Thermal Engineering: Basic and Applied
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Lecture - 36
Analysis of Impulse Steam Turbine

I welcome you all to the session of thermal engineering basic and applied and today we shall discuss about the impulse stream turbine. If you try to recall, in the last class we have talked about the classification of steam turbines and we had seen that steam turbines can be classified into 2 different categories. One type is impulse type & another is the reaction type. You have also studied about turbines in the context of fluid machinery or fluid mechanics course and you have seen that the hydraulic turbines also can be classified into impulse and reaction types.

So, we have discussed that in the impulse steam turbine the name itself suggests that impulsive effect is responsible for the spinning or rolling action of the turbine wheel. And what is that? So, impulsive effect is nothing but the difference in momentum of jets which is reflected by the blades. And that is described by Newton's second law of motion. So, we had seen that this particular type of turbine works on the basis that high velocity jets of water from a flow nozzle is directed onto the vents or blades and the when the Jets is flowing through the passage between blades the Jets get deflected and there is a change in or loss of momentum. So, the resultant impulsive effect is due to change in momentum and the resultant impulsive effect spins or rotates the turbine wheel and we are getting torque and output in the form of work.

So, let me tell you that turbines are basically work interacting devices and we are getting energy output in the form of work. But to get that work, we also need to supply certain amount of energy. So, basically the amount of work that we are getting at the shaft of the turbine is at the cost of some input energy. So, the input energy is basically the kinetic energy of jets when that Jets of water strike the turbine blades. So, that energy is getting converted into another form and we are getting work output. So, objective should be to estimate the fraction of the input energy that is getting converted into output energy of course in the form of work. And if we can quantify that, then we can estimate the efficiency and that is very important. You have studied many other subjects and we have seen that when any mechanical device is designed, several aspects are considered for the design of that particular device and one of the most important aspect is the efficiency. So, again while a designer is designing an Impulse turbine he or she must be careful about the efficiency.

So, that means we need to know the amount of work that we are getting at the shaft of the turbine. And that work output we are getting at the cost of some input energy. So, to do that analysis we need to know little more about the impulse turbine and that is what the topic of our today's class is. So, let me tell you once again that before we go to discuss about that analysis let us first draw the schematic depiction of this particular type of turbine and from there we shall try to draw the velocity triangles. Because without knowing the velocity components or the working principle in a deeper way, it will not be possible to understand about this energy transfer process. So, it is convenient to establish that particular energy transfer mechanism or in the form of mathematical expression, if we can draw the velocity triangles.

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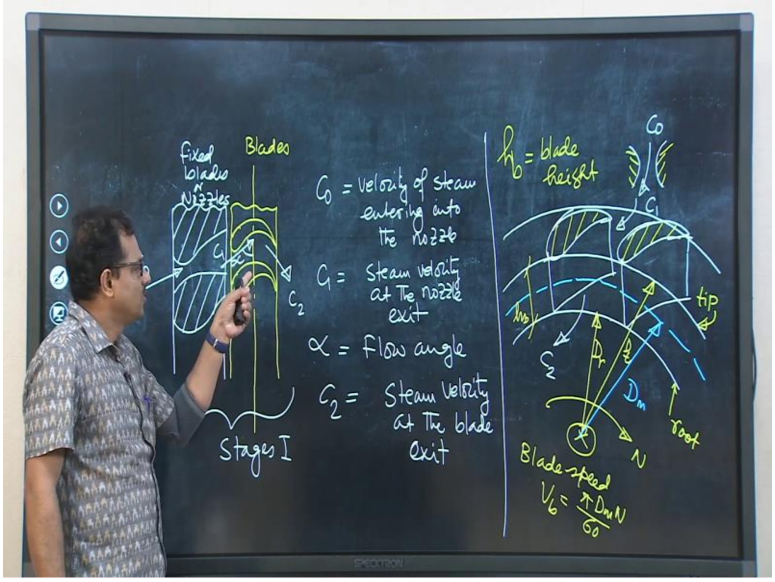

So, first let us draw the schematic of the impulse turbine. So, we have drawn the first row of moving blades or blades and the first row of nozzle or fixed blades in the slide. We have drawn here only one nozzle and 2 blades because we need to know the passage between 2 consecutive blades and we are interested in analyzing the working principle in a deeper way and that too we are interested in the velocity components. So, these 2 rows constitute together to form a stage and that is the first stage. And we know that C_0 is the velocity of steam which is entering into the nozzle. So, steam which is coming out from the turbine is now entering into the flow nozzle and as I said that steam turbine is basically assemblage of the row of fixed blades and row of moving blades or blades.

So, the steam which is entering into the first row of moving fixed blades or nozzles is essentially coming out with a higher velocity and that is how the nozzles are designed and that velocity is say C_1. So C_0 is the velocity of steam entering into the nozzle, C_1 is steam velocity at the nozzle exit. And the steam is striking the blade or blades at an angle which is α. As we have discussed that after striking the turbine blades at a velocity C_1 that steam will come out from the blade say at a velocity C_2. So C_0, C_1, C_2 are the absolute velocities. So, these are the vector quantities but I am not going to write that for the sake of the convenience in the representation.

So, now we shall be drawing the velocity triangles but before that let us now look at the kind of this blading arrangements in a more clear way. So we have drawn 2 consecutive blades and we can see that the steam which is coming from the flow nozzle striking the blades. The mean diameter is D_m. The flow nozzle is also drawn and steam is entering with a velocity C_1 and it is eventually coming out from the blades with a velocity C_2. We can understand that there are 2 diameters; root diameter D_r and tip diameter D_t and these 2 diameters are not same. So, to calculate the velocity of the blade we have marked the mean diameter in the diagram. The blade speed is V_b.

$$V_b = \frac{\pi D_m N}{60} \text{ ; where } N = \text{RPM}$$

Basically blade height is h_b. So, this diagram is the typical arrangement of blades which are mounted on the wheel of the turbine with the flow nozzle. So, steam is entering into the flow nozzle with a velocity C_0. Steam is coming out from the flow nozzle with velocity C_1 and that is definitely higher than C_0.So C_1 is the velocity of steam at the inlet of the blades. And after doing certain amount of work, steam is coming out with a velocity C_2 from the blades and steam jet is striking the turbine blades at an angle α that is the flow angle.

So, now with this understanding let us try to draw the velocity triangles and these velocity triangles are very important to know the energy transfer process or mechanism. So, let us briefly discuss about the velocity triangles.

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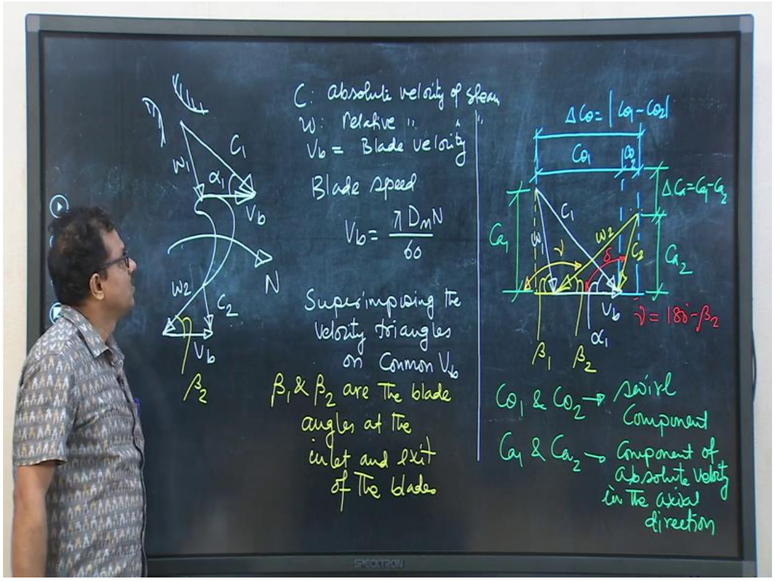

And to do that if we say consider a single with blade velocity V_b and V_b is drawn in the slide. Then this is the nozzle. So, the absolute velocity of steam leaving the flow nozzle and entering into the blade passage is C_1. The blades are rotating at a speed N RPM and that we can see from this schematic. So, since blades are rotating relative to the blade velocity we shall have the relative velocity and that is w_1 and the flow angle is α_1. So, the suffix 1 is used to denote quantities at the inlet of the blades.

Similarly C_2 is the absolute velocity of steam leaving the blades and since blades are rotating, so relative to the blade velocity this would be the absolute velocity and we can draw the velocity tangles. So this particular blade is rotating with N RPM. So, we can say that the blade speed corresponding to N RPM can be written

$$\text{Blade speed}, V_b = \frac{\pi D_m N}{60}$$

So, we have calculated this based on the mean diameter and that is why I had mentioned the need of this particular mean diameter.

Since the blade speed is same for both the triangles we can superimpose the inlet velocity triangle and outlet velocity triangle on the common V_b that is the blade speed. So, let us we try to superimpose these 2 velocity triangles on a common V_b as shown in the slide. So let us first draw the inlet triangle with C_1, w_1, V_b and angle α_1. Now we shall superimpose the outlet velocity triangle here with components C_2, w_2. Now this angle is β_2 that is the blade angle at the exit. So, this angle is β_2 and this angle is β_1. So β_1 & β_2 are the blade angles at the inlet and exit of the blades.

Now from this superimposed velocity triangles, our next objective should be to know about the rate of work done by the Jets on the blades. So, basically the steam is coming out from the flow nozzle with the velocity C_1. So, if we know the mass flow rate of steam we can calculate the kinetic energy of steam jets leaving the nozzle and striking the turbine blades.

At the cost of that input energy, our next objective should be to quantify the output energy in the form of work, because essentially we are getting work output at the shaft of the turbine. Now to estimate that quantity, this superimposed velocity triangle is very important. Next we have drawn $C_{\theta 1}$ & $C_{\theta 2}$ in the velocity diagram. These 2 are the velocity components in the tangential direction. So, at the inlet, the component of absolute velocity (C_1) in the tangential direction is $C_{\theta 1}$ and similarly component of absolute exit velocity (C_2) is in the tangential direction is $C_{\theta 2}$.

$$\Delta C_\theta = |C_{\theta 1} - C_{\theta 2}|$$

So, the difference in tangential component of absolute velocity is responsible to produce tangential thrust and that thrust would give rise to torque and we will be getting work. So, this quantity is very important to estimate the work done by the jets on the blades.

Similarly if you look at carefully we still can have this particular component and that is $\Delta C_a = C_{a2} - C_{a1}$. Similarly we could define all component that is $C_{\theta 1}$ & $C_{\theta 2}$. So $C_{\theta 1}$ & $C_{\theta 2}$ are known as swirl component of velocity and in some books these velocities are also known as wall component.

So, change in swirl component of velocity is responsible to produce tangential thrust. Similarly C_{a1} & C_{a2} are the component of absolute velocity in the axial direction and you can see that $C_{a1} \neq C_{a2}$. So, difference in the component of absolute velocity in the axial direction that is ΔC_a is still there and that component produces axial thrust.

By drawing velocity triangles, we can see what would be the magnitude of this component ΔC_a. So, this difference in component of absolute velocity in axial direction can be observed if we draw the velocity triangles properly at per scale.

So I would like to tell you that this particular axial component is responsible for the axial thrust that would be absorbed by the axial thrust bearing. So, basically the turbine wheel is mounted on a shaft and that axial thrust bearing should be there to absorb this axial thrust whereas this ΔC_θ that is the difference of swirl component is responsible to produce tangential thrust.

So, there are 2 important angles here that would be useful. So, if we try to draw the angles in a clockwise direction then the angle γ is the exit blade angle that is nothing but $180° - \beta_2$. Similarly we can also have another angle, if we try to measure the angles in the clockwise direction and that is the angle δ. So δ is the angle made by the exit absolute velocity of steam leaving the blades with the plane of rotation of the wheel while α is the flow angle that is the angle subtended by the nozzle axis in the direction of rotation of the wheel. So, these 2 are important.

So, this means we could identify 3 different velocity components; C is the absolute velocity of stream, w is the relative velocity of steam and V_b is the blade velocity. The absolute velocity would be there because steam will come out from the flow nozzle with an absolute velocity C_1 but all turbine blades are always rotating, so relative to the blade velocity steam which should be impinging on the blade with a relative velocity w_1.

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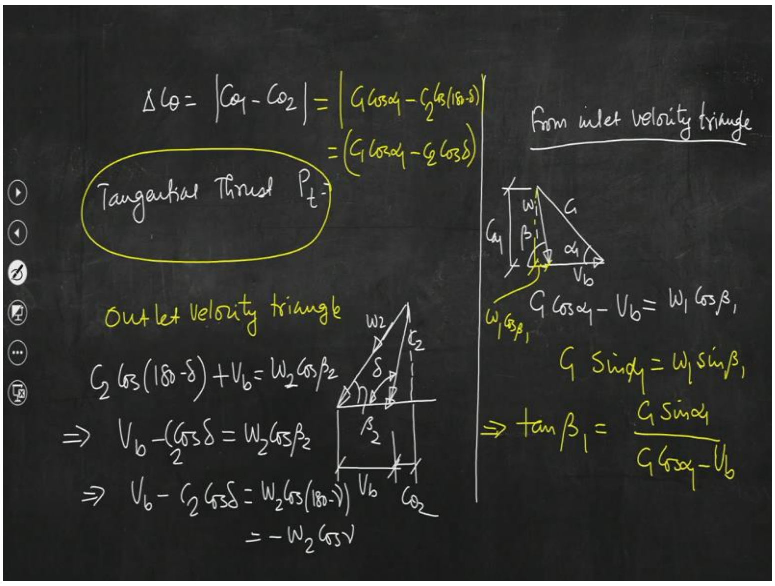

Now with this understanding, tangential thrust that is P_t is due to the change of difference in swirl component of velocity. We know that

$$\Delta C_\theta = |C_{\theta 1} - C_{\theta 2}|$$

Now if we try to look at the inlet velocity triangle. So, let me again draw the Inlet velocity triangle with angle β_1, α_1 and velocity w_1, C_1, V_b. From the Inlet velocity triangle

$$C_1 \cos \alpha_1 - V_b = w_1 \cos \beta_1$$

So, the component $w_1 \cos \beta_1$ is marked in the velocity diagram. We can also write

$$C_1 \sin \alpha_1 = w_1 \sin \beta_1$$

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

Now $C_{\theta 1}$ is basically component of absolute velocity in the tangential direction and that is nothing but

$$C_{\theta 1} = C_1 \cos \alpha_1$$

Now let us try to draw is the outlet velocity angles with velocity V_b, C_2 & w_2 and angle β_2 & δ. We could define δ is the angle made by exit absolute velocity of steam leaving the blades with the plane of rotation of the wheel So, we have drawn this β_2 that is the blade angle and of course if we can draw the angles in the clockwise direction then γ would the exit blade angle that is $(180 - \beta_2)$.

So, from the outlet velocity triangle we can write that

$$C_2 \cos(180 - \delta) + V_b = w_2 \cos \beta_2$$

$$\Rightarrow V_b - C_2 \cos \delta = w_2 \cos \beta_2$$

If you are measuring the angles in the clockwise direction then it would be

$$V_b - C_2 \cos \delta = w_2 \cos(180 - \gamma) = -w_2 \cos \gamma$$

So, I am just trying to write the expressions that we can get from the velocity triangles because this expressions will help us to estimate about several other quantities. Now

$$C_{\theta 2} = C_2 \cos(180 - \delta) = -C_2 \cos \delta$$

So, now I can complete the below expression that is

$$\Delta C_\theta = |C_{\theta 1} - C_{\theta 2}| = (C_1 \cos \alpha_1 - C_2 \cos \delta)$$

So, you know that we can have $C_1 \cos \alpha_1$ from the expression

$$C_1 \cos \alpha_1 - V_b = w_1 \cos \beta_1$$

Similarly we are getting $C_2 \cos \delta$ from the expression

$$V_b - C_2 \cos \delta = w_2 \cos \beta_2$$

So, knowing these 2 expressions, we can quantify the change in swirl component of velocity and that particular component is responsible for the tangential thrust.

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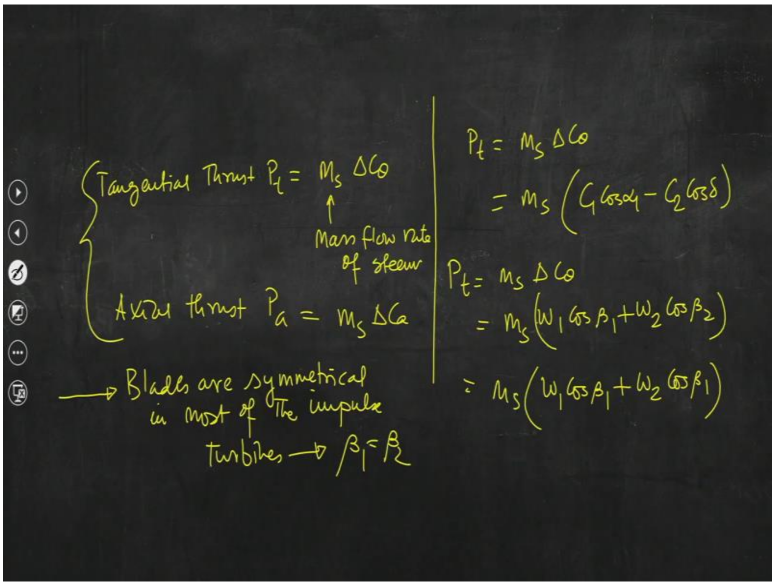

$$\text{Tangential Thrust}, P_t = m_s \Delta C_\theta$$

This M_s is mass flow rate of steam. If it is mass flow rate then it should be $\dot{m}_s$ but it is mass flow of steam m_s, it is Similarly you can have

$$\text{Axial Thrust}, P_a = m_s \Delta C_a$$

So, we can quantify these 2 quantities, while the tangential thrust is responsible for the work output that means it will produce torque and we will be getting work output, the axial thrust is also important equally while someone is designing the impulse turbine. Because this thrust should be absorbed by the axial thrust bearing. So, you can understand, to estimate the work output from this particular energy transfer process P_t is important and P_a is also important. Though this component P_a is not giving any work or energy output yet this component is important because the axial thrust bearing should be designed accordingly, so that this axial thrust can be absorbed. Otherwise this particular thrust will lead to several mechanical or operational issues.

$$P_t = m_s \Delta C_\theta = m_s (C_1 \cos\alpha_1 - C_2 \cos\delta)$$

This expression can be further simplified using the expressions we found from inlet and outlet velocity triangle. So, this is one way of calculating this expression and you can also rewrite this if we go to the previous slide wherein we have superimpose these 2 velocity triangles. So, basically you know that

$$P_t = m_s \Delta C_\theta = m_s (w_1 \cos\beta_1 + w_2 \cos\beta_2)$$

Now in most of the cases the impulse turbine is designed so that the blades are symmetrical. So, that means $\beta_1 = \beta_2$. If that is the case we can write

$$P_t = M_s (w_1 \cos\beta_1 + w_2 \cos\beta_1)$$

So let me tell you here that when stream is entering into the blade passage and leaving the blade passage, then these two relative velocities w_1 & w_2 are not same. Though we are calculating the blade speed based on the mean diameter yet these 2 relative velocities are not same. And it is due to the friction that the steam jet will encounter while passing through the passage between 2 blades. This also depends on the roughness of the blade. So, the roughness of the blade surface will provide a resistance to the flow of steam while passing through the passage between 2 blades and it is because of this reason $w_1 \neq w_2$. So w_2 is always less than w_1 and the ratio of these 2 relative velocities steam at exit to inlet is known as blade friction coefficient.

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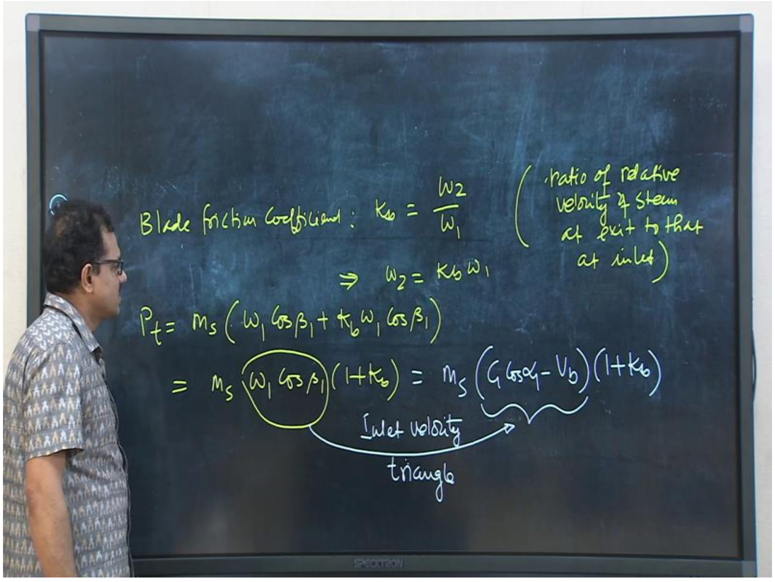

So, we can define that

$$\text{Blade Friction Coefficient}, k_b = \frac{w_2}{w_1}$$

So, this is the ratio of relative velocity of steam at exit to that at inlet and we have seen that these 2 velocities are not equal because stream while passing through the passage between 2 consecutive blades will have to face resistance and that will come from the frictional effect that is roughness of the blade surface. So $k_b \neq 1$. So, we can write from this expression that

$$w_2 = k_b \times w_1$$

So, we can write

$$P_t = m_s(w_1 \cos\beta_1 + k_b w_1 \cos\beta_1)$$

$$\Rightarrow P_t = m_s w_1 \cos\beta_1 \,(1 + k_b)$$

From the inlet velocity triangle we have already establish the below expression

$$w_1 \cos\beta_1 = C_1 \cos\alpha_1 - V_b$$

Now we can write that

$$P_t = m_s(C_1 \cos\alpha_1 - V_b)(1 + k_b)$$

So, try to understand that our objective is to express this tangential thrust in terms of blade velocity, flow angle and the blade friction coefficient.

So, you know that since $w_2 \neq w_1$, there is always a loss of energy due to friction while steam is passing through the blade passage and that is nothing but $\frac{w_1^2 - w_2^2}{2}$. When steam jets come out from the flow nozzle and strikes the turbine blades, a part of the input energy would be utilized to overcome the frictional losses. And that is due to the surface heterogeneity of the blades, roughness factor most importantly.

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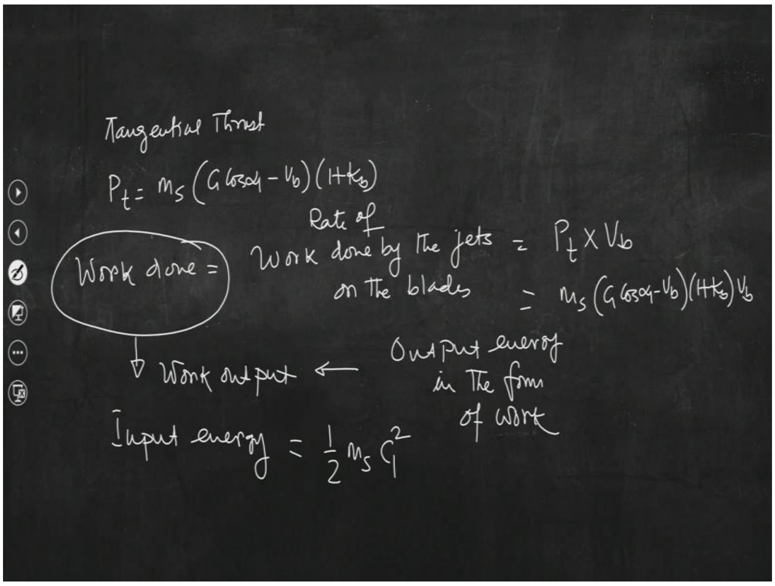

So, if we go one step further then we can write that

$$P_t = m_s(C_1 \cos\alpha_1 - V_b)(1 + k_b)$$

So, this is the tangential thrust. So, what is work done by the Jets on the blades?

$$\text{Work done} = \text{Rate of work done by the jets on the blades} = P_t \times V_b$$

So, this is work output is the energy output in the form of work. So, this is output energy in the form of work, now what about input energy?

$$\text{Input Energy} = \frac{1}{2} m_s C_1^2$$

Because C_1 is the absolute velocity of steam leaving the flow nozzle and striking the turbine blade. So, if M_s is the mass flow rate of steam then we can write this. So, from these 2 quantities we could express the work output that is considering the energy transfer process representing the velocity triangles both at inlet and outlet of the blades. And from this analysis we could write the work done that is

$$\text{Work done} = P_t \times V_b = m_s(C_1 \cos\alpha_1 - V_b)(1 + k_b)V_b$$

Now what we can do? So, the energy output in the form of work and the energy input are certainly not the same. If they are same then efficiency should be 100% and that is not possible because we all have studied about thermodynamics.

So, these 2 quantities are not same and in fact we also have studied in thermodynamics that work is high grade energy and heat is low grade energy. So, basically we are supplying heat to the boiler and at the cost of that input energy we are getting this work output. So, work that you are going to get at the shaft of the turbine should not be equal to the input energy that we are supplying through the steam Jets.

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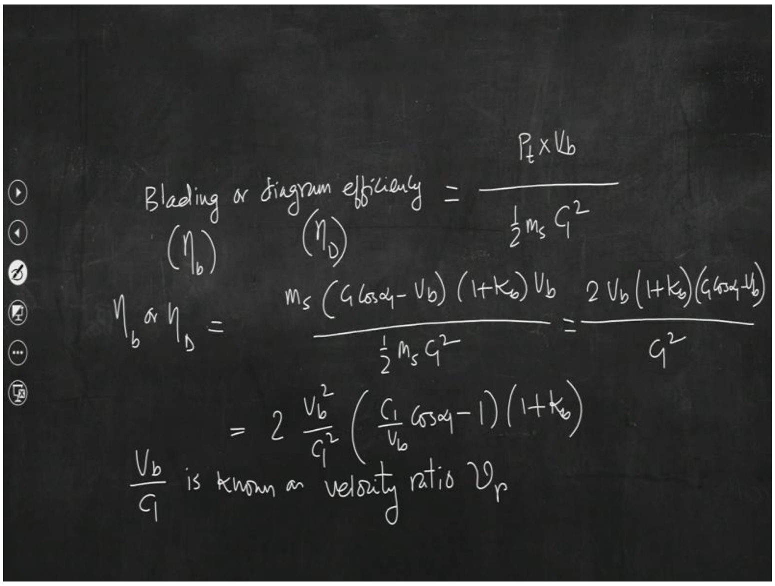

So, we can estimate the efficiency and that efficiency is known as blading efficiency or diagram efficiency. So, this blading efficiency is denoted by η_b or diagonal efficiency is denoted by η_D and that is nothing but the rate at which work is done by the Jets on the blades.

$$\text{Blading efficiency}, \eta_b \text{ or Diagonal efficiency}, \eta_D = \frac{P_t \times k_b}{\frac{1}{2} M_s C_1^2}$$

$$\eta_b \; or \; \eta_D = \frac{m_s(C_1 \cos\alpha_1 - V_b)(1 + k_b)V_b}{\frac{1}{2} M_s C_1^2} = \frac{2V_b(1 + k_b)(C_1 \cos\alpha_1 - V_b)}{C_1^2}$$

$$= 2\,\frac{V_b^2}{C_1^2}\left(\frac{C_1}{V_b}\cos\alpha_1 - 1\right)(1 + k_b)$$

So, the ratio of ${}^{V_b}/_{C_1}$ is known as velocity ratio v_r. And if we express ${}^{V_b}/_{C_1}$ as v_r then we can write η_b or η_D like this.

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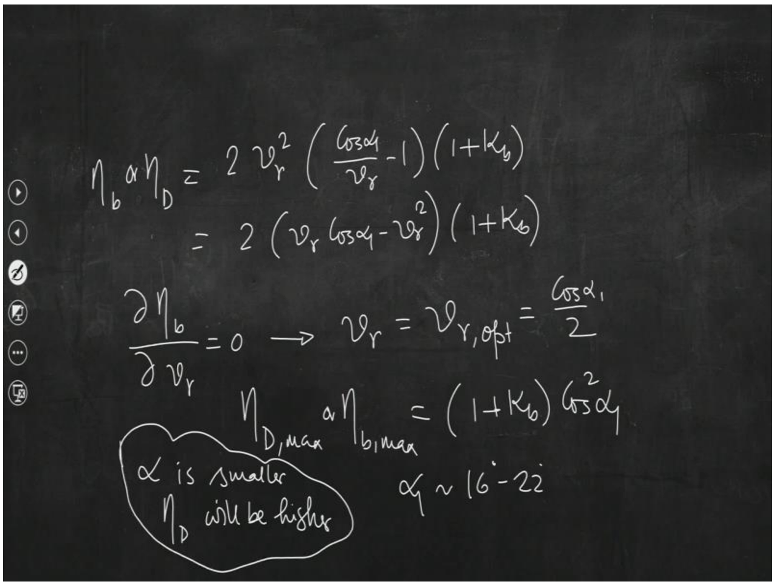

$$\eta_b \ or \ \eta_D = v_r^2 \left(\frac{\cos\alpha_1}{v_r} - 1\right)(1 + k_b)$$
$$= 2(v_r \cos\alpha_1 - v_r^2)(1 + k_b)$$

So, we can see that this diagram efficiency or blading efficiency expression gives us an estimate about the energy transfer. So, it gives us an estimate of the fraction of the input energy that is going to be converted in the form of useful work that we are getting at the shaft. You know I cannot say that is a useful word because the work which is available at the shaft may not be available in real applications. Because there will be several other losses like frictional losses, bearing losses etcetera, but at least we can see from this expression about the fraction of input energy that would be converted into the work.

Now, we can see that this bleeding efficiency or diagram efficiency is a function of flow angle, blade friction coefficient and most importantly the velocity ratio. So, there must be an optimum value of v_r for which this diagram efficiency or blade bleeding efficiency should be maximum. Because we know α_1 is fixed as it depends on the designer. Here k_b is basically blade friction coefficient and it cannot be equal to 1 but ideal situation would be that if we can maintain somehow $k_b = 1$. And $v_r = {}^{V_b}/_{C_1}$. So, basically C_1 is important because the nozzle steam jet is coming out from the flow nozzle and striking the turbine blades, so there would be certain amount of loss of energy. That means there is an optimum velocity ratio for which this efficiency is maximum. So

$$\frac{\partial \eta_b}{\partial v_r} = 0 \rightarrow v_r = v_{r,opt} = \frac{\cos \alpha_1}{2}$$

And if we plug in the optimum value of v_r into the expression of η_b then we can write

$$\eta_{b,max} \; or \; \eta_{D,max} = (1 + k_b) \cos^2 \alpha_1$$

So, we can see that we could establish the expression of blading efficiency or diagram efficiency and we had seen that the blading efficiency or diagram efficiency is function of velocity ratio, flow angle and also the blade friction coefficient. To obtain the optimum velocity ratio for which the efficient should be maximum and we had seen that the optimum value of velocity ratio is $\frac{\cos \alpha_1}{2}$. And plugging in the value of this in the expression of blading efficiency we can get the maximum diagram efficiency or maximum blading efficiency and that is nothing but $(1 + k_b) \cos^2 \alpha_1$.

So, what we can conclude from here is that if we reduce α_1 then efficiency should be maximum. So, if we can reduce the flow angle at the inlet then blading efficiency or diagram efficiency can be maximized. But if we reduce the flow angle drastically, then there would be certain amount of loss of energy. And to maintain a balance between the loss of energy and maximum efficiency the typical value of α_1 is 16° to 22°. So, if α_1 is smaller, then η_D will be higher. So, this is what we can see from this exercise but we cannot go beyond the above value, otherwise instead of having maximum efficiency, there will be a loss of energy even at the inlet of the blades and that is why the value of flow angle is maintained within this range.

To summarize today's class, we have discussed about the energy transfer process inside the impulse turbine. And from there, we could explain the velocity triangles. Mapping the velocity triangles on a common V_b we have tried to estimate the tangential thrust which is responsible for the work output. And finally we could express the blading efficiency or diagram efficiency and then we had seen that this particular efficiency is function of several parameters. And from that particular expression, we had established the optimum velocity ratio leading to maximum diagram or blading efficiency. And finally we had seen that the recommended value of α_1 for which efficiency will be maximum without inviting extra loss of energy at the inlet of the blades. So, with this I stop here today.