POWER PLANT SYSTEM ENGINEERING

Lec 7: Rotodynamic Machines

Dear learners, greetings from IIT, Guwahati. We are in the MOOCs course Power Plant System Engineering, Module 2, Vapour Power System Part 2. So, in this lecture number 5, we will try to focus on Rotodynamic Machines, Impulse Principles Velocity Diagrams. So, prior to this lectures, we have seen that how the steam power plant is being used for power generation systems. Now, one of the integral component of this power generation system is the turbine, but this turbine is considered as a protodynamic machines and these machines have certain characteristics. So, we will try to emphasize under what category does this steam turbine fall.

Then based on that, we will try to classify these turbines mainly in two aspects, one is through impulse principle, other is through reaction principles. So, the reaction principle based turbines or reaction turbines will be touched upon in the subsequent class. And in this lecture, we will specifically focus on impulse principles and velocity diagrams and we will try to see how these principles helps us in generating power by using steam as the working fluid. So, let us give some brief introduction about the Rotodynamic Machines.

So, this word Rotodynamic Machines comes under the broad roof of fluid machines, when you talk about compressors, turbines which are used in the gas turbine power plants. Again we also use in the hydraulic power plants, we have impulse turbines, we have reaction turbines like we have impulse wheels or Pelton wheels, then we have Francis turbine, we have Kaplan turbines. So, these are the terms that are used when you are using hydraulic machines. But all of them falls under the common roofs because they are Rotodynamic Machines. While rotating either they produce power or they produce pressure head.

So, these are the two categories under which Rotodynamic Machines work. So, basically speaking a Rotodynamic Machine means it is the one in which fluid flows freely through an impeller or rotor and during this motion what happens that there is a energy transfer between the fluid and rotor which happens in a continuous manner. So, there is a change in the angular momentum of the fluid as the result of torque on the rotor. There are two possibility in this situation, the rotor can transfer energy to the fluid or fluid can transfer energy through the rotor. So, based on these two we say whether it is a power consuming device or power producing device.

Now, when the energy is transferred from the fluid to rotor that means, fluid is carrying a substantial amount of energy and that energy is being utilized in rotating the blades of the rotor. So, then it is known as a turbine. On the other hand if the energy is transferred to the fluid from the rotor then the machine is referred as fan compressor or pump. Normally fans are used for small pressure differences, compressors are used for large pressure differences and both fan or compressor they are mainly used for fluid as a gas. Whereas, the word pump is being used when you are using liquid, when you are want to increase the pressure head of the liquid.

Rotodynamic turbine is also classified by the direction of the flow of fluid relative to the rotor through which the angular momentum of change is achieved. So, these fluid directions can be either parallel to the axis of the rotor or in the radial direction or in the mixed mode. So, basically speaking here if you look at this figure, this figure shows that we are trying to concentrate on a steam power plant which compose a boiler, turbine, condenser and pump. We are now focusing on this turbine component or to some extent pump component, but mainly we will be focusing on the turbine component. And this turbine fall under the roof of radial flow machine or axial flow machines.

What happens in a radial flow and axial flow machines? We can see here. These machines are normally classified the way by which the flow direction is achieved with respect to the rotor positions or the direction of the rotor. So, on that basics we can have axial flow machines or radial flow machines. So, this figure shows the schematic diagram of an axial flow machines and radial flow machines. So, what happens in a radial flow machines? As you see one of the cross sections, so, if you see from this side view what happens? The flow comes axially and it tries to pass through the impeller and impeller consist of number of blades and this energy from the fluid is taken away by this impeller and finally, the fluid comes as a outlet. So, what we see here is that in a radial flow machines, the flow across the blade involves substantial radial flow component at the rotor inlet exit or both. But when you refer to the axial flow machines what happens? Majority of the component flow comes in the axial directions. So, that is the basic difference. So, they are termed as axial flow machines.

In some cases we can have a mixed flow machines, normally this happens when we are using liquid that means, in water particularly in hydraulic turbines, we can have a mixed flow machines because purely axial or purely radial is almost difficult to have. So, mixed flow machines are already considered. So, in that case the velocity components may have both radial and axial directions. So, another way of looking at our philosophy or viewpoint that we will be looking mainly on steam turbines and these steam turbines are mainly referred as the axial flow machines, but they are based on two fundamental principles, one is impulse principle other is reaction principle. So, accordingly we call them as impulse turbines or reaction turbines.

So, in our subsequent lectures mainly our attention will be focused towards impulse and reaction turbines and their analysis. So, the analysis is done in two folds one is based on the rotodynamic principles, other is based on the thermodynamic aspects. So, both we are trying to link up that what is the efficiency that we get while producing the power. So, let us start the first one which is impulse turbines. So, before we go for the impulse turbines we will try to focus on the fundamental principle what is called as impulse.

The word impulse normally refers is the very short duration forces, that means a force comes instantly and it dies down. So, how to explain this impulse principles for that reasons, we consider a horizontal fluid jet which impinges on a fixed plate and what happens this fluid jet has velocity Vs and it is moving in the positive x directions and this plate is fixed. So, obviously, when the jet comes and hits it and since the plate cannot move and it tries to deflect. So, deflection normally happens in the direction almost 90 degree to this plane and from the both sides. So, obviously, whatever energy it carries since the plate is not moving, so, there is efficiency of the jet or kinetic energy of the jet almost vanishes or goes as a loss. But in other scenario let us see that if you relax this fixed conditions. So, that means, we can make these things that plate is moving. So, how do you make this plate moving? So, you keep this plate stand on a roller and that roller is such that it fixes this blade or plate and when the jet comes and impinges obviously, the fluid will deflect as well as this roller will also move, means that plate will also move. So, let us see that if you say that the plate velocity is Vb and that means, this Vb is initiated due to the fluid jet when it impinges on these things and side by side the fluid also deflects.

So, let us think about how much force we are applying and how much energy is being transferred. So, since this plate is moving that means, there is work is done by the fluid on the plate. So, let us calculate them by simple fundamental principle, what we call as impulse principles. So, by knowing this velocity of fluid jet and velocity of the plate what we can first find out is that force or impulse imparted plate on the jet will be $F = \dot{m}V_s$ and if it is in a fixed case, but if it is in a moving plate, then since plate is moving. So, difference in the velocity that means, relative velocity comes into picture. $F = \dot{m}$ $(V_s - V_B)$.

So, $V_s - V_B$ is nothing, but the velocity of jet relative to the plate. Now, moving further we will try to see how much work is being done. So, referring to the same figure we need to find out what is the work done per unit time. So, we know that is nothing, but force multiplied by velocity and this term comes as $\dot{m}V_B(V_s - V_B)$ and this is the work done per unit time that is $\dot{W}$, but this work is being achieved from the fluid jet which has initial power which is nothing but your kinetic energy and that kinetic energy is nothing, but

$\frac{1}{2}\dot{m}V_s{}^2$. So, we have calculated the work, we have calculated the initial power, then we will be now in a position to define the efficiency of the plate.

So, this efficiency of the plate can be defined by the ratio of work with respect to initial power and so, by taking this ratio $\frac{\dot{W}}{KE}$ we can arrive at this expressions. But under what conditions this work done per unit time will be maximum. Now, we will be trying to find out, we have mathematical expressions to find out optimum plate velocity that maximizes the power. To do that we can differentiate this work done per unit time with respect to plate velocity Vb. So, by differentiating this that is $\frac{d\dot{W}}{dV_B} = 0$ we can arrive at expressions $\dot{m}(V_s - 2V_B) = 0$.

This gives the optimum blade velocity $V_{B,opt} = V_s/2$ that means the optimum velocity for which the power is maximum should be $V_s/2$. And for this optimum velocity the maximum power that we can achieve is $\frac{1}{4}\dot{m}V_s^2$. By putting V optimum speed on this work expressions we can find out the maximum power. Now, at this optimum plate velocity, we can also find out the maximum efficiency of the plate, this can be achieved about 50 percent. So, this gives an indication that from a fluid jet having kinetic energy of $\frac{1}{2}\dot{m}V_s{}^2$, only 50 percent of the energy is being utilized to achieve maximum power and for which the blade velocity is or plate velocity is half of the fluid jet velocity.

But still there is a question mark how we can improve this, that means we can go for maximum power, but efficiency is less. So, to do that let us try to change the configuration of the plate. So, for that what you change is configuration of the plate, from this plate shape we can imagine to have a curved surface. So, instead of plate we will just say the blade. So, what does this do is that so here if you see that Vs when it impinges it spreads on both the directions.

But here we will try to see that the fluid jet enter in a curved blade and the fluid jet also reflects or comes back in a particular direction in a particular concise manner. So, to do that let us see if you can improve this efficiency or you can increase this power. So, what we have observed here that instead of a flat plate if you take a cylindrical blade that allows the jet to reverse its directions and this blade is considered as fictionless. So, that there is neither expansion or contraction of the fluid from entry to exit. So, basically that we are allowing this fluid jet to travel in a organized manner just it enters at this point, we say it is a inlet and it leaves this blade and we call it as a outlet.

So, basically this is in a organized manner. So, through this process it is possible to calculate the impulse on the blade, power and blade efficiency and further optimum velocity also can be found out that gives the maximum power. In this case also we will follow this analysis that optimum velocity will be half of the jet velocity which is same as the flat plate, but the maximum power will be twice this of the flat plate and also this equals to the kinetic energy. So, in other words we can achieve 100 percent efficiency. By doing so, let us see how you can prove this mathematically.

So, for that reasons we also consider the same philosophy that we say Vs is the velocity of the jet in the horizontal directions, V_B will be the velocity of the blade in the horizontal directions. So, relative velocity of the fluid at the center entry would be $V_s - V_B$ since the blade is moving at V_B. So, relative velocity will be at the entry and exit will also be same, but then what will happen to absolute velocity, so the absolute velocity at the exit would be $V_B - (V_s - V_B) = (2V_B - V_s)$. So, absolute velocity at the entry is Vs, but absolute velocity when it leaves is $V_B - (V_s - V_B)$ because the jet turns the direction opposite and we are looking at the blade velocity in positive x directions and with respect to this positive x directions fluid jet moves relative to this. So, which means that we will have a absolute velocity at the exit will be $2V_B - V_s$.

So, we know the inlet and exit velocity of the fluid, we can find out the what is the rate of change of momentum that is force that we can find out as $2\dot{m}(V_s - V_B)$. So, in the same philosophy we can find out the also work done. So, here you see that the force becomes two times from the previous value for the case of simple plate. Then work done will be $2\dot{m}V_B(V_s - V_B)$. Initial power for same fluid would be the kinetic energy as $\frac{1}{2}\dot{m}$ V_s^2. So, ultimately we will be able to find out the blade velocity.

So, $\eta_b = \frac{\dot{W}}{KE} = 4\left[\left(\frac{V_B}{V_s}\right) - \left(\frac{V_B}{V_s}\right)^2\right]$. So, we can now able to differentiate the work done with respect to Vb to find out the optimum velocity that maximizes the power. So, this gives a conditions that $V_{B,opt} = \frac{V_s}{2}$, optimum velocity remains same as that of flat plate, Wmax is $\frac{1}{2}\dot{m}V_s^2$, but earlier it was $\frac{1}{4}\dot{m}V_s^2$ which means that you just compare kinetic energy of the jet and maximum power they are same. So, obviously efficiency of the blade is 100 percent.

So, it means it gives an indication that theoretically it is possible that entire kinetic energy of the fluid can be converted to arrive at work done on the blade if we can align the fluid jet in a cohesive manner or in a organized manner. So, this particular philosophy was utilized to generate continuous power. So, here what we have shown this figure is that the concept of this simple curve blade is extended by using a series of blades arranged in an organized fashion, and here the gap between each of the blade is utilized where the fluid jet is supposed to pass. Now, through these things what may happen is that so in a single blade it is possible to deflect the fluid jet in a completely opposite directions, but since there are finite widths of the blade and when we have a large number of blades or series of blades they have to be mounted in certain finite widths of the rotor and of course we also have to see that the fluid passes and it moves smoothly in this passage. So, it is almost impossible to achieve 180 degree deflections.

So, one particular angle and in practical cases the deflection is always less than 180 degrees and of course we cannot again hit the tip of the blade when you make this theta as 0 degree for all the series of blades, we have to keep some angle theta and this theta we call this as a the entry angle of the fluid jet into these blades and many times you refer this as a nozzle angles. So, what I have explained here is that continuous power can be obtained by incorporating series of cylindrical blades mounted on the circumference of the wheel so that face of the jet continuously rotate the wheel, but then a high speed jet needs a nozzle that means to achieve this fluid jet we require a nozzle and of course it is almost impossible to fix the nozzle that gives the fluid jet at 0 degree value of theta and that will cater all the blades. So, for that reasons a shallow angle of theta is maintained and that is with respect to horizontal direction of the jet and of course we cannot achieve 180 degree deflections, so the practical blade turn angle is less than 180 degree. Now, moving further to extend this impulse principle if you want to really find out how much power or efficiency of the blade which we are going to get then what you see here is use the principle of impulse momentum concept. We says that work done on the blade can be found out by the force in the direction of the blade which is equal to the change in the momentum of the fluid in the direction of the motions and the component of the stream velocity in the direction of the blade motion is we call this as a velocity of whirl.

So, for that reasons what we require is that velocity vector diagrams. So, we consider a single blade and try to find out the velocity diagrams. So, here we refer that when the fluid jet comes and hits so this is what we say inlet velocity triangle and this is outlet velocity triangle. If you see this blade direction is V_B and the angle at which the jet impinges that is θ what we see is the relative velocity Vr1. So, for inlet condition we use the word 1 for outlet conditions we use the word 2.

So, let us analyze that since the blade is moving what we see is the relative velocity Vr1 and the absolute velocity of the fluid jet is Vs1 the net effect between these two velocity is the V_B which actually the blade velocity. Now, similar to this what we see, since the blade is moving we see the relative velocity of the fluid that leaves as Vr2, V_B is the same blade velocity and Vs2 is the absolute velocity of the fluid jet. Now, what we do? here we include this angle and typically one is θ which is referred as a nozzle angle other is ϕ

nothing but is the angle that between Vr1 and horizontal directions. Another angle is $\gamma,$ which is with respect to horizontal and in the outlet triangle with respect to relative velocity fluid at the exit, then we have another angle δ that is absolute velocity of the fluid at the exit that makes with the horizontal. Then what you do you try to put them in a single plot or you try to merge them.

So, there could be two possibilities one is the this $\delta < 90$ or $\delta > 90$. So, ideally speaking when you analyze this velocity triangles we will come back what is the significance of these two things, mainly this delta value will detect whether your work output will be maximum or not. So, what we are now trying to see here with this information of theta, gamma, phi and delta, we need to create the shape of the blade in such a way which maximizes the work output or work done by the blade. So, how do you do that? So, for that reasons we have to find out what is the force imparted in the direction of the motion of the blade. So, that is always we see that positive x directions when you say V_B direction is this, that is positive x direction we always refer.

So, by looking at this velocity diagrams we can find out that force imparted in the direction of the motion of the blade would be $F = \dot{m}(V_{s1}\cos\theta - V_{s2}\cos\delta)$. So, here if you say this particular figure, so Vs1 and Vs2 they are in the same directions, but if you look at this particular figure, we have Vs2 and Vs1 they are in opposite directions. So, that does not matter to us because this δ will take care whether this quantity is a positive or negative. So, basically speaking in order to have maximum impact of this force, the entire quantity has to be added up. That means your delta value should be such that if the $\cos\delta$ becomes negative then this term gets added up.

So, obviously since we call this as a whirl velocities so we write them as $F = \dot{m}(V_{w1} - V_{w2})$. So, this whirl velocity that has to be added so that the force will be higher. So, this is the philosophy of designing the blade. Then using this velocity triangles we can find out what is whirl velocity at the inlet and at the exit. We also can find out what is the relative velocity of the fluid which is entering and exit in the positive x direction.

So, now once we are able to find out the force, then we can find out what is the work done per unit time. This is again multiplied by force into velocity that is $\dot{W} = \dot{m}V_B(V_{s1}\cos\theta - V_{s2}\cos\delta)$. So, we can find out initial kinetic energy of the jet also $\frac{1}{2}\dot{m}V_{s1}^2$ that is the kinetic energy at the inlet or entrance. Now, by knowing work done per unit time and initial kinetic energy we will be in a position to find out the blade efficiency by taking this ratio. So, here I have already mentioned that whether the term cos delta is positive or negative that depends on the what is this angle.

So, ideally while doing this design of the blade one should ensure that entire term that work done term that $V_{s2}\cos\delta$ that means the angle delta should be chosen in such a way that this gives an additional term to the work done per unit time. So, this will be more clear once you solve this problem by using this velocity diagrams. So, once we have force then we have work done per unit time then we can calculate the initial kinetic energy we are in a position to find out the blade velocity. So, next step is to find out what is the optimum blade speed and maximum work and maximum efficiency. For that reasons again we have to use the same expression that is work done per unit time and kinetic energy then we have to find out the blade efficiency.

Then for optimum blade velocity we must differentiate this work expression with respect to V_B and this gives the optimum blade speed would be $\frac{V_{s1}\cos\theta}{2}$. So, here if you recall our earlier expression that it was $V_s/2$ in a curved blade or in a flat plate, but here since the jet is impinging at an angle theta. So, it becomes $\frac{V_{s1}\cos\theta}{2}$ and correspondingly it gives $\frac{\dot{m}(V_{s1}\cos\theta)^2}{2}$ and this maximum work refers to the optimum blade velocity. So, maximum blade efficiency, we can take the ratio, we say it is $(\cos\theta)^2$ which means if theta is 0 means at 0 degree nozzle angle we have maximum blade efficiency.

This is the theory what we get for the simple single curved blade. Now, another point I need to emphasize many a times we consider this term $\phi = \gamma$ just to emphasize the fact so that relative velocity at the inlet and exit remain same. So, this particular condition is called as a symmetric blade. So, that is no loss of velocity coefficients that means during there is no loss of relative velocity from the entrance to the exit. So, this is another design criteria and of course exit whirl velocity is 0 and absolute velocity is straight in the exit direction this is what it means.

Now, let us understand the velocity diagram in a difference perspective in terms of thermodynamic effects. So, here what we have done so far using the rotodynamic principle or velocity diagrams you try to emphasize how much work we are going to get. But the other side is that when the steam comes it comes with certain energy associated with it because it is a superheated steam it has a very high value of enthalpy. Now, how that enthalpy we are trying to correlate with this rotation of the blade. So, for that we find that work transfer per unit time by using this thermodynamic equations as $\dot{W} = (H_1 - H_2) + \dot{m}\left(\frac{V_{s1}^2}{2} - \frac{V_{s2}^2}{2}\right)$.

Now typically since the blade is rotating so instead of absolute velocity we see this relative velocity $H_1 - H_2 = \dot{m}\left(\frac{V_{r2}^2}{2} - \frac{V_{r1}^2}{2}\right)$. So, by putting this one we can write $\dot{W} = \frac{\dot{m}}{2}\left[\left(V_{s1}^2 - V_{s2}^2\right) - \left(V_{r1}^2 - V_{r2}^2\right)\right]$. So, this is the actual expressions that we are going to get. But ideally speaking what we see here because of this rotation, this relative velocity term reduces the work. So, which means if you want to maximize the power this relative velocity difference components has to be totally removed.

So, for that reasons we introduce this concept that if it has to be purely impulse that means, you design the blade in such a way that we will have negligible difference in this relative velocity components. So, that turbine will be called as pure impulse turbines where absolute velocity of the fluid takes the dominance. So, this is the concept of looking for a pure impulse turbines and while designing the blades it has to be ensured that this difference should be as minimal as possible. Now to account for whether it is a pure impulse or not, we define a term called as velocity coefficients that takes the ratio that $k_v = \frac{V_{r2}}{V_{r1}}$. So, if there are some frictions obviously, there will be a relative velocity difference from the exit to entrance.

So, we introduce a term what is the tolerance level, what velocity coefficient we can assume that is one aspect. Second aspect what we can say is that we can find out the energy which is being carried by the fluid that is nothing, but the enthalpy drop of the fluid when the energy is dumped onto the blade. So, that is $\dot{m}(\Delta h_s)$ that comes from separately from the energy the fluid carries and that is being transferred in getting this work. So, the ratio between $\frac{\dot{W}}{\dot{m}(\Delta h_s)}$,we call this as a stage efficiency which is defined as the ratio of work transfer through the blade divided by the total enthalpy drop of the fluid for entire stage.

Stage means that includes nozzle as well as blade. So, in our previous case we say that nozzle is the integral part of the blade because it supplies the fluid onto the blade. So, that is the reason the entire stage means it includes nozzle as well as the blade, if the fluid were isentropic. So, this is all about you need to discuss, now we will try to solve a numerical problems based on our discussions. So, till this point of time we are clear about the impulse principle, we are clear about the velocity triangles at the entrance, at the exit.

Now, based on this philosophy we are trying to solve this problem. What it says is that the steam enters the nozzle at an angle 20 degree for an impulse turbine at 30 bar and 320 degree centigrades. Exit condition is 15 bar. The mass flow rate of the steam is 45 kg per second and nozzle efficiency is 90 percent. The blade is symmetrical and it travels optimum velocity with velocity coefficient of 0.97. It means that blade is symmetrical and due to the frictions only there is a hardly loss of 3 percent of velocity from the entrance to the exit. So, we need to draw the velocity diagram first. Now, after drawing this velocity diagram we have to calculate the following parameters like blade angles. The blade angle I mean the tip of the blades or the angles that is gamma, delta and phi, power delivered by the turbine per stage and blade efficiency and stage efficiency. So, for that reason if you recall our diagram like this, already I have explained Vs1, Vr1, V_B, angle between Vs1 and V_B is theta, angle between Vr1 and with horizontal direction is phi. Similarly, this is your inlet and at the exit the angle between Vs2 and horizontal is delta, angle between Vr2 and horizontal is gamma. But to analyze the velocity diagram in a different way we have to merge these two diagrams. But before you do that first we need to find out what is about the steam conditions.

So, for that we have to recall our study that either you draw temperature entropy diagram or enthalpy entropy diagram. We see that the steam that comes somewhere from the nozzle and had this process been isentropic it would have come back to this s that means, isentropic process otherwise it is coming as s1. And at this, particular condition is 30 bar and 320 degree centigrade and exit condition is 15 bar. So, this pressure is 15 bar and this pressure is 30 bar. So, we have to use our previous study or concept to find out the steam conditions.

So, first thing we need to find out what is this Vs1. So, Vs1 information will come from this nozzle efficiency and enthalpy drop. To calculate this enthalpy drop we need the steam conditions at the inlet of the turbine and the exit of the turbine.

$$@\ 30\ bar, 320°C \rightarrow h_n = 3043.4\frac{kJ}{kg}, s_n = 6.6245\frac{kJ}{kg-K} = s_s(as\ isoentropic)$$

$$@15\ bar, s_s = 6.6245\frac{kJ}{kg-K} \rightarrow h_s = 2899.3\ kJ/kg$$

From Nozzle efficiency, $\eta_n = \frac{h_n-h_{s1}}{h_n-h_s} = 0.9 \rightarrow h_{s1} = 2913.7\frac{kJ}{kg}$

$$V_{s1} = \sqrt{2(\Delta h)} = \sqrt{2(3043.4 - 2913.7) \times 1000} = 509.3\ m/s$$

So, this is the condition that Vs1 we are able to find out. Now, once you are able to find out the Vs1 then our next step is to construct velocity triangle . So, a simplified way of constructing the velocity triangle is to merge both inlet and exit condition in a single graph.

So, what we see is that because in the both entrance and the exit angle the common is V_B . So, we say that Vs1 comes and this angle is theta, then we have Vr1 this angle is phi, then we have this Vs2 and Vr2 and this angle is delta, this angle is gamma and this angle would be 180 minus delta. So, what we can do we can drop a vertical from this point and this point. So, from this diagram we will be now using the trigonometric principle we have to analyze inlet velocity triangle and exit velocity triangle .

$$\textit{From Inlet traingle ADB}: AD = V_{r1}\sin\phi = V_{s1}\sin\theta\,; CD = V_{s1}\cos\theta - V_B = V_{r1}\cos\phi$$

$$\tan\phi = \frac{V_{s1}\sin\theta}{V_{s1}\cos\theta - V_B}$$

$$\textit{From Outlet traingle}: PR = V_{r2}\sin\gamma = V_{s2}\sin(180-\delta) = V_{s2}\sin\delta\,;$$

$$CR = CB + BR \rightarrow V_{r2}\cos\gamma = V_B + V_{s2}\cos(180-\delta) \rightarrow V_B = V_{r2}\cos\gamma + V_{s2}\cos\delta$$

$$\tan\delta = \frac{V_{r2}\sin\gamma}{V_B - V_{r2}\cos\gamma};\; k_v = \frac{V_{r2}}{V_{r1}}$$

$$V_B \textit{ or } v_{opt} = \frac{V_{s1}\cos\theta}{2} = 239.3\, m/s$$

$$\tan\phi = \frac{V_{s1}\sin\theta}{V_{s1}\cos\theta - V_B} = 0.728 \rightarrow \phi = 36°$$

$$V_{r1}\sin\phi = V_{s1}\sin\theta \rightarrow V_{r1} = 296.8\, m/s$$

$$k_v = \frac{V_{r2}}{V_{r1}} = 0.77 \rightarrow V_{r2} = 288\, m/s$$

$$\tan\delta = \frac{V_{r2}\sin\gamma}{V_B - V_{r2}\cos\gamma}\,(\gamma = \phi = 36^\circ\ as\ blade\ is\ symmetric) \rightarrow \delta = 88^\circ$$

$$V_{r2}\sin\gamma = V_{s2}\sin\delta \rightarrow V_{s2} = 171\ m/s$$

$$\dot{W} = \dot{m}V_B(V_{s1}\cos\theta - V_{s2}\cos\delta) = 5089\ kW$$

$$\eta_b = \frac{\dot{W}}{\frac{1}{2}\dot{m}V_{s1}^2} = 87.2\%$$

$$Stage\ Effieciency\ \eta_s = \frac{\dot{W}}{\Delta H_s} = \frac{\dot{W}}{\dot{m}(h_n - h_s)} = 78\%$$

So,basically speaking here in the entire exercise tells us the important fact is that when you calculate this particular term, this cos delta term is either very small. So, in this case this number is negligible with respect to this or delta value will be such that this negative term becomes positive, this one aspect.

So, this will give the benefit of for maximizing the work. Then other important concept is that the velocity diagram or triangle should be drawn properly and more or less we observe that in a given steam turbines the blade efficiency or stage efficiency should be in the range of a 80 percent or above. That means, when you are doing this exercise or design the blade and finding this efficiency is not more than 80 percent, then it will be considered as an inefficient design. So, this is the important thrust point in the design of blades by choosing a suitable blade angles. With this I will conclude. Thanks for your attention.