Applied Thermodynamics
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Reaction Steam Turbine: Degree of Reaction, Velocity diagrams, work transfer, blade efficiency
Steam Power System
Lecture - 14
Reaction Steam Turbine

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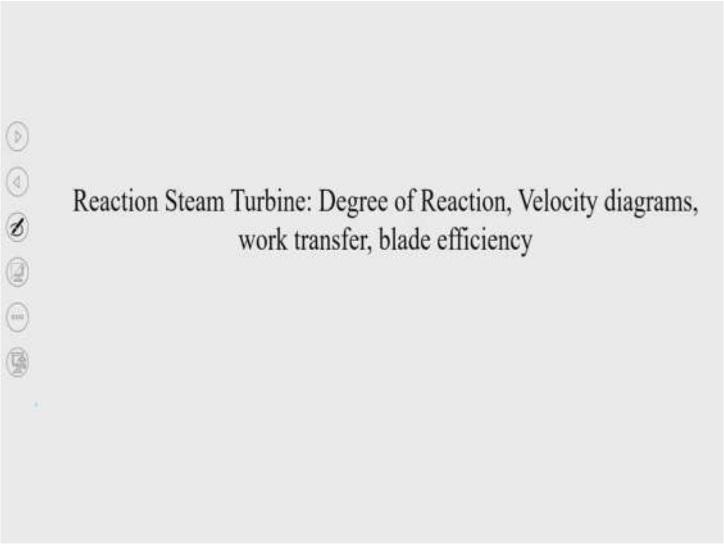

Reaction Steam Turbine: Degree of Reaction, Velocity diagrams, work transfer, blade efficiency

I welcome you all to the session of applied thermodynamics and the topic of our today's discussion is the reaction steam turbine. In the last lecture we have discussed about the impulse turbine and by drawing the velocity triangles both at the inlet and outlet we have discussed about the work transfer and also the blading efficiency.

Now if you try to recall in the last class we also have discussed about the optimum velocity ratio for which the diagram efficiency or blading efficiency becomes maximum and we could not discuss the implications of the optimum velocity ratio in the context of the design of the impulse turbine blades. So, before going to discuss about the reaction turbine let us briefly discuss about that particular aspect.

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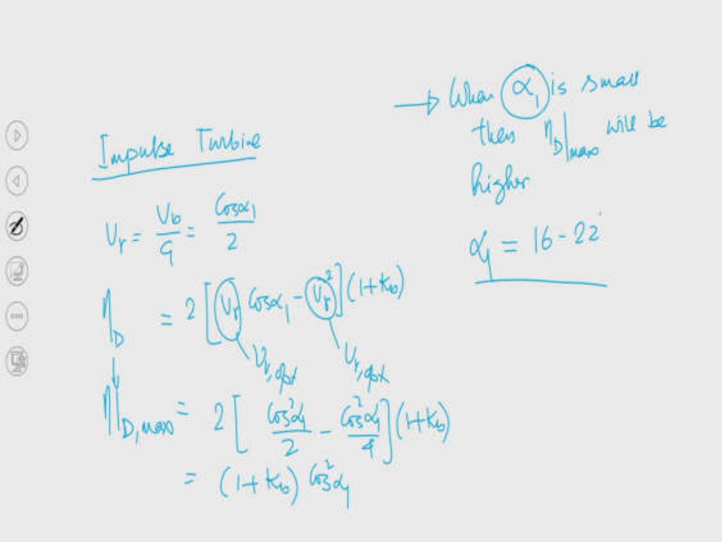

Impulse Turbine

$V_r = \frac{V_b}{C_1} = \frac{\cos\alpha_1}{2}$

$\eta_D = 2\left[\boxed{V_r}\cos\alpha_1 - \boxed{V_r^2}\right](1+K_b)$

$V_{r,opt}$ $V_{r,opt}$

$\eta_{D,max} = 2\left[\frac{\cos^2\alpha_1}{2} - \frac{\cos^2\alpha_1}{4}\right](1+K_b)$

$= (1+K_b)\cos^2\alpha_1$

→ When α_1 is small then $\eta_D|_{max}$ will be higher

$\alpha_1 = 16-22°$

So, you know that for the impulse turbine, this velocity ratio $v_r = \frac{v_b}{C_1} = \frac{\cos\alpha_1}{2}$. Now for this particular velocity ratio; diagram efficiency maximum is nothing but $\eta_D = 2\left(v_r \cos\alpha_1 - v_r\right)\left(1+K_b\right)$

Now I cannot say this is maximum rather this is the expression of the diagram efficiency. Now it will be maximum that is $\eta_{D,\max}$ when this v_r will be $v_{r,opt}$. So, if you plug in the value of $v_{r,opt}$ from this expression over here then we will be getting the maximum diagram efficiency that is nothing, but $\eta_{D,\max} = 2\left[\frac{\cos^2\alpha_1}{2} - \frac{\cos^2\alpha_1}{4}\right]\left(1+K_b\right)$.

So, this is nothing, but $\cos^2\alpha_1\left(1+K_b\right)$. So, now, can you see that from this expression we can say that when α_1 is small then $\eta_{D,\max}$ will be higher.

If we consider very less flow angle (angle subtended by the nozzle axes with the tangential direction of the wheel), $\eta_{D,\max}$ that is maximum diagram efficiency will be high.

But we cannot reduce this α_1 arbitrarily otherwise the loss will be very high. That part it is beyond this scope of the discussion in this particular course, but the recommended value of α_1 is 16° to 22°. So, we need to keep within these range if we try to reduce the magnitude of α_1 beyond 16° then associated problem will be there.

So, now, another important thing that I wanted to discuss today in the context of impulse turbine that $v_r = \frac{v_b}{C_1} = \frac{\cos\alpha_1}{2}$.

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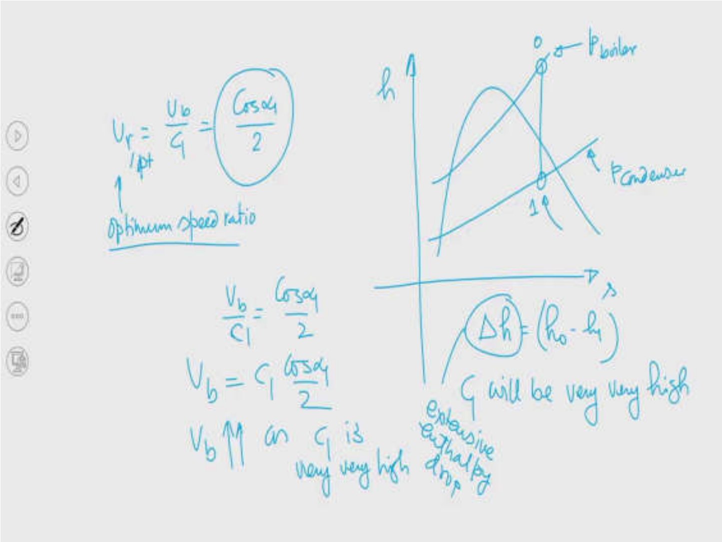

$V_{r_{opt}} = \frac{V_b}{C_1} = \boxed{\frac{\cos\alpha_1}{2}}$

optimum speed ratio

$\frac{V_b}{C_1} = \frac{\cos\alpha_1}{2}$

$V_b = C_1 \frac{\cos\alpha_1}{2}$

$V_b \uparrow\uparrow$ as C_1 is very very high

$\boxed{\Delta h} = (h_0 - h_1)$

C_1 will be very very high

extensive enthalpy drop

So, this is the optimum speed ratio. If we try to draw the h-s plane, that is also known as Mollier diagram; this is very very useful diagram for calculating properties which are essential for the design of the steam power plant. So, in h-s diagram, we will be having pressure, temperature and dryness fraction. So, it is very easy to get properties from the mollier chart. Now, say this is the condenser pressure, $P_{condenser}$ and this is P_{boiler} . So, this is basically in the mollier chart.

Since, there is no pressure drop when steam is passing through the passage between two blades and entire pressure drop takes place in the nozzle itself; that means, you can try to understand if we allow steam pressure to fall from boiler pressure to condenser pressure inside the first set of nozzle only, then the enthalpy drop is $\Delta h = h_0 - h_1$. This huge enthalpy drop will be there inside the nozzle.

So, if this there is a huge enthalpy drop then C_1 will be very high. Try to understand, we are trying to increase the kinetic energy of steam and the steam will come out from the nozzle in the form of a jet. So, if we have this pressure drop only in one set of nozzle then accounting this high enthalpy drop, the velocity of steam at the exit of the nozzle will be very high. Now $v_b = \frac{C_1 \cos\alpha_1}{2}$. So, for a given flow angle or nozzle angle, if C_1 becomes very high, v_b will also be very high.

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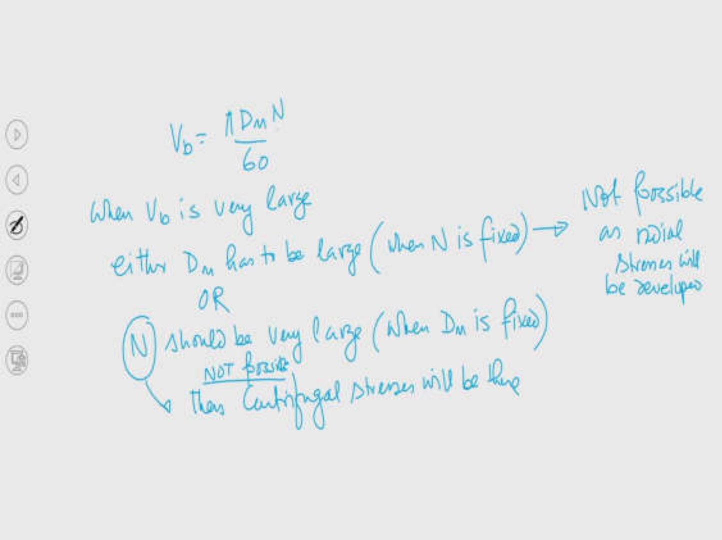

$V_b = \frac{\pi D_m N}{60}$

When V_b is very large

either D_m has to be large (when N is fixed) → Not possible as radial stresses will be developed

OR

N should be very large (when D_m is fixed)

NOT possible

Then Centrifugal stresses will be huge

Now $v_b = \frac{\pi D_m N}{60}$. So, when v_b is very high either D_m has to be large when N is fixed or N should be very large when D_m is fixed.

We cannot increase D_m very high as D_m is nothing but $(D_{root} + D_{tip}) / 2$. So, if we increase D_m then centrifugal stress will be there. So, we have seen that there will be a axial thrust. So, again radial thrust will be there.

So the centrifugal stress will be very high if we increased D_m. So, we cannot. This is also not possible as radial stress will be there. So, that means, neither we cannot increase D_m keeping N fixed nor we can increase N keeping D_m fixed right. So that is why it is not allowed to have total enthalpy drop in a single row of nozzle. And to circumvent the problem associated with this what is done that is called staging.

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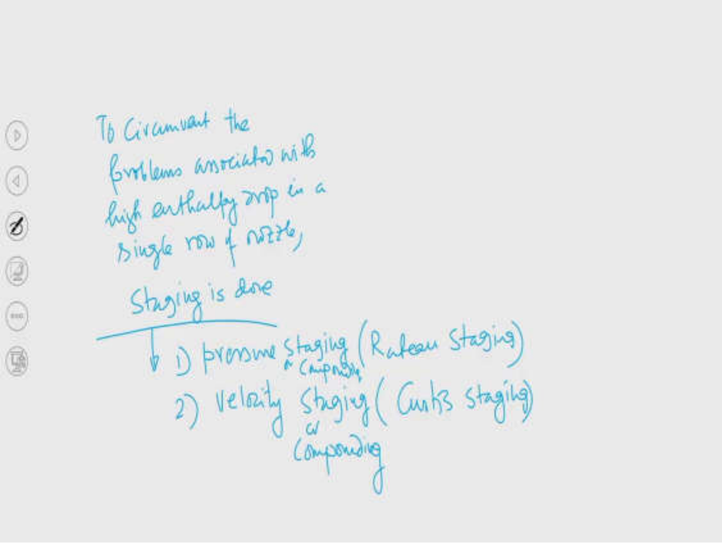

To Circumvant the
problems associated with
high enthalpy drop in a
single row of nozzle,

Staging is done

1) pressure staging (Rateau Staging)
or compounding

2) Velocity Staging (Curtis staging)
or
Compounding

So, to circumvent the problems associated with high enthalpy drop in a single row of nozzle staging is done. So, this is call steam staging and there are two staging; one is called pressure staging or also known as rateau staging and number 2 is velocity compounding or velocity staging. This is also known as curtiz staging or compounding.

Objective is that instead of allowing total pressure drop to takes place in a singles row of nozzle, we can have multiple rows of nozzles. As we discussed that one row nozzle and one row of blade constitute together to form a stage. So, if you would like to have multiple rows of nozzles then we will be having multiple stages. So, either pressure is allowed to drops through multiple stages through pressure compounding or velocity compounding.

So, this part is not there in this course, but only to have the understanding why the staging is done in the context of the impulse turbine operation, I have discussed this. Now with these let us now move to discuss about the reaction turbine.

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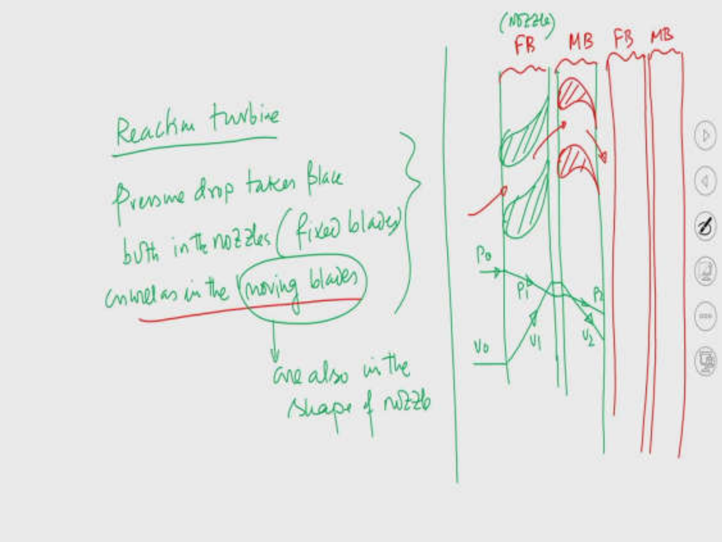

Reaction turbine

Pressure drop takes place both in the nozzles (fixed blades) as well as in the (moving blades)

are also in the shape of nozzle

So, we have seen in impulse turbine, entire pressure drop takes place in the first row of nozzle. There is no pressure drop of steam when it is passing through the passage between two blades, but in case of a reaction turbine pressure drop takes place both in nozzles and sometimes known as fixed blades and as well as in the moving row of blades.

Pressure drop takes place both in the nozzles as well as in the moving blades. So, this part was not there for this steam turbine. So, there is a pressure drop inside the moving blades. Here the moving blades are also in the shape of nozzle.

So, now let us quickly draw the reaction turbine, then it will help us to understand. So, I will be drawing only one stage. Now, this is moving blades and this is row of fixed blade. Now steam goes in this direction through the nozzle and come out. So, if you draw the pressure velocity diagram; say pressure is p_0 and pressure will fall like this; this is p_1 and then there also will be pressure drop; this is p_2.

Now, there will be V_0, this is V_1 and this is V_2. So, pressure drops in the nozzle that is even there for the impulse turbine. In addition to that there is a pressure drop when steam is passing through the moving blades that was not there in case of a impulse turbine. Velocity will increase definitely while passing through the fixed blades also the shape of the moving blade is also like nozzle. So though I have seen a dropping velocity, but still you can see the velocity is even higher than V_0. So, still there is increase in the kinetic energy. So, if we try to compare V_0 is the velocity of steam which is coming out from the boiler.

Now as it is passing through the first fixed blade that is nozzle, velocity increases. Again this is passing through the moving blades because of the shape velocity decreases still it is V_2 which is higher than the velocity V_0.

Now what I would like to tell you that why it is called reaction turbine? So, when steam is passing through the moving blades still there is an increase in the kinetic energy. And this is only because that the moving blade are also in this shape of the nozzle. Now, when steam is passing through the moving blades there is a change in the direction. So, impinging effect impulse is impinging effect. So, basically when steam is passing through the moving blades there is a change in the direction, impulse effect will be getting that is due to change in momentum.

So the impulse effect impressed by the jet on the blades will be there and on the top of that there is also change in the kinetic energy when the steam is passing through the moving blade. See the velocity of the steam when it enters into the moving blades and when it leaves the moving blade is not same. So, there is change in kinetic energy and this is because of this change in kinetic energy, a reaction force will be impressed a by the steam jet on the blade in the opposite direction.

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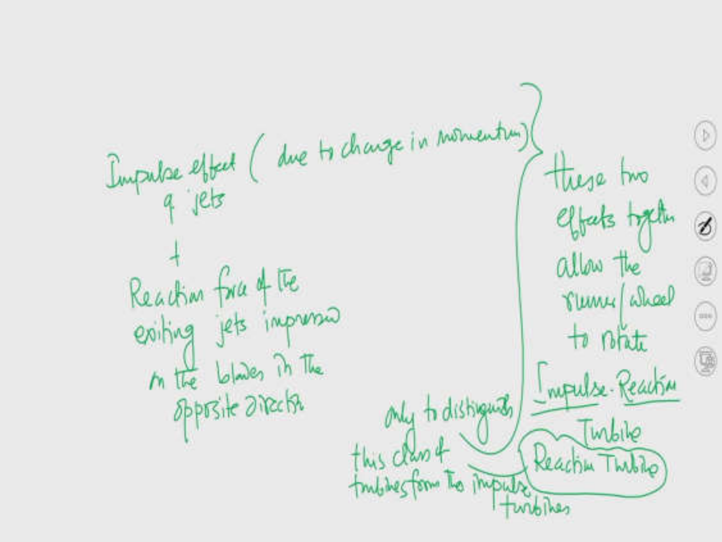

Impulse effect (due to change in momentum)
of jets

+

Reaction force of the
exiting jets impressed
on the blades in the
opposite direction

these two
effects together
allow the
runner/wheel
to rotate

Impulse-Reaction
Turbine

Reaction Turbine

only to distinguish
this class of
turbines from the impulse
turbines

Impulse effect that is due to change in momentum of jets plus reaction force of the exiting jets impressed on the blades in the opposite direction allows wheel to rotate.

And since impulse effect is there and also reaction effects is there; that is why it is called impulse reaction turbine. So, ideally a reaction turbine is the impulse reaction turbine because these two effects together will allow the wheel or turbine that has to rotate.

So though we cannot trivially ignore the impulse effect while wheel is rotating, ideally it is impulse reaction turbine, but only to distinguish this class of turbine from the impulse turbine, the name reaction turbine is coming to the place.

So now quickly we will discuss about one term so, that is called degree of reaction which is known as R.

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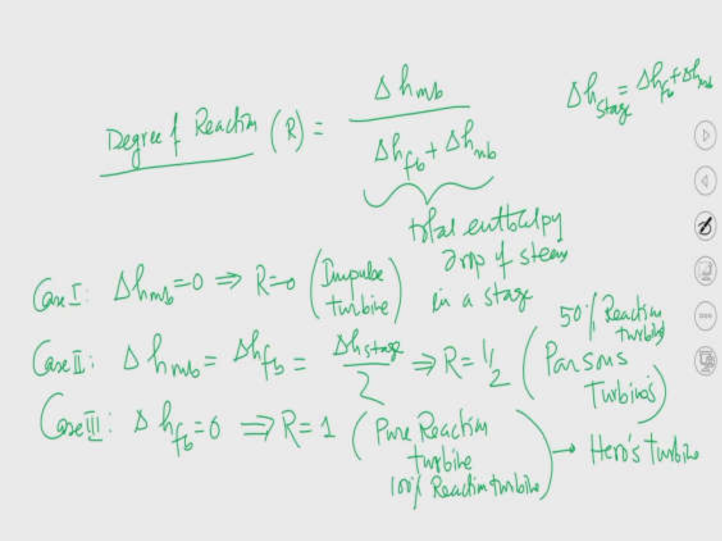

$$\text{Degree of Reaction } (R) = \frac{\Delta h_{mb}}{\underbrace{\Delta h_{fb} + \Delta h_{mb}}_{\text{total enthalpy drop of steam in a stage}}}$$

$$\Delta h_{stage} = \Delta h_{fb} + \Delta h_{mb}$$

Case I: $\Delta h_{mb} = 0 \Rightarrow R = 0$ (Impulse turbine)

Case II: $\Delta h_{mb} = \Delta h_{fb} = \frac{\Delta h_{stage}}{2} \Rightarrow R = \frac{1}{2}$ (Parsons Turbines) 50% Reaction turbine

Case III: $\Delta h_{fb} = 0 \Rightarrow R = 1$ (Pure Reaction turbine 100% Reaction turbine) → Hero's turbine

So, you can understand that not only in the nozzle, but pressure also drops in the moving blades. So, when pressure drop takes place both in the moving blade as well as in the fixed blades that is fine because this is nozzle shape.

So, when steam is coming out from the boiler it is having high enthalpy. So, at the cost of the enthalpy drop, we are getting work output from the turbine. So, as enthalpy drops the energy is getting converted into the kinetic energy.

So now in case of the reaction turbine, the enthalpy drop takes place both in the fixed blades as well as in the moving blades. So, now, accounting this particular aspect, the degree of reaction is defined is the ratio of enthalpy drop in the moving blades by the total enthalpy drop. In case of the impulse turbine, there is no enthalpy drop when steam is passing through the moving blades.

$$R = \frac{\Delta h_{mb}}{\Delta h_{fb} + \Delta h_{mb}}$$

But in case of a reaction turbine, there is enthalpy drop when steam is passing through the moving blades. So, I really do not know what fraction of enthalpy drop is there when steam is passing through the moving blades. So degree of reaction in a way indicates the fraction of enthalpy drop when steam is passing through the moving blades. So, when this Δh_{mb}= 0, R = 0. So, this is perfectly impulse turbine. There is no pressure drop or enthalpy drop when steam is passing through the moving blades.

As $\Delta h_{mb} = \Delta h_{fb} = \frac{\Delta h_{stage}}{2}$. So if the enthalpy drop is equal both in the moving blades and fixed blades then in that case R = 0.5; 50 percent reaction turbine. So, this is known as Parson's turbines . Now when Δh_{fb}=0, R=1.So, this is called hundred percent of pure reaction turbine or hero's turbine. So, when there is no enthalpy drop as steam is passing through the fixed blades, then we need to have total enthalpy drop when steam is passing through the moving blades only; in that case it is call pure reaction turbine 100 percent reaction turbine.

So, if we do not have the row of moving fixed blades, steam will directly go to the moving blades; in that case, probably there will not be any change in direction. So, steam will go and it will come out.

Here nozzles are there only to direct steam into the moving blades at a proper angle. So, the row of fixed blades is there wherein there is enthalpy drop, there is pressure drop and at the cost of this pressure drop we are getting velocity and the steam is coming out from the nozzle in the form of a jet which is tracking the blades. And it is designed in such way that it will direct the steam to strike the blades at a proper angle.

So if we do not have the fixed blades or row of fixed blades then there is no enthalpy drop in that case it is called perfectly or 100 percent reaction turbine; example is hero’s turbine. So, now, if we try to summarized todays discussion we have discussed about the implication of optimum velocity ratio in the context of the design of the impulse turbine and from there we have seen that if we allow the enthalpy to drop only in single row of nozzles, then the velocity of steam at the exit of the nozzle will be very high and which in turn will increase the velocity of the blades. So, from that particular definition you have seen that it is not possible to increase D_m or N essentially to accommodate that high velocity of the blades. So, to circumvent the problem associated with this particular case we need to go for staging that is we will be having velocity compounding and pressure compounding that is basically staging.

Then we had started our discussion with the reaction turbine. In case of the reaction turbine the enthalpy pressure drop takes place both in the fixed blade as well as in the moving blades. From there we have tried to see why this particular turbine is call impulse reaction turbine, but only to differentiate this particular class of turbine from the impulse turbine we simply say this is reaction turbine.

We have defined what do you mean by degree of reaction from there we have tried to understand if the degree of reaction becomes 0, 1 and half, then the relative importance of the enthalpy drop and from there we have tried to understand that which is call 50 percent reaction turbine, which is call 100 percent reaction turbine. So, with these I stop here today and we shall continue our discussion in the next class.

Thank you.