POWER PLANT SYSTEM ENGINEERING

Lec 9: Reaction Turbine

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 our attention will be focused towards turbines and in the turbine category we will discuss mainly on reaction turbine. Subsequently, we will talk about velocity triangles. So, having drawn this velocity triangles, then we will be able to find out the operating parameters for the reaction turbines.

So, these operating parameters are the power developed by the turbine, we call this as a power output. Blade speed, what is the optimum blade speed the turbine should operate, then we need to find out nozzle efficiency, moving blade efficiency and stage efficiency. So, these quantifications are required for reaction turbines. So, towards the end of lecture we will try to summarize the two types of turbines we have discussed so far.

One is the impulse turbines which we are discussed in previous two lectures and reaction turbines. So, let us start the reaction turbines. So, normally the word reaction comes from the Newton's third law of motions for every action there is a equal and opposite reactions. So, taking that advantage of the law, the reaction turbines are develops. So, prior to that we are going to discussed about this reaction principle.

Normally, the reaction machines are device that cause the fluid to exit at high speeds and this high speed exit fluids gives substantial force onto the body which means that fluid beginning with zero velocity creates a force in the direction of motion and there is a corresponding equal force that tends to move the device in the opposite directions. So, a typical examples that we are seeing in our day to day life is that aircraft or rocket when is moving, it is based on the reaction principles which means that the exhaust that comes out from the rocket nozzles that drives the rocket or aircraft at certain altitudes. Other rotary devices we can find out the lawn sprinkler which means that we might have seen machines installed for the gardening purpose in the lawn which typically rotates and side by side water jet comes out of it. So, it means that when jet of the water gives a force that rotates the sprinkler in the opposite directions. So, these are the some of the examples of reaction turbines and similar concept we are going to use while developing the relations for reaction turbines.

So, prior to that what we have seen in the impulse turbines is that there is no pressure drop in the moving blade. So, one can imagine to have a blade passes through which there will be a pressure drop then blade would have reaction force moving in the opposite directions. So, if you use in the impulse turbine of course, there is no pressure drop in the moving blades, but if you can imagine that if at all we can create some device which will move the blade when the fluid passes through the blade passage. So, that is the concept of reactions. So, however, in reality a pure reaction blade does not exist because the blade passage is not a reservoir or where steam can have zero velocity, it will have some finite velocity.

So, in reality reaction turbines are partial impulse and partially reactions. Here the term reaction is used despite the fact it is a pure reaction turbine are not built. So, in other words many books refer them as a equal pressure or unequal pressure turbines as impulse and reaction turbines. Now coming back to the concept of reaction turbine in which it works. So, let us understand these figures and we will see how pressure drops and velocity changes across the blades.

You might have aware that when we discussed about impulse turbine there were a set of nozzles that supplies to the fluids and that rotates the moving blades. So, there is no pressure drop in the moving blades in an impulse turbines whatever pressure drop takes place that takes place in the nozzle only. Now you imagine a situations that we can think about array of fixed and moving blades in a organized fashions which means that this fixed blade passage acts as a nozzle entry for the a moving blades. That means, it supplies the fluid to the moving blade in directions with a appropriate orientations as the blades are designed. So, that we can maximize the fluid intake and this is the role of the fixed blades and once the fluid passes through this moving blades then again it goes to the next round of fixed blade because the expansion may not have been to a full extents, it may have certain kinetic energy at the exit of the first set of moving blades.

So, they again realigned through another set of fixed blades to the next set of moving blades and this process continues till the fluid velocity comes down to a very marginal level. So, accordingly what happens if you look at the absolute velocity. So, in the fixed blades, the velocity increases and of course, pressure decreases and in the moving blades the velocity decreases, again in the fixed blade it increases and it decreases. The side by side there is a continuous increase and decrease in the velocity, but if you look at the pressure drop pressure drop is very gradual. So, however, one point that to be noticed is that at the initial stage the slope is little bit high, but when you run towards the later stage, the slope may be less because the fluid loses the energy in a subsequent stages.

So, this is how the reaction turbines work. The reaction turbine is constructed through rows of fixed blades and rows of moving blades and here the fixed blades act as nozzles. The moving blades move as a result of impulse of the stream received through the change in the momentum and also as an expansion and acceleration of the stream relative to them. This particular picture shows a three stage reaction turbines that means, there are three sets of fixed blades and three sets of moving blades. Now, moving further if you want to quantify the fluid energy in terms of enthalpy we can say that the enthalpy drop per stage; per stage means one row of fixed blade and one row of moving blade is often equal. So, we already have emphasized that it is not possible to construct a complete reaction turbines, it has to be partly impulse and partly reactions. In some sense a very reasonable argument could be 50 percent reaction turbine and 50 percent in impulse turbine. In other words it means to us that 50 percent of enthalpy drop takes place during impulse stage and 50 percent drop takes place in the reaction stage that is 50 percent drop takes in the moving blade and 50 percent takes in the fixed blade and in fact, this fixed blades act as the nozzle. So, for that reasons we encounter a parameter which is called as a degree of reactions.

Since complete reaction turbine is not possible that is the reason we define a term what is called degree of reactions and it is defined as the ratio of enthalpy drop in the moving blade to the enthalpy drop in the stage. Stage means fixed and moving blades. So, in this figure we say it is a stage 1 and this is stage 2 and this is the third stage. When the pressure drops are not equal then they may be considered as a pressure compounded impulse turbines. So, the concept of pressure drop in a pressure compounded turbine and a reaction turbines are more or less same, but the viewpoint is different because when you say the pressure drops are not equal we normally refer them as a pressure compounded impulse turbines which we discussed earlier.

But when they are equal we say it is a completely 50 percent reaction and 50 percent impulse mode. Now, this word 50 percent is very vital in terms of steam power plant terminology because this concept of reaction turbine was first invented by C. A. Parson. So, that is the reason this is called as a Parson turbine which has 50 percent degree of reactions and he has developed a three stage of three reaction stages each composed of a row of fixed blade and a row of moving blades.

Now, the stationary blades are designed in such a way that passage between them form a flow area of the nozzle and these are the nozzles with full stream admission around the rotor periphery. Now, coming back to the distinguishable features if you look at fixed and moving blades or impulse turbines and reaction turbines, normally the reaction turbines have a moving blades and these blades designs are little bit different than than that of impulse blade and they are generally curved in the opposite directions to perform a nozzle actions and they are aligned with fixed blade in such a way that fluid is directed in a unified directions so, that complete coverage of this fluid in the moving blades is accounted. Now, one interesting thing or maybe significant inference for this reaction turbine is that the pressure continually drops through all the rows of the blades whether it is a fixed as well as moving, but the pressure changes is greater at higher pressures. That means, slope is high in the beginning stage and slope is less at the later stage, high slope and this is low slope which says that pressure change is greater at higher pressures.

So, the absolute velocity changes within each stage and that repeats from the stage to stage. So, the fluid passage it can come like this goes like this then again enters to the next set of fixed blades, second stage of moving blades, then next stage of fixed blades and then next stage of moving blades. So, this is how the orientation of the locus or path of the fluid that takes place in a reaction turbine. Now, to analyze this performance of reaction turbine the most important thing that we need to discuss is the velocity triangles because this mechanics principle based on drawing the velocity diagrams will help us in two things one is in designing the blades with their appropriate angle, number 2 is that the component of velocity that justifies the power. So, one thing we have blade velocity, other thing is that the fluid velocity that comes out from the exit.

So, these two things we need to find out while calculating the power developed from the turbines. So, typical velocity diagram for a two stage is given in this picture. So, firstly enthalpy drop per stage is defined and it is further divided into two parts one is fixed part and moving parts. That means, if you want to design a set of things, first thing we need to know how much expectation of power we have, then we have to divide them in two parts one is fixed part other is moving parts. Now, in the fixed part we have to see how many stages of fixed part is required and how many stages in the moving part of the required.

Once you have these numbers then we can design the blades and align them accordingly. Now the after that, the work done of a reaction turbine can be obtained through momentum impulse principles that is change in the momentum on the blade in a positive directions is nothing but the change of the components in the relative velocities in that direction. So, we will see how this velocity diagram look like, as I told the direction of the fluid that comes here and enters from the fixed blade then enters to the moving blades then further enters to the fixed blade then goes from the moving blades and finally, it comes out. So, this fluid passage continuously have this. So, basically if you take one particular stage we have one first blade category that is fixed blade for this fixed blade we can see Vs1 is the velocity flow of fluid that enters V_B is blade velocity and this gives a relative velocity of the fluid that enters.

So, when you see the moving blades it enters at Vr1 and it goes at Vs2. So, we have $V_{r1}, V_{r2}, V_{s1}, V_{s2}, and\ V_B$. similarly next stage we have Vs3 the fluid velocity, relative velocity of the fluid Vr3 and blade velocity is V_B. So, likewise the velocity diagrams can be constructed and here the theta normally refers to the angle at which the absolute velocity of the fluid enters into the moving blades and phi is for the relative velocity of the fluid when it enters to the moving blades. So, these angles are very vital because this gives the orientation of the blade. Now, coming back to the mathematical insight, we need to find out at the end of our analysis is that what are the working equations and how much power we are going to get it.

So, for that reasons the velocity diagram with respect to enthalpy drop in the fixed and moving parts of the turbine has to be analyzed. So, if you say enthalpy drop per stage that means, if you are considering n number of stages. So, the enthalpy drop per stage is $\Delta h = \frac{\Delta h_s}{n}$, n stands for number of stages and now we are saying that it is a person turbine. So, 50 percent drop has to takes place in the fixed blade and 50 percent has to take in the moving blades. So, you can divide them equally, then from this velocity triangle one can find out $\Delta h_f = \Delta h_m = \frac{\Delta h}{2}$ and again from this velocity triangle by combining for one stage we can find out the combined equations of this relative velocity, stream velocity and blade velocity as $V_{r1} \cos \phi = V_{s1} \cos \theta - V_B$.

Then ultimately we can find out change in the momentum on the blade in the direction of positive x direction. So, we can find out F. So, from the F we can find out the rate of power and subsequently the final expression that we are going to use is for W.

$$F = \dot{m}(V_{r1}\cos\phi + V_{r2}\cos\gamma) \Rightarrow F = \dot{m}(V_{s1}\cos\theta - V_B + V_{r2}\cos\gamma)$$

Rate of work or power, $\dot{W} = FV_B = \dot{m}V_B(V_{s1}\cos\theta - V_B + V_{r2}\cos\gamma)$

Using first-law principle: $\dot{W} = \frac{\dot{m}}{2}[(V_{s1}^2 - V_{s2}^2) - (V_{r1}^2 - V_{r2}^2)]$

So, this is the final expression that we are going to use. Then after calculating the work output from the turbine we will be able to find out the optimum blade speed at which the reaction turbine should operate.

For that reasons, since we have already assumed to be a 50 percent reactions. So, based on that there are some assumptions that blades needs to be geometrically similar for which theta should be equal to gamma and that is our user friendly requirement. Then from this we can find out the final expressions for rate of work or power by assuming these blade conditions then we can find out the expressions for work done or developed by the turbines and for maximum work we can differentiate this work expressions with respect to V_B and we will get the optimum blade velocity and your optimum blade velocity is $V_{s1}\cos\theta$ whereas, in other cases it was $\frac{V_{s1}\cos\theta}{2}$. That means, in a reaction turbine we are able to operate it at a higher blade speed. Then from this we can also find out the maximum work.

Rate of work or power, $\dot{W} = \dot{m}V_B(V_{s1}\cos\theta - V_B + V_{r2}\cos\gamma)$

When fixed moving blades are geometrically similar, $\theta = \gamma$

$$\Rightarrow \dot{W} = \dot{m}V_B(2V_{s1}\cos\theta - V_B);$$

V_B:Blade velocity For maximum work, $\frac{d\dot{W}}{dV_B} = 0 \Rightarrow 2V_{s1}\cos\theta - 2V_B = 0$

Optimum blade velocity, $V_{B,opt} = V_{s1}\cos\theta$; Maximum work: $\dot{W} = \dot{m}V_{B,opt}^2$
$= \dot{m}(V_{s1}\cos\theta)^2$

So,this is how the blade design of reaction turbines is all about.Now after having said this we will be now looking into the efficiency part. So, when you talk efficiency here, we see that enthalpy drop takes place both in fixed blade and moving blades. So, for that we have fixed blade efficiency we have also moving blade efficiency and of course, the fixed blade and moving blade they constitute a stage. So, that means, we have a stage efficiency.

So, once we have everything then again we can think of the enthalpy drop that takes place in an isentropic manner or in an actual manner. So, considering all these things, we have to revisit this Mollier diagram which is normally done with enthalpy and entropy and this is normally done for all types of reaction turbines and we call it as a condition curve. That means, what is the condition of fluid when it expands in each stage. So, what has been plotted here in this Mollier diagrams we have the saturation line. On the saturation lines these are the constant pressure lines that is $P_0, P_1, P_2, P_3, and\ P_4$.

So, interesting fact is that when you go along this pressure line, the divergence is higher that means, higher you go the divergence becomes higher and higher. So, we take this advantage that means, if you draw a vertical line at this location and if you draw a vertical line at this location for same pressure difference, in the second case enthalpy drop will be higher. So, you take this advantage as what happens in a fixed blade and moving blades. So, that is one thing, second thing that means, that is the advantage that when you go for higher pressures, we have a larger enthalpy drop which is available to us. So, this gives a higher power output that means, higher pressure drop or super heated steam at higher pressure and temperature gives a higher enthalpy drop.

So, you take this as a advantage and we keep heating the fluid that is one thing. Second thing that when you look at the drop actually that means, if a fluid which is initially at state 0 and it expands to 4, this is the final realistic curve that means, this is the final enthalpy drop that takes place from 0 to 4, but in between what happens? It passes through a fixed blade, moving blade, fixed blade, moving blade. So, correspondingly the points are located as 1, 2, 3 and 4. Now, what we are saying that for example, if at state 1 had this process been isentropic then it would have landed as 1 to s, from process point 2 had this process been an isentropic then drop would have been 2 to 3s, isentropic drop would have been this. So, likewise this dotted lines signify the all this numbers.

And finally, in fact, if you totally ignore all types of blades, if the fluid drops from 0 to 4, isentropic drop would have been 0 to 4_{Ts}, but actual drop is 0 to 4. So, this logic we are going to use to define the terms which are called as fixed blade efficiency, moving blade efficiency and stage efficiency. And for that the actual expansion curve that is 0-1-2-3-4 is referred as condition curve. Of course, from the Mollier diagrams we take the advantage that the constant pressure lines diverge to the right side of the Mollier diagrams. So, that means, the isentropic drop change to row or stage is greater than the succession rows or stage for an entire turbine.

Now, looking at our explanation like this, first thing we define the term what is called as a degree of reactions which is defined as the ratio, enthalpy drop in the moving blade divided by enthalpy drop from this stage. And referring to the figure if you say one set of fixed blade and moving blade we say it is $\frac{h_1-h_2}{h_0-h_2}$. Now if you stay first stage, second stage, third stage whatever I have explained that Δh_{fs} means isentropic enthalpy in the fixed blade and Δh_{ms} means isentropic enthalpy for moving blades. So, we can find out for first stage what is happening and second stage what is happening and effectively they are normally equal because we have assumed in that way. Then we can see that one particular term that is $(h_0 - h_{2ss}) + (h_2 - h_{4ss}) > (h_0 - h_{4ss})$ which means the constant pressure lines diverge when you go for higher entropy and enthalpy.

Then we are now in position to to define what is fixed blade efficiency and we normally refer as the nozzle efficiency. It is nothing but the ratio of kinetic energy change to the isentropic energy change and across the fixed blade. Then for moving blades we have two things one is already we are saying that 50 percent enthalpy drop should happen in the moving blade. At the same time there is a kinetic energy which is available from the exit of the first set of fixed blades. So, which means that energy which is available is the sum of kinetic energy of incoming stream and isentropic enthalpy drop across it.

The stage efficiency of the reaction stage is the nothing, but the work of the moving blade in the stage divided by isentropic enthalpy drop for the entire stage. So, whatever we have explained if you represent them as mathematically then we say nozzle efficiency $\eta_N = \frac{\left(\frac{1}{2}\right)(V_{s1}^2 - V_{s0}^2)}{\Delta h_{fs}} = \frac{h_0 - h_1}{h_0 - h_{1s}}$. Then moving blade efficiency which is $\eta_B = \frac{\dot{W}}{\dot{m}\left[\left(\frac{V_{s1}^2}{2}\right) + \Delta h_{ms}\right]} = \frac{\dot{W}}{\dot{m}\left[\left(\frac{V_{s1}^2}{2}\right) + (h_1 - h_{2s})\right]}$. Then we have stage efficiency that is $\eta_{stage} = \frac{\dot{W}}{\dot{m}\Delta h_s} = \frac{\dot{W}}{\dot{m}(h_0 - h_{2ss})}$ and for the terms that we are going to use we have to use this condition curve. So, we are now able to understand how the reaction turbines work, what is its working principles.

Now, before you complete let me summarize what is a reaction turbine and what is an impulse turbines what we have learnt so far. This particular feature summarizes the type of turbines that we have come across in all our lectures so far. So, first thing that we studied is the impulse turbine in a single stage. So, when you say it is a single stage we have a one row of blades that moves and the blade receives the fluid from this nozzle and that rotates the blade. So, accordingly we say that complete pressure drop takes place in the nozzle itself and the moving blades just rotates.

So, accordingly we have pressure and velocity diagrams. So, this is what we call as a single stage impulse turbines and which is denoted as DeLaval turbine. Some modification was done in terms of compounding where we say that single stage is also difficult because when available of steam is at very superheated steam at very high enthalpy, then loss will be more if you go for a single stage. So, the idea was thought of let us do some kind of other approach. So, that compounding approach was done there are two types of compounding one was velocity compounding other was pressure compounding.

So, through the velocity compounding normally this is referred as a curtis stage what it says is that let us think about a situation that you instead of losing this entire fluid energy at a single stage or releasing, you keep on doing it with a fixed set of stationary blades and that means, you allowed that exit fluid to pass through another set of stationary blade then again expand. So, through this process also that pressure line again continued and slowly we drop the velocity gradually in two stage and we call this as a curtis stage and it is a Curtis turbines. But then there are other advantage and if you have too many high pressure and the blade velocity also needs to be high or when the fluid is available at very high pressure and superheated conditions, another approach people follow is that instead of doing this velocity compounding do pressure compoundings that means, you remove this stationary blades and same fluid energy you supply to different stage of moving blades. So, here the basic difference between this velocity and pressure compounding is that same set of nozzle is used for all moving blades, but here different nozzles are used or a set of nozzle is used for a set of moving blades.

That means, there are two nozzles here whereas, it is a single nozzles. Now, through this process we also see the advantage that pressure drop which happens it also falls in stages. So, we have pressure drop in the stages of course, velocity increases when there is a pressure drop in the nozzle. So, this we call as a pressure compounded impulse turbines. So, it is called as Rateau turbines, but unfortunately there may not be equal pressure drop in each stages.

So, it is pressure compounding turbines. So, what we see here is that a continuous drop in pressure as well as the changes in the velocity. Now, further design which people think in the reaction mode is that instead of doing this unequal pressure stages you think about a continuous or a smooth curve of pressure drop across all the blades of the turbines. So, this design is called as a Parson turbines, we says that there are let us assume that 50 percent drop will takes place in the fixed blade stage and rest 50 percent has to be taken into moving blades. And you can see that the pressure drop is very gradual and which is much much better than any of this cases. And through this process we have also advantage that we can run the blades at higher velocities.

So, these are the some advantages we have, but however, for logistic point of view there are some restrictions that may be there are more than two stage curtis turbines although it is possible in design, but it is not economical. And when we have very high speed jet which is available to us, it is better to use this pressure compounding rather than reactions. So, there are some relative advantage between reaction and impulse turbines. So, some of them are listed here that in any turbine the blade speed is limited by the centrifugal stress induced by the blade materials. The stream velocity of reaction turbine is almost half of the pressure compounded turbines and the reaction turbine is not efficient machines which is suitable for large capacity as compared to impulse turbine.

That means, impulse turbines are used for large capacity. On the contrary the work production the reaction turbines is almost half of that of an impulse turbine for same blade velocity. So, first point says that reaction turbines are efficient machines for large capacities, but the rate of production is almost half. The reaction stage has a pressure drop across the moving blade that makes less suitable for work at high pressure and because that adds to steam leakage around the blade tip, more steam leakage may be when fixed blade and moving blades are aligned together and this leakage becomes severe at higher pressures. The impulse staging is preferred in the entrance stages of the turbines when the pressures are high and the steam specific volumes are low and the blade height is small.

So, this allows low stream velocities. In low pressure stages the reaction mode is accepted because the pressure change across the moving blade is less. The blades become progressively longer so that tip clearance becomes smaller relative to the blade height. This is something with respect to the blade designs how we need to be accounted for.

Large reaction blading negates the disadvantage of lower pressure drop per stages as compared to impulse turbines for same blade speeds. So, this is all about the overall picture of impulse and reaction turbines.

Now, we are able to know all the transient details of impulse and reaction turbines. So, before I conclude this lecture let me jump into one simple problems which is based on the Parsons turbines. So, normally when the word parson is used it is a reaction turbines and parson turbines assumes the fact it is a 50 percent reaction and 50 percent impulse. So, this is first assumption we do. Second thing in terms of velocity triangle there are certain assumptions that some blade angles are equal.

So, we which we will come to know when you draw the velocity diagrams. So, the problem statement goes like this. In a parson turbines the speed of rotation of blade group, blade group means it is a set of moving blades and set of fixed blades . They are having an rpm of 3000 rpm. So, 3000 rpm means you it has to be converted to the blade velocity as well and the main blade speed is 100 meter per seconds.

When the fluid comes from the fixed blade and enters to the moving blades, the ratio which is given that blade velocity to fluid velocity at the moving blade this is nothing but 0.56. So, exit angle for the fluid is 20 degree and the mean height of the blade is 25 mm.

So, these are the numbers which are used to find out the volume flow rate. So, first question is that we have to draw the velocity diagrams. Second thing this is asked for the what is the mass flow rate that means, from the mass flow rates we will come to know the volume flow rate. For the volume flow rate these dimensions are required. And last statement is that if there are 5 pair of blades in a group ,calculate the total enthalpy drop.

So, for these problems so, let us recall our again same velocity diagrams which we draw for impulse turbines. Same nomenclature we are going to use we say that blade velocity V_B. So, this Vs1 in the impulse case it was coming from nozzle, but here it will come from fixed blade because this fixed blades in this reaction turbines acts as a nozzle. So, here we have Vs1 and this is Vr1 and V_B.

So, this is the inlet triangle for fixed blade. Then at the outlet what we see is something like this. So, it is Vr2, then Vs2 and the angle that we normally are interested it is gamma and this is your theta, this angle would be phi. So, we drop a vertical, here also in the inlet triangle you drop a vertical, So, looking at this velocity diagrams and in fact, in our last problem we use the same expressions as we are using for inlet triangle.

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

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

$$V_{r1} = \frac{V_{s1}\sin\theta}{\sin\phi}$$

So, these expressions are required to find out these values, but before you do that for this Parsons turbines let us see what are the requirements. So, for this Parsons turbine which means 50 percent reaction which says that $\Delta h_f = \Delta h_m = \frac{\Delta h}{2}$ that is the first requirement. Again we say $\gamma = \theta = 20°\ as\ blade\ is\ symmetric.$

Now, since we have 50 percent reactions other assumption should be $V_{r2} = V_{s1}, V_{r1} = V_{s2}$. These norms has to be considered and of course, the data which is given normally this is called as velocity ratio, $\frac{V_B}{V_{s1}} = 0.56 \rightarrow V_{s1} = 100/0.56 = 178.6\ m/s.$

$$Blade\ height: h_b = 25\ mm = 0.025\ m;$$

$$N = 3000\ rpm, V_B = 100\ m/s = \frac{\pi D_m N}{60} \rightarrow D_m = 2/\pi$$

So, volume flow rate is nothing but $V = \dot{m}v = (\pi D_m h_b)V_{s1}\sin\theta$ that is volume of the fluid that passes into $V_{s1}\sin\theta$ this is the component of the fluid velocity that takes part into this volume. So, from this expressions we can find out the data for mass flow rate.

$$\dot{m} = \frac{(\pi D_m h_b)V_{s1}\sin\theta}{v}; v = 0.65\frac{m^3}{kg} \rightarrow \dot{m} = 4.7\ kg/s$$

$$\dot{W} = \frac{\dot{m}}{2}[(V_{s1}^2 - V_{s2}^2) - (V_{r1}^2 - V_{r2}^2)]$$

So, $\dot{W}/\dot{m}$ is the enthalpy drop per stage, but here it is 50 percent reaction and 50 percent impulse. So, this expressions we can use it in a different way and we can rewrite for moving blade $\Delta h_m = \frac{\Delta h}{2} = \frac{1}{4}[(V_{s1}^2 - V_{s2}^2) - (V_{r1}^2 - V_{r2}^2)]$.

$$\Delta h_m = \frac{1}{4}[(V_{s1}^2 - V_{s2}^2) - (V_{r1}^2 - V_{r2}^2)] = \frac{1}{2}[(V_{r2}^2 - V_{r1}^2)]$$

$$V_{r2} = V_{s1} = 178.6\ m/s$$

$$\tan\phi = \frac{V_{s1}\sin\theta}{V_{s1}\cos\theta - V_B} = 0.9 \rightarrow \phi = 42°$$

$$V_{r1} = \frac{V_{s1}\sin\theta}{\sin\phi} = 91.3\ m/s$$

$$\Delta h_m = 11.8\frac{kJ}{kg};\ \Delta h_f = \Delta h_m = \frac{\Delta h}{2} \rightarrow\ \Delta h = 23.6\ kJ/kg$$

So, we are now able to find out the total enthalpy drop per stage. Now there are 5 pair of groups and we have already calculated the mass flow rate as 4.7 kg/s and we have 5 pair .

So, total work done $\dot{W} = \dot{m}(\Delta h_t) \times 5 = 554.6\ kJ$. So, this gives a broad picture that how a Parsons turbines develops power output while considering both fixed blade and moving blades in an equal manner . So, this concludes this today's lecture. Thank you for your attention .