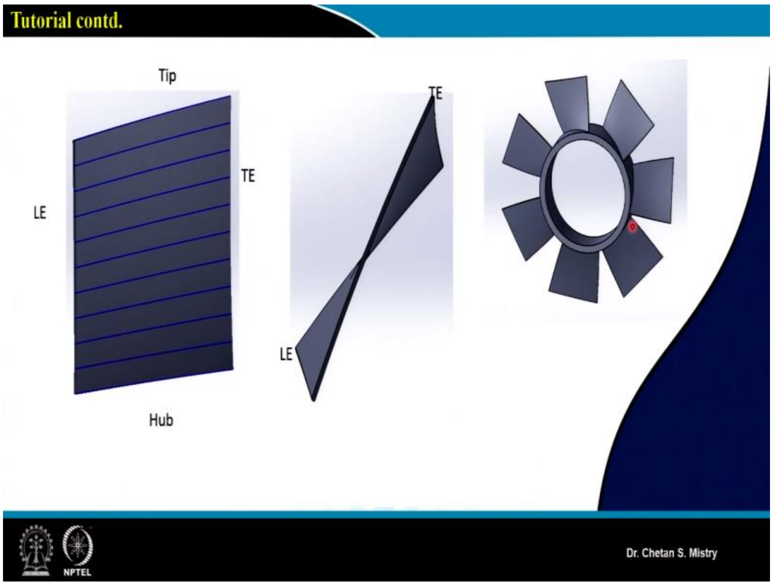

Tutorial contd.

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So, let us look at the blade how it will be looking like. So, this is what is as we have discussed. So, we need to bend our plate, my leading edge and trailing edge that need to be slightly circular one in order to avoid the flow separation; we know when we are having sharp edge there are more chances for the flow to get separated. So, in order to have smooth entry we need to give certain amount of radius at the leading edge and trailing edge, okay.

We can say this is what is my blade looking like here in this case my variation of $\theta$ that what we say camber angle, that's what is lower; but at the same time stagger angle you can see that's what is varying all the way from hub-to-tip. Now, in order to understand how my blade will be looking like near the hub region and near the tip region. So, this is what is a rotor we are discussing for this ventilation fan.

This is how my ventilation fan, that’s what has been designed with. So, in overall if you look at, this whole course, that’s what is specifically been designed with configuration that person or say engineer or individual who is working in a different areas where we are looking for different applications, whatever maybe the application, let it be say for application for industry, for say home appliances, maybe for computational tools or maybe for your say heating or maybe for cooling purpose, let it be all purposes.

By going through this lecture series what we are running you will be able to do design. So, you know, first cut design or preliminary design, that’s what I am confident you all will be able to do. Once you are going through all these lectures. So, here we are stopping with Week 11. See you in the next lecture, we will be discussing further for what all will be the further discussion in terms of applications of CFD that’s what is the excitement for all of you! Thank you, thank you very much!