Applied Thermodynamics
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Steam Power System
Lecture - 13
Impulse Steam Turbine: Velocity Diagrams, Work Transfer, Blade Efficiency (Contd)

We shall start our discussion today on the Impulse Steam Turbine, and we shall try to understand the velocity diagrams by drawing the velocity triangles. We will then try to estimate the blade efficiency and also what is the work being transferred. So, basically we know that when steam is allowed to flow through the turbine steam works on the rotating part of the wheel. So, we need to understand also the magnitude of the work transfer.

So, now, as we have discussed that for the steam turbine through the schematic depiction that steam produced in the boiler is allowed to flow through a nozzle before it enters into the turbine. So, while passing through the nozzle, kinetic energy of steam and velocity of the steam is increased at the cost of the pressure drop.

And we shall discuss about the flow nozzle in a separate lecture, but for the time being we should understand that while steam is flowing through the nozzle, velocity increases at the cost of the pressure drop, so pressure will fall. Now, when the steam is coming out from the nozzle rather at the exit of the nozzle, steam velocity is very high.

And that high velocity steam in the form of a jet strikes the turbine blades. And while steam is passing through the passage between two consecutive blades, there is a deflection. We have discussed that the impulsive effect which is nothing but the difference of momentum of the jets.

So, when high velocity steam jets striking the turbine blades and in the course of flow through the blade passage, there is a deflection. And as a result of which from the Newton's second law, there will be a thrust which is essentially because of the change in momentum. So, we shall try to understand the thrust which will be impressed by the jet on the blades eventually will give rise to the work. So, I mean torque and from there will be trying to estimate the work.

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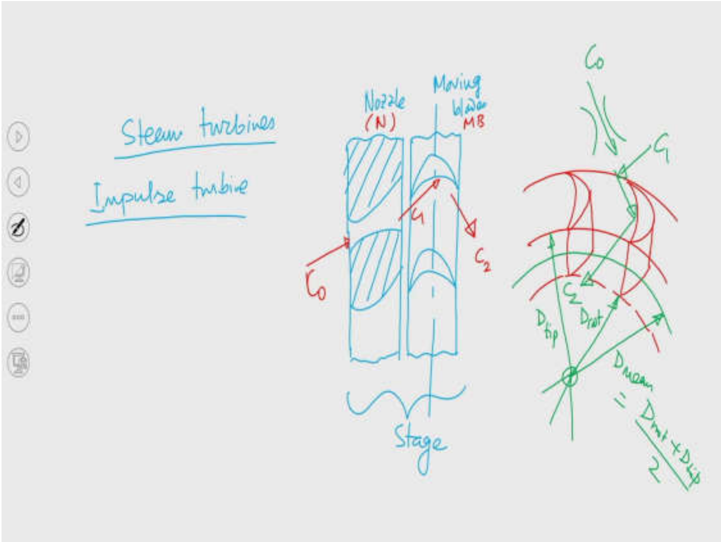

So, now, today if we discuss about steam turbine, specifically we will be discussing about impulse turbine. But before I go to discuss about impulse turbine as we have discussed in the last class because of this impulsive effect we are getting net work output and that is why the name impulse is coming.

So, let us first draw the diagram. So, this is nozzle, which will be followed by one row of moving blade. So, one row of nozzle followed by one row of moving blades, these two constitute together to form a stage. Though it is not there in this course content, but still I am discussing that one row of nozzle or fixed blade which is followed by one row of moving blade. These two rows constitute together to form a stage.

So, the steam which is coming out from the boiler is allowed to flow through the nozzle, and it is having velocity say this is C_0. While steam is passing through the flow nozzle, the velocity will increase and that velocity will strike the turbine blade with a velocity C_1.

And eventually that steam after striking, it will come out from the turbine say with a velocity C_2. So, what is done in practice is that steam is allowed to pass through nozzle; while steam is entering the flow nozzle, it is entering with a velocity C_0; it comes out from the nozzle with a velocity C_1. C_1 will be definitely higher than C_0.

And we need to design the system accordingly, so that the steam coming out from the flow nozzle will strike the turbine blade with a velocity C_1. So, this is the exit velocity of steam from the nozzle. And the angle should be designed accordingly, so that it will strike with a certain angle that is called the flow angle. And after striking, it is coming out from the moving blades with a velocity C_2.

The steam after striking is coming out with a velocity C_2, what, but what we can see from this diagram is that there is a change in direction. So, a thrust will be impressed by the jet. So, when steam is coming out from the flow nozzle, it is coming in the form of a jet. After striking, it is coming out from the blades with a velocity C_2, but the there is a deflection. So, along the steam path, there is a deflection of the jet.

And the deflection is essentially caused by the presence of the moving blades. And as a result of which as I told you from Newton's second law, there will be change in momentum and a thrust will be impressed. And as if the thrust is impressed by the jet on the blades and from there we will be getting the torque.

Now, if we try to draw a few blades that will help you to understand.

So, we have studied in hydraulic machines, so this is called root diameter, so this is called D_{root}. This is called tip diameter. So, this is tip of the blade, and this is root of the blade.

As you have studied in hydraulic machines, for calculating the associated parameters essentially to estimate the efficiency we focus on the mean diameter. Should we consider tip diameter while calculating associated parameters, or should we calculate, should we consider only root diameter while calculating the associated parameters?

So, to avoid confusion, it is convenient to use the mean diameter that is nothing but $(D_{root} + D_{tip}) / 2$.

Now, say we have one flow nozzle and the steam which is coming out is striking the turbine blade with a velocity C_1. And after striking, the steam is coming out from the turbine with a velocity C_2. So, now, let us draw the velocity triangles because after drawing the velocity triangles we will be in a position to find out what is the work transfer.

And from there we will try to estimate the efficiency which is very important for the turbine design such that it will eventually meet the overall efficiency of the plant. So, you know that in a thermal power plant, there are at least four major components we have discussed boiler, pump, turbine and condenser.

So, if we try to find out the overall efficiency of the plant, efficiency of individual component is very much important. So, the turbine designer should look into those aspects, so that efficiency of the turbine should be such that it will not compromise the overall efficiency of the plant. So, we will be discussing about velocity triangles.

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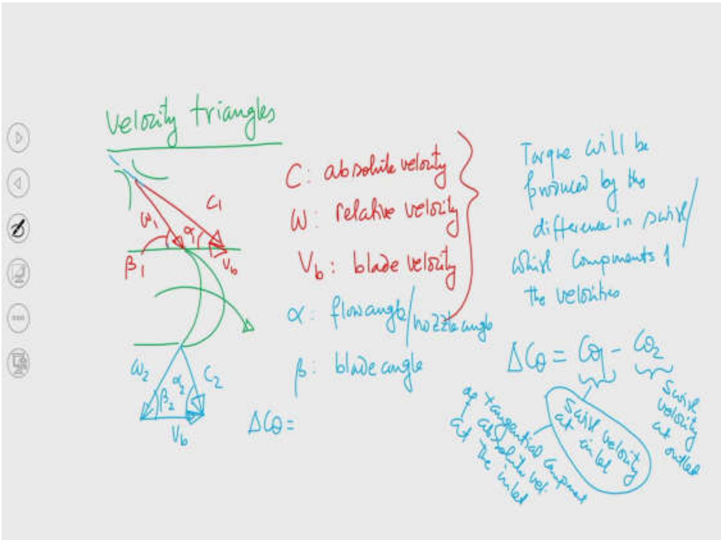

So, we will be discussing about velocity triangles. If we consider only one blade, so try to understand the blade it will be rotating like this. So, say this is C_1 and this is w_1 and this is v_b.

This angle is α_1, and this angle is β_1. So, this is the inlet velocity triangle. Steam which is coming out from the nozzle will strike the turbine blade, but the turbine blade is not stationary, it is moving. So, we will be having absolute velocity of steam that is the velocity of steam coming out from the nozzle. And since the blade is also rotating with the velocity v_b will be having a component or a velocity relative to the blade velocity. So, the resultant will be a velocity which is relative to the blade velocity.

So, the steam which is coming out from the flow nozzle with an absolute velocity C_1, as the blades are rotating with a velocity v_b; so, relative to the blade velocity, there will be a component that is resultant and that is nothing but the absolute velocity w_1. So, I am writing C is the absolute velocity, w is the relative velocity, and v_b is the blade velocity.

Now, similarly for the outlet, this is the velocity of steam which is relative to the blade and that is w_2. And this is C_2, and that is v_b. So, while calculating the v_b, if the turbine is rotating say N rpm, it is convenient to use the mean diameter.

So, the blade velocity will may differ from this point to that point. So, essentially to have fair estimate of the efficiency in an analytical framework, we shall try to consider v_b in terms of the mean diameter. So, you try to understand this is β_2 and this is α_2. So, α is the flow angle and β is the blade angle.

This α is also called nozzle angle. So, this is the angle subtended by the nozzle axis with the direction of the blade velocity. 1 and 2, these two subscripts are used to denote the inlet and outlet, or inlet and exit quantities.

So, now having understood the inlet and outlet velocity triangles, the C_1 which is coming out that is parallel to the axis of the nozzle, and it will make an angle α with the direction of the rotation of the wheel or blade and that is nozzle angle. And the resultant velocity is w_1 because the blade is also rotating with a velocity v_b.

Next we will try to find out at least what is work transfer transfer and also the blading efficiency from the velocity triangles, and also while calculating we shall try to discuss about the trigonometric relationship of different velocities.

So, what we what we understand from last class, the impulsive effect will be due to the change in momentum. So, the high velocity jets upon striking the turbine blades will lead to the development of the torque. So, basically let us write that the torque which will be produced due to the change in swirl component of velocity.

So, what is swirl/whirl component; component of absolute velocity in the tangential direction. So, torque will be produced by the change or difference in swirl or whirl components of the velocities. The key is that there is a difference in swirl component of velocity which is responsible to produce torque, this indicates that swirl component of velocity at the inlet is not equal to the swirl component of velocity at the outlet. So, that means, we have to find out change in swirl component of velocity at the inlet and outlet that is nothing but $\Delta C_\theta = C_{\theta_1} - C_{\theta_2}$. So, C_{θ_1} is the swirl component at the inlet.

This swirl velocity C_{θ_1} is nothing but tangential component of absolute velocity at the inlet. Similarly, this will be the tangential component of absolute velocity at the outlet. So, the difference in these two velocity components will be responsible for the torque that will be developed out of this complex phenomenon.

So, now, it would be nice if we can superimpose this two velocity triangles in the same plane. And from there, we can estimate the work transfer and the efficiency. So, let us draw the velocity triangles.

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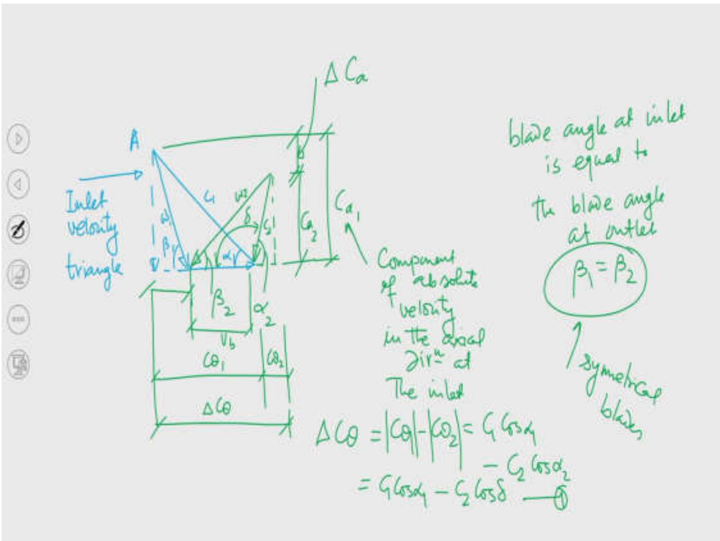

So, if I try to draw the velocity triangles. So, this is C_1; this is w_1. Now, say this point is A. This is this is inlet velocity triangle. This angle is α_1, and this is β_1. So, this is β_1 that is nothing but the angle made by the relative velocity in the tangential direction.

If we try to superimpose the outlet velocity triangles here, so this is say this is C_2, this is w_2. And this angle is β_2, and this angle is α_2. So, this component is C_{θ_1}, that is nothing but the component of absolute velocity in the tangential direction. Similarly, this component is C_{θ_2}; difference in magnitude between C_{θ_1} and C_{θ_2} is responsible for the torque that will be produced.

So, this is ΔC_θ. Similarly this is C_{a_1}, this is C_{a_2} that is the component of absolute velocity in the axial directions.

So, C_{a_1} is nothing but component of absolute velocity in the axial direction at the inlet. And this is also component of absolute velocity in the axial direction at the outlet, this is nothing but ΔC_a.

That difference in the axial velocity components will responsible for the axial thrust. So, the change in whirl or swirl component of velocity in the tangential direction will give rise to the tangential thrust which will be responsible for the torque that will be produced.

The difference in the axial velocity components will result in the axial thrust. So, now let us take one particular case typically which is considered that blade angle at inlet is equal to the blade angle at the outlet. Why it is so? So, basically it is important to understand here is that $\beta_1 = \beta_2$. So, blades are symmetric.

Now, just by looking at the inlet and outlet velocity triangle, we can easily calculate $\Delta C_\theta = C_{\theta_1} - C_{\theta_2} = C_1 \cos\alpha_1 - C_2 \cos\alpha_2$

So, now if we consider this angle is δ, then we can write $\Delta C_\theta = C_1 \cos\alpha_1 - C_2 \cos\delta$. Why you are doing so? So, we are trying to measure the angles in the clockwise direction. So, this is α_1, we are measuring in the clockwise direction. We are also measuring in the clockwise direction that is $\delta = 180 - \alpha_2$.

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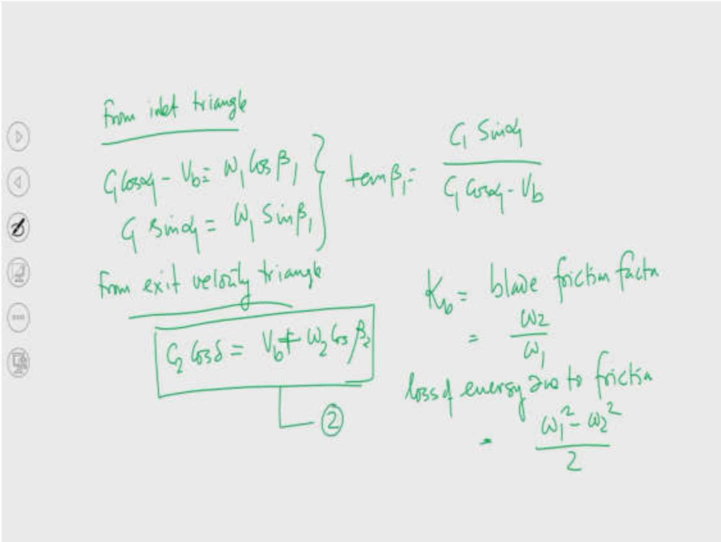

Also, we can write from inlet triangle; $C_1 \cos\alpha_1 - v_b = w_1 \cos\beta_1 ; C_1 \sin\alpha_1 = w_1 \sin\beta_1$

$$\Rightarrow \tan\beta_1 = \frac{C_1 \sin\alpha_1}{C_1 \cos\alpha_1 - v_b}$$

From the exit velocity triangle, we can write $C_2 \cos\delta = v_b + w_2 \cos\beta_2$. Now, here the component of relative velocity at the exit is not equal to the relative velocity component at the inlet. So, the ratio of relative velocity components is known as the blade friction coefficient. So, here I am writing $K_b = \frac{w_2}{w_1}$.

Since the relative velocity components are not equal, so the relative velocity of steam at the exit is not equal to the relative velocity of steam at the inlet that will depends on the β_1 and β_2, also the magnitude of the absolute component of velocities. So, now, the ratio of relative velocity at the outlet to the relative to the inlet of steam is known as the blade friction factor.

Now, since these two velocities are not equal, we will be having loss. So, basically loss of energy due to friction equal to $\frac{w_1^2 - w_2^2}{2}$. So, loss of energy per unit mass essentially due to friction is nothing but $\frac{w_1^2 - w_2^2}{2}$.

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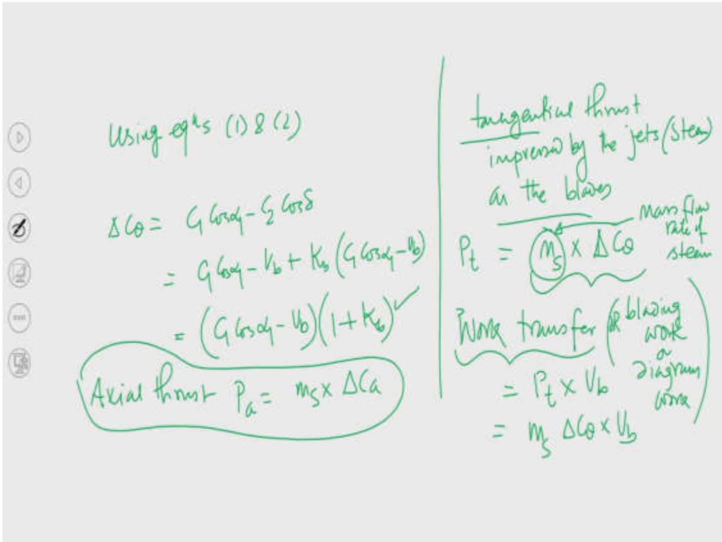

So, we can write that $\Delta C_\theta = C_1\cos\alpha_1 - C_2\cos\delta = C_1\cos\alpha_1 - v_b + K_b\left(C_1\cos\alpha_1 - v_b\right)$
$\Rightarrow \Delta C_\theta = \left(C_1\cos\alpha_1 - v_b\right)\left(1+K_b\right)$

So, now, I am writing the tangential thrust impressed by the jets on the blades is $P_t = m_s\Delta C_\theta$.

The change in swirl velocity components is responsible for the you know tangential thrust, a change in a difference in the axial velocity components is responsible for the axial thrust. And for that, we need to give kind of bearing, axial thrust bearing; but the tangential thrust will be absorbed by the wheel and for which you will be getting work output. So, the tangential thrust component is responsible for the work transfer that you have studied in your dynamics of machinery course, and then work transfer will be $P_t \times v_b$.

So, having established the expression of tangential thrust, and this tangential thrust will be responsible for the work that will be transferred from the flowing steam to the rotating part of the turbine. So, that is nothing but $P_t \times v_b$.

So, this will be $m_s\Delta C_\theta \times v_b$. See m_s is nothing but the mass flow rate of steam. If we allow m_s kg of steam to flow, then that will be the work transfer. Now, as I told you axial thrust is $P_a = m_s\Delta C_a$.

So, we need to make a special arrangement so that the turbine blade will not have any kind of vibration. So, we need to dampen out this axial thrust for which axial thrust bearing will be there.

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So, this work transfer is also known as blading work, or diagram work. Similarly, if it is blading work, so this is the work being transferred from the internal energy of the steam into the rotating part of the wheel.

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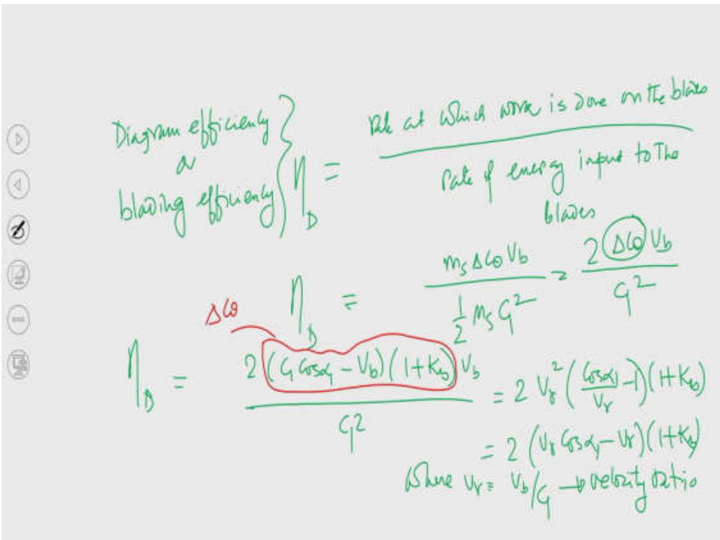

Now, if we try to find out the efficiency, or blading efficiency or diagram efficiency, that is nothing but rate at which work is done on the blades by the steam divide by rate of energy input to the blades. And if we do this mathematical exercise, so this is $\eta_D = \frac{m_s \Delta C_\theta \times v_b}{\frac{1}{2} m_s C_1^2}$. So, this is the absolute velocity of steam striking the turbine blade. So, this is the input energy to the blade.

And out of this input energy, this is the amount of work getting transferred to the rotating part of the wheel or rotating part of the turbine. So, $\eta_D = \frac{2\Delta C_\theta \times v_b}{C_1^2}$. So, you can write,

$$\eta_D = \frac{2\left(C_1 \cos\alpha_1 - v_b\right)\left(1+K_b\right)\times v_b}{C_1^2}$$

So, $\eta_D = 2v_r^2\left(\frac{\cos\alpha_1}{v_r} - 1\right)\left(1+K_b\right) = 2\left(v_r \cos\alpha_1 - v_r\right)\left(1+K_b\right)$ where $v_r = \frac{v_b}{C_1}$

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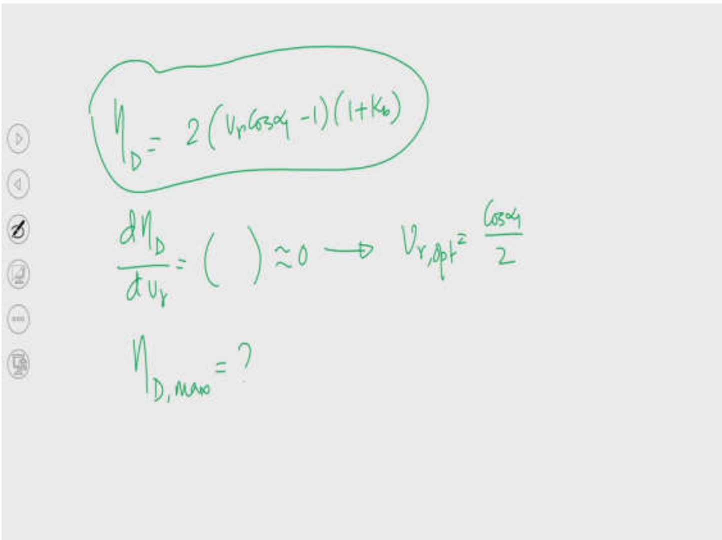

Now you can try to find out $\eta_D = 2\left(v_r \cos\alpha_1 - v_r\right)\left(1+K_b\right)$ and if you try to find out the maximum value of bladding efficiency, we will be getting one quantity. And if you make them 0, then from there you will try to find out $v_{r,opt} = \frac{\cos\alpha_1}{2}$.

And for this optimum speed ratio, we can find the maximum blade efficiency. So, to summarize today, we have tried to discuss about the operational principle of the impulse turbine. From there, we have tried to discuss about the velocity triangles both at inlet and outlet. And from there by drawing the velocity triangles, we have estimated the work transfer, and finally, from there you have tried to find out what is the efficiency. We have also tried to find out that there exists a speed ratio or velocity ratio for which diagram efficiency becomes maximum.

And from there, you try to find out the expression of maximum efficiency, and from there we will try to find out that if we need to attain the maximum efficiency what will be the design considerations. And afterward, we will try to find out the implications of several design aspects from the operational point of view of the impulse turbine.

So, with this, I stop here today. And we shall continue our discussion in the next class.

Thank you.