Thermal Engineering Basic and Applied
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Lecture – 35
Steam Turbines Types and Analysis Using Velocity Triangles

I welcome you all to the session of thermal engineering basic and applied and in this module of this course, we shall discuss about the steam turbines. We have discussed about the flow nozzles and we have also briefly discussed about steam turbines when we have discussed about steam power cycle. So if we just recall exactly what we have discussed in the context of steam power cycle then we will be able to see that steam which is produced in the boiler or steam generator that steam is allowed to flow through turbine. As the working fluid which is flowing through the turbine is steam, hence the name is steam turbine. And while steam is flowing through the turbine, there are several blades which are mounted on the turbine wheel and in the course of flow of steam jets through the turbine, there is a deflection and hence that steam jets suffer a loss of momentum and that loss of momentum basically gets absorbed by the rotating part of the wheel and it eventually produces shaft work.

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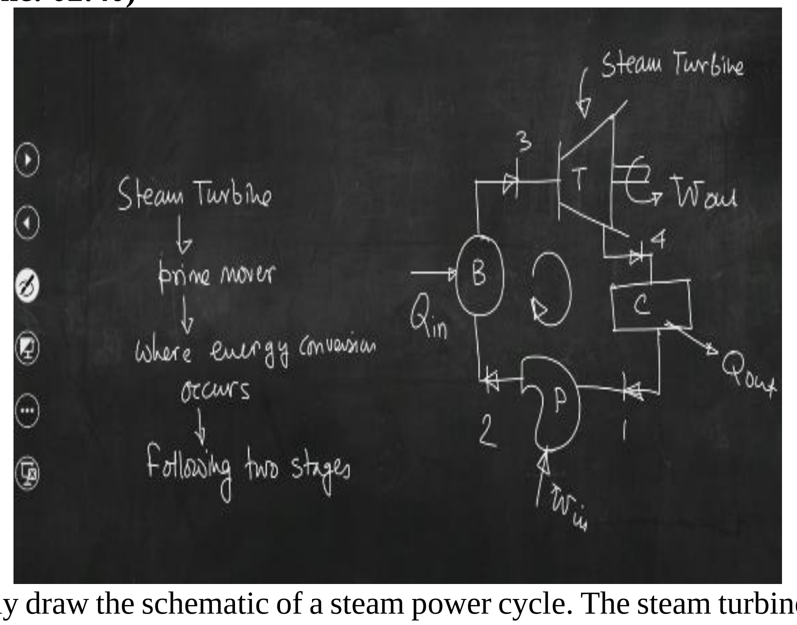

Now let us briefly draw the schematic of a steam power cycle. The steam turbine is an important component of this cycle. What we can see that steam while passing through the turbine, the sole objective of it is to rotate the turbine wheel from where you are getting work output. Now we have discussed that steam is not directly allowed to go into the turbine. So let us discuss this aspect today. We have marked the state points 1, 2, 3 and 4 as shown in the slide.

So steam at state point 3 is having high pressure, high temperature. So that high pressure, high temperature steam when flows through the turbine, energy conversion takes place. So from the flowing steam, thermal energy now gets converted into the mechanical work or shaft work. As this energy conversion takes place inside the turbine, so essentially this turbine is an energy conversion device. It is a prime mover, but it is an energy conversion device and this is used to convert thermal energy of the flowing steam into mechanical work or shaft work.

Now when you are talking about this energy conversion that is conversion of thermal energy into the mechanical energy, this conversion of energy takes place following 2 stages. So steam turbine is basically a prime mover where energy conversion occurs. We have learned from basic thermodynamics that the flowing steam is having internal that is thermal energy. So basically if we consider that this is a control volume, so there is 1 inlet and 1 outlet. So inlet steam which is entering into the control volume is having thermal energy. For this flow process, the thermal energy is represented by enthalpy. So steam which is entering into the turbine is having high enthalpy. And while it is expanding inside the turbine at the cost of enthalpy drop, we are getting some mechanical work and this conversion takes place in the turbine. And for that we need to have certain arrangements.

So this energy conversion occurs following 2 stages. Let me tell that it is not a case that steam which is produced inside the boiler will be taken directly into the turbine. Instead there will be a few flow nozzles and steam will be taken first into the flow nozzle. And while it is passing through the flow nozzle, it will expand and the sole purpose of providing flow nozzle is to increase the kinetic energy of steam before it leaves or before it strikes the turbine blade. So before it leaves the nozzle and strike the turbine blades, kinetic energy of the steam jet should be very high and while striking the turbine blade, there will be some deflection and that is definitely decided by the turbine blades angle and at the cost of that there is momentum change. So loss of momentum will be there and that momentum will be absorbed by the wheel and it is producing a torque. When steam is leaving from the turbine in the course of this impressing a torque on the rotating part of the turbine, we are getting shaft work.

So the total energy conversion occurs following 2 stages. First high pressure, high temperature steam is allowed to flow through the nozzle wherein it gets a chance to increase the kinetic energy. So steam is coming out from the nozzle in the form of a jet. That steam jet or steam jets is now allowed to flow through the turbine and when the steam jets flow through the passage between turbine blades, it suffers a loss of momentum and that momentum is getting absorbed by the rotating part of the turbine that is turbine wheel and we are getting torque and we are getting work output. So this is how the total energy conversion takes place.

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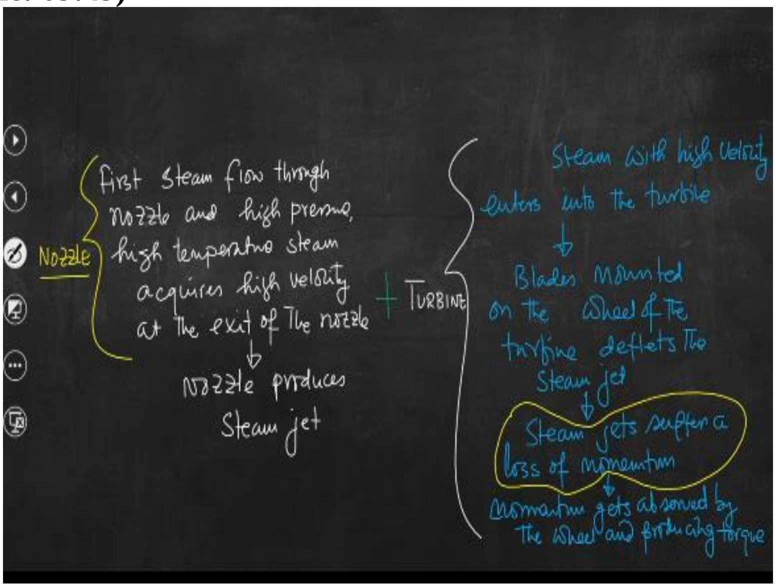

So first steam flows through nozzle and high pressure, high temperature steam acquires high velocity at the exit of the nozzle. So I can say that high pressure, high temperature steam will be allowed to flow through the nozzle and at the exit of the nozzle, we are getting steam in the form of a jet. So kinetic energy has increased and this is what is occurring inside the nozzle. So nozzle produces steam jet.

Steam with high velocity enters into the turbine. Blades are mounted on the wheel of the turbine deflects the steam jet. The consequence is that steam jets suffer a loss of momentum and that momentum gets absorbed by the wheel producing torque. So this is how the energy conversion occurs following 2 different stages. So this is what is occurring inside the turbine.

So, these 2 stages constitute together the total energy conversion and we can understand torque is produced or shaft work is produced from the steam which is having high pressure and high temperature at the inlet to the turbine. And that’s why this boiler is there because the sole purpose of this particular device is to generate or produce steam of high pressure and high temperature.

Now you can understand that though we could not see the flow nozzles but flow nozzles are the integrated part of the turbine. So steam turbine is essentially an assemblage of flow nozzles and the blades. Steam will be first allowed to flow through the nozzles that what we have discussed and then the steam will flow through the passage between the blades. And while steam is flowing, we have understood how it is possible to get torque or shaft work and that is how this device works. Now the most important part here is underlined in the slide that is the steam jets suffer a loss of momentum which is created by the blades. So blades which are mounted on a wheel are responsible for the deflection of steam jets. And depending on the blades used and of course the energy transfer process, we can classify steam turbines into 2 different categories.

Let me tell you once again that if we have if steam jets suffer a loss of momentum and if that loss of momentum is high, then definitely shaft work or torque produced would be high. So if we can extract significant amount of momentum from the flowing steam and if we can somehow design in a way that the momentum would be absorbed by the wheel, then we will be getting higher work output. So blades play an important role in this energy transfer process. So depending on the number of blades and energy transfer process, we can classify steam turbine into 2 different parts.

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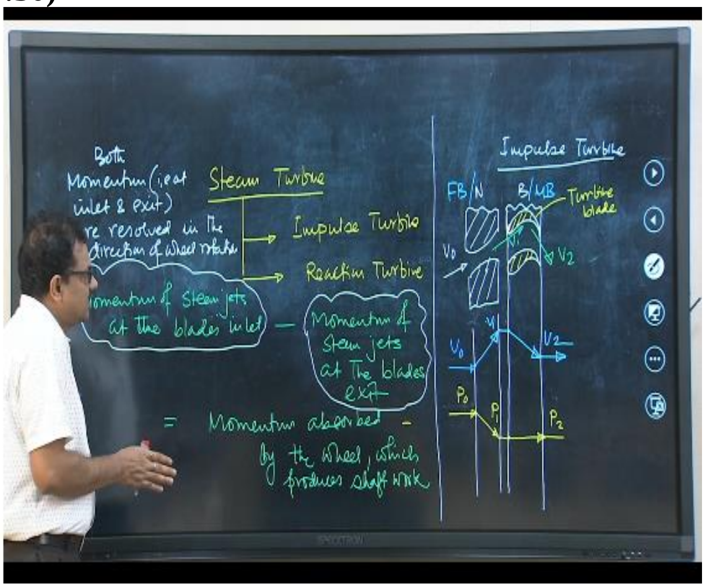

So steam turbine is classified into 2 different types, impulse turbine and reaction turbine. If you have studied hydraulic machines, you also have studied that hydraulic turbine can be classified into impulse turbine and reaction turbine. Similar to that classification, we also can classify steam turbines into these 2 types. So let us discuss about the impulse turbine and reaction turbine. First let us discuss about the impulse turbine.

Impulse turbine

So you can understand from the name itself that it works on the basis of impulsive effect. So what does impulsive effect mean? So this is basically change in momentum. So the wheel will rotate solely due to change in momentum of the flowing steam jets. So a set of flow nozzle and a set of blades constitute together to form a steam turbine that is what I have said few minutes back. Steam turbine is an assemblage of flow nozzles and blade.

So let us draw the nozzle and blades as shown in the slide. So there is the first row of flow nozzle in the diagram. There might be multiple nozzles, but I have drawn only a single nozzle in the slide. Similarly there is the first row of blades. Basically I have drawn only 2 blades to show the passage which is formed between 2 consecutive blades. So there can be multiple blades in this row. Now let's say steam is entering with a velocity v_0, which is coming out from the steam generator or boiler. The shape of nozzle is just like a convergent divergent type that we have discussed. Now when steam is coming out from the steam generator or boiler, the velocity is v_0. Then it is allowed to expand inside the nozzle and velocity will increase at the cost of the pressure drop. And now steam is striking the turbine blade at velocity $v_1$which is coming out from the first row of blades. Sometimes in many books, it is written fixed blades that is for nozzle and moving blades to signify the blades. So I am writing nozzle and blades. So what we can see that steam entering into the nozzle at a velocity v_0, it is now expanding inside the nozzle. Velocity at the exit of the nozzle would be v_1 and definitely $v_1 > v_0$. And that is why this particular mechanical device is there. At the exit of the nozzle, steam is in the form of a jet and that steam jet strikes the turbine blade and you can see that after striking, it is because of the presence of blades, there is a deflection of the steam jet. And at which angle jet will be deflected that depends on the blade designer and finally after striking, the steam is coming out from the blade at a velocity v_2.

So basically in the diagram there is 1 row of nozzle followed by 1 row of blades and these 2 rows together constitute 1 stage. So here in this diagram, this is called first stage or single stage. And there might be multiple stages and in that case it is called multiple stage turbine. So for the analysis purpose, single stage is good enough.

I would like to show that impulse turbine solely works due to the impulsive effect that is due to change in momentum of the flowing jet. Now let us try to plot pressure and velocity in the diagram. So v_0 is the velocity of steam at the inlet of nozzle. And this velocity is now increasing to v_1. And finally while steam is flowing through the passage formed between two consecutive blades there is a drop in velocity. And it is because of this drop in velocity, there is loss of momentum. And that momentum would be absorbed by the rotating part. So basically these blades are only rotating while nozzles are fixed. So the first row of nozzles are not rotating and that is why in some books it is written as fixed blades or FB. So these (1^{st} row) are also known as fixed blades and these (2^{nd} row) are also known as moving blades. So this particular row of moving blades is rotating and the velocity that is v_2 would be less.

Now we know that at the cost of reduction of some parameter, we are increasing the velocity of steam at the exit of nozzle and that particular parameter is pressure. So let us now try to draw pressure in the diagram. So at first pressure is p_0 which is available with the steam at the inlet of the nozzle. And then while steam is flowing through the nozzle, pressure will fall to p_1. Now when steam is passing through the blades or row of moving blades, then for the impulse turbine there is no pressure drop. So after then pressure will remain constant at p_2.

So now we have discussed that the blades or moving blades are designed for this special type of turbine in such a way that there will be no pressure drop of steam while passing through the passage between 2 blades or passage of consecutive blades. So this particular aspect is different than what is in a reaction turbine. So what we can see only velocity is going to change while steam is passing through the moving blades and the velocity is decreasing to v_2. So $v_2 < v_1$. So momentum is getting changed and that momentum is getting absorbed by this wheel and we are getting shaft work. From this particular analysis we can say for the impulse turbine

So change in momentum of steam inside the nozzle is not responsible to produce any torque or work. And momentum of steam jets at the blades inlet and momentum of steam jets at the blades exit are definitely not same. Momentum of steam jets at the exit of the blades is less than the momentum of steam jets at the inlet of the blades. And that is how the momentum change or momentum absorbed by the wheel produces shaft work.

$$\text{Momentum of steam jets at the blade inlet} - \text{Momentum of steam jets at the blades exit} \\ = \text{Momentum absorbed by the wheel which produces shaft work}$$

So momentum absorbed by the wheel produces shaft work. We know that these blades will rotate solely due to change in momentum of the jets. Let me tell you once again the blades or moving blades are mounted on the wheel. And this row of fixed blades or nozzles is stationary.

And that is why sometimes nozzles are known as fixed blades because this part is not rotating. So the second the row of moving blades is rotating solely due to change in momentum of the flowing jet and that is the impulsive effect.

Both momentum of steam jets at the blade inlet and momentum of steam jet at the blades exit; these 2 momentum are resolved in the direction of wheel rotation and that is responsible for the shaft work. We shall discuss about this while deriving the blade efficiency and there we will see that only the momentum which is resolved in the direction of wheel rotation is responsible for the shaft work and other component is not responsible for the shaft work. So what we can understand is that the row of moving blade is rotating solely due to the impulsive effect that is due to change in momentum.

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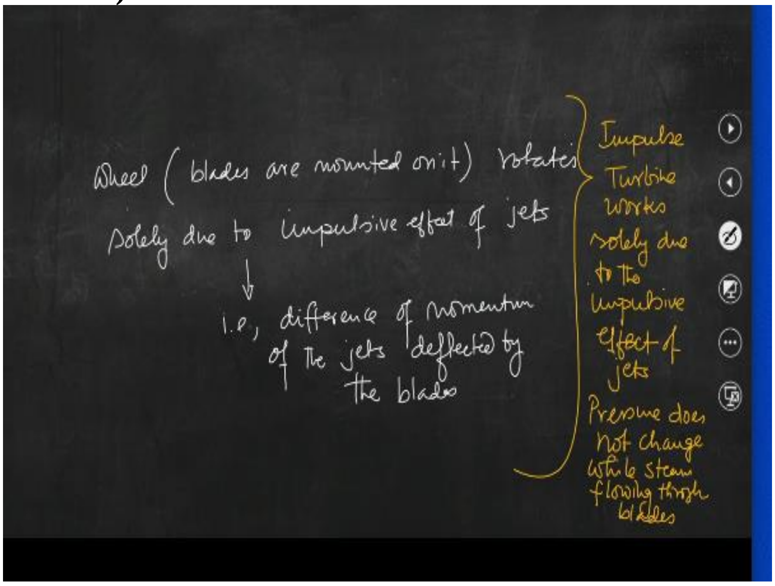

So wheel (blades are mounted on it) rotates solely due to impulsive effects of jet that is the difference of momentum of the jets deflected by the blades. And that is why this special type of turbine is known as impulse turbine. That means the blades which are mounted on the wheel and that wheel will be rotating solely due to the impulsive effect that is the difference of momentum of the jets deflected by the blades. So this is the impulse turbine. So here the momentum gets absorbed by the wheel and it produces torque. So the change in momentum of the jets is deflected by the blades only. So there is no other mechanism to rotate the wheel. So next let us talk about the reaction turbine.

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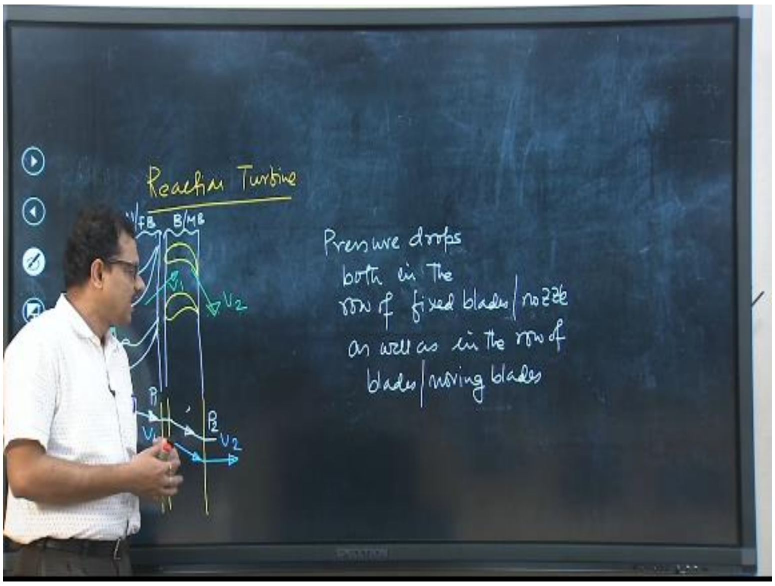
say v_2.



We have understood that impulse turbine rotates or works solely due to the impulsive effect of the jet. That means there is no pressure drop while steam is passing through the blades or moving blades. Importantly pressure does not change while steam flowing through blades.

Reaction turbine

Now for the reaction turbine again let me draw at least first row of nozzle or moving blade. There would be multiple blades but we are drawing only a few fixed blades and a few moving blades only for the analysis. And now let us try to plot both pressure and velocity change as steam passes through first row of nozzle and first row of blade. So steam is entering into the nozzle with a velocity v_0 and as usual when steam is passing through the nozzle, it will expand and at the cost of the pressure drop, the velocity will increase to v_1. And when steam is coming out that means when steam will enter into the row of moving blades, here we have only drawn 2 blades in this first row, then steam will get deflected by the moving blade or normal blade. And the resulting velocity is v_2. Now if we try to draw the pressure and velocity quickly, we can see that first inlet is velocity v_0 and that velocity will increase when steam is passing through these fixed blades or nozzle. And when steam is again passing through the passage between these 2 consecutive blades that we have drawn in the diagram, velocity will fall to say v_2.

We have also drawn the same when we have talked about the change in velocity and pressure in the context of impulse turbine. Now here let us try to plot the change in pressure, when steam is passing through both fixed blade and moving blade. So this is say pressure p_0 then you can see that the pressure will fall definitely. So next we are plotting p_1. We have seen in the impulse turbine that pressure is remaining constant when steam jet is passing through the passage between 2 consecutive blades. Blades deflect the steam jet but the pressure is remaining constant and that is how this type of turbine is designed because wheel will rotate only due to the impulsive effect. But in case of this reaction turbine pressure drops both in fixed blades or nozzle and moving blades. So still there will be certain drop in pressure and say this is p_2.

If pressure is remaining constant as we have seen for impulse turbine, then perhaps velocity would have been little lesser at the exit of the moving blade. Let me tell you once again. So what we can see that in this particular type of turbine pressure drop occurs both in the row of nozzle and as well as blade or moving blade. It is because of this drop in pressure that we can see in the row of moving blades, there will be a little gain in kinetic energy of the steam jet. So steam will be deflected by the blades and there is also a little gain in kinetic energy of the jet and that is due to the drop in pressure because velocity will increase. If pressure remain constant while steam is passing through the moving blades, in that case velocity would have decreased even more than what we can see here in reaction turbine.

So there will be little increase in velocity due to this drop in pressure when steam is passing through the row of moving blades or blade. Steam or jet will gain little kinetic energy and that kinetic energy will give rise to a reaction force in the opposite direction. So that reaction force also will help to rotate the wheel. So of course because the steam jet which is leaving from the row of moving blades already has suffered a loss of momentum due to this deflection but additionally what we can see that since it is designed in such a way that steam jet will be having further drop in pressure while passing through the passage between blades, it is because of this reduction pressure there will be little gain in kinetic energy and that little gain in kinetic energy in case of reaction turbine is compared with Impulse turbine where pressure is remaining constant when steam is passing through the blades. So if we can compare then pressure remain constant when jet is passing through the moving blades are blade in that case velocity would have been even lesser than what we can see in case of reaction turbine.

So it is because of this drop in pressure, the velocity has increased little as if the jet is gaining kinetic energy. The gain in kinetic energy will give rise to a reaction force in the opposite direction. So that will help the wheel to rotate. So wheel is rotating not only due to the impulsive effect that is due to the deflection of steam jet by the blades rather it is the combination of loss of momentum due to deflection of steam jet by the blades plus the reaction force that we can see. So these 2 force together will allow the wheel to rotate. That means we can write that in the reaction turbine pressure drops both in the row of fixed blades or nozzle as well as in the row of blades or moving blades. It is because of this drop in pressure, there will be a little gain in kinetic energy of the exiting jet from the row of moving blades and that kinetic energy will give rise to a reaction force in the opposite direction. So wheel will rotate due to the impulsive effect as well as due to the reaction force.

So, for the reaction turbine, let me tell you once again impulsive effect due to deflection of steam jet by the blades will be there over and above that impulsive effect, the exiting steam will be having a gain in kinetic energy and following Newton's third law of motion that gain in kinetic energy will give rise to a reaction force in the opposite direction. So this reaction force together with this impulsive effects will be responsible for the wheel rotation.

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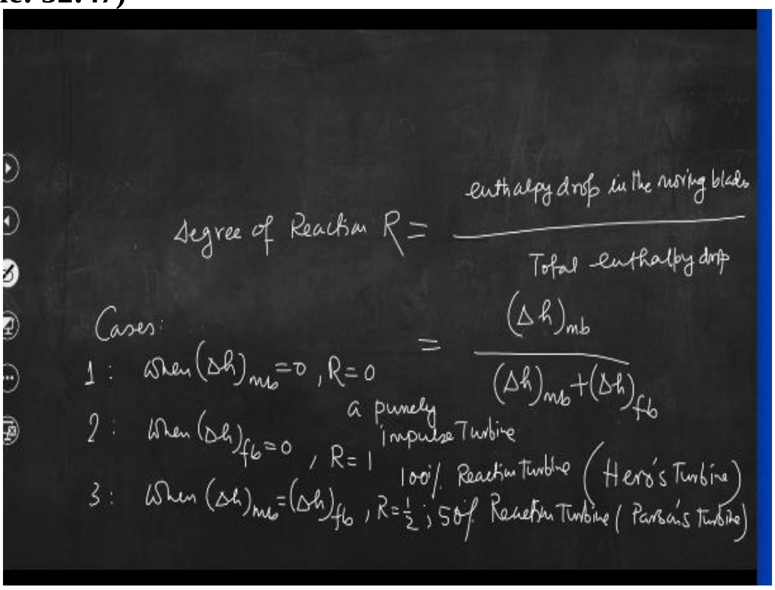

And hence for the reaction turbine one term is defined that is called degree of reaction R.

$$\text{Degree of reaction, } R = \frac{\text{Enthalpy drop in the moving blades}}{\text{Total enthalpy drop}}$$

$$\Rightarrow R = \frac{(\Delta h)_{mb}}{(\Delta h)_{mb} + (\Delta h)_{fb}}$$

$$\text{Here, } (\Delta h)_{mb} = \text{Enthalpy drop in the moving blades \&}$$

$$(\Delta h)_{fb} = \text{Enthalpy drop in the fixed blades}$$

So you can understand that $(\Delta h)_{mb}$ is only due to the reaction force. So it is because of this reaction force we can define the degree of reaction. So as I said you that the steam jet will gain a little kinetic energy while exiting from the first row of moving blades as here in this particular analysis we have considered only one stage. So that steam jet which is exiting from the first row moving blades is gaining kinetic energy and that will give rise to a reaction force in the opposite direction following Newton's third law of motion and that reaction force together with the impulsive effect will rotate the wheel.

Now if we need to know the extent of reaction force that is responsible for the wheel rotation then we are defining this term that is degree of reaction *R*. So I shall discuss several cases.

Case-1

When $(\Delta h)_{mb} = 0$; then $R = 0$. So this is a purely impulse turbine.

Case-2

When $(\Delta h)_{fb} = 0$; then $R = 1$ or 100% = 0. So turbine is 100% reaction turbine. Example of 100% reaction turbine is known as Hero's turbine.

Case-3

When $(\Delta h)_{mb} = (\Delta h)_{fb}$; then $R = \frac{1}{2}$. So that means it is a 50% reaction turbine. An example of this is Parson's turbine.

So what you can understand? We have understood that some degree of reaction force would be there to rotate the wheel in a reaction turbine. Hence the name is reaction turbine now to know the extent of reaction force that is there in a particular type of reaction turbine, we are defining this particular term that is degree of reaction. And it is defined as the ratio of enthalpy drop in the moving blades to the total enthalpy drop and total enthalpy drop is basically enthalpy drop in moving blades plus enthalpy drop in fixed blades. Then we have taken 3 different cases; when there is no enthalpy of in the moving blades that is a purely impulse turbine. So turbine will rotate solely due to impulsive effect. When $(\Delta h)_{fb} = 0$ that means there is no impulsive effect at all. Solely the turbine will rotate due to the reaction force and example is Hero's turbine that is 100% reaction turbine. But a case may be there when$(\Delta h)_{mb} = (\Delta h)_{fb}$, then degree of reaction is half and it is known as 50% reaction turbine and an example is Parson's turbine.

So if we try to summarize, then we have discussed about the steam turbine rather operational principle of steam turbine. From there we could classify steam turbines into 2 different categories. And we have then discussed about the working principle of both the type of steam turbines. Finally in the context of reaction turbine, we could define one particular term that is called degree of reaction which in a sense gives us the extent of reaction force that would be responsible for the rotation of the wheel and we could define the degree of reaction and we had taken 3 different cases. For a purely impulse turbine degree of reaction is equal to 0, for a purely reaction turbine or 100% reaction turbine degree of reaction equal to 1 and if the degree of reaction is half then 50% reaction force and 50% impulsive effects, these 2 will rotate the turbine wheel. So with this I stop here today.