Applied Thermodynamics for Marine Systems

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Lecture - 12
Steam Turbine - Impulse

Good afternoon. We were studying the analysis of impulse turbine in our last class and I like to do a little bit of recapitulation of that topic. Then we will proceed with the further analysis.

In an impulse turbine there will be two important components, one is a nozzle and another is the impulse blading.

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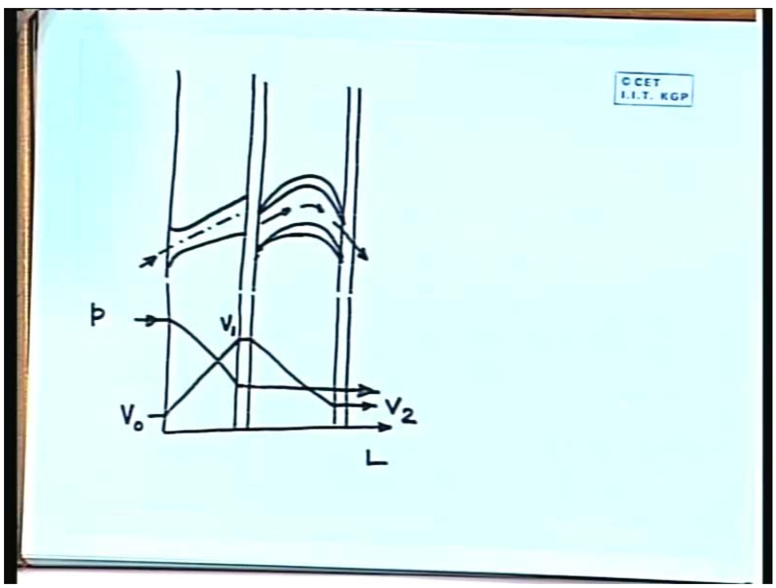

If we see a schematic representation of the impulse turbine, it is something like this. There is a nozzle through which the steam is flowing and when the steam flows through this nozzle, there will be a drop in the pressure and there will be increase in velocity. Then, this steam will pass through the blade passages of the impulse turbine. I have shown two rows. This is the row for the nozzle and this is the row for the impulse blading. This is a stationary row where a number of nozzles will be there. This is a row of moving blades where a very large number of blades will be there and that will be rotating as they are mounted over the turbine drum or turbine disk.

The steam path will be something like this. The steam is entering here; it is going through the nozzle, moving through this blade passage and coming out like this. This could be one particular stage of an impulse turbine and after this, this steam should go to the next stage of the impulse turbine. What could be the different stages, we will see later on.

It is important to know how the pressure and velocity changes, when steam is flowing through these rows of nozzles and blading of an impulse turbine. Here, steam is entering at a high pressure. As it passes through this nozzle, there will be a fall in pressure. After that, it is passing through the blade passage. In impulse turbine, there is no change of pressure when this steam passes through the impulse blading. If I call this as p, this is the length direction L. The pressure change can be represented like this. For velocity, when the steam is entering the nozzle it will have a very low velocity. When it is passing through this nozzle gradually, the velocity will increase. There is a small gap between the nozzle row and the blade row; here the velocity will remain constant. After that when it is again passing through this blade passage the velocity will fall and ultimately it will come out like this.

We can call this as V_0 - the velocity with which it is entering the nozzle. At the exit of the nozzle velocity is equal to V_1; that means it is entering the blade passage with a velocity $V_{1.}$ When it is coming out of this blade passage, it will have a different velocity. Let us say the velocity is V_2. What can we say is that the inlet velocity of steam to the blade is V_1 and exit velocity or outlet velocity of steam from this blade passage is V_2. We have to remember that the blade passage is not a stationary passage, all the blades are moving. The velocity which I have denoted here, this is the absolute velocity of steam which is entering the blade passage and which is leaving the blade passage. This is one way of representing how the velocity is changing through the blade passage.

There is another way of representation, where we can see in a very clear-cut manner how the velocity change is taking place in an impulse blading.

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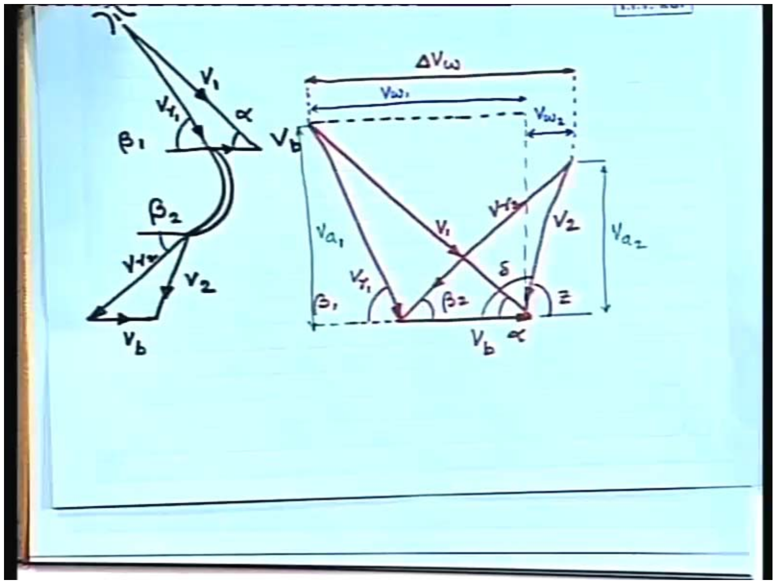

Here also we are representing the nozzle and the blade but on a different plane. Let us say this is the nozzle through which steam is coming. This is the nozzle axis and this is the direction in which steam is coming out of the nozzle. This will be the absolute velocity of the steam coming out of the nozzle and this is the absolute velocity of steam which is entering the blade passage and this is represented as V_1. This direction is the direction of rotation. Let us say the nozzle makes an angle alpha with the direction of rotation. We can say that the absolute velocity of steam makes an angle alpha with the direction of rotation. Here, this is the relative velocity of steam as it enters the blade passage. This is the blade passage. This angle is known as blade inlet angle and this is denoted as beta$_1$. This component of velocity is the blade velocity due to rotation and it is denoted as V_b. This V_b is obtained simply from the RPM of the blade and the blade diameter.

We can imagine that steam is entering the blade passage; it will glide over this blade and come out. If this V_{r1} is the relative velocity of the incoming steam, V_{r2} will be the relative velocity of the outgoing steam. One can observe that V_{r1} is tangential to the blade at the entry. That means if the blade angle at the entry is beta$_1$, V_{r1} also makes an angle beta$_1$ with the direction of rotation at the entry. Again, V_{r2} is the relative velocity at the exit and it is tangential with the blade at the exit. We will have the same magnitude and direction for V_b. That is the velocity of the blade in the direction of rotation. Joining these two, we will get the absolute velocity at the exit that is V_2. This is $beta_1$ and this angle is $beta_2$. One is blade inlet angle and another is blade outlet angle.

We have got another representation of different components of steam velocity, when it enters the blade and when it goes out of the blade. This is basically a triangular representation. The top triangle is known as an inlet velocity triangle and the triangle at the bottom is known as the exit velocity triangle or outlet velocity triangle. These two triangles can be superimposed over one another because they have got a common component that is V_b. If we do that, then, other analysis will follow from that combined velocity diagram.

The combined velocity diagram can be drawn like this. First, let us draw the common velocity component V_b. We will have the inlet velocity triangle like this. This is our V_1, this is our V_{r1} and this is V_b. We will have $beta_1$ and this is alpha. Again, let me repeat. $Beta_1$ is the inlet velocity angle and alpha is known as the nozzle angle. We can see from the geometry alpha is smaller compared to $beta_1$.

We can draw the other velocity triangle that means the exit velocity triangle. We will have something like this. This is $V_{r2,}$ the relative velocity at the exit. This angle is $beta_2$, this is V_b and this is V_2 absolute velocity at the exit. Another angle has to be defined. So, let us say this angle and let us give a name delta. Now, we can define a few more things, let us do that. If I project the vertical lines from the apex of these two velocity triangles and join them, the quantity which I get is denoted as V_{omega}. This is known as …?... component of velocity. Again, this can be divided into two parts. Maybe if I use another colour, it will be better. This I can call as V_{omega1} and then this I can call as $V_{omega\ 2}$. Similarly, I can have V_{a2} and V_{a1}. So V_{a2} or V_a in general, is axial velocity or axial component of velocity. V_{a1} is the axial component of velocity at the inlet and V_{a2} is the axial component of velocity at the outlet or exit.

If we imagine the steam turbine, there is a turbine shaft. The shaft axis is the axial direction and this component of velocity is in the direction of the axis of the shaft and the …. component of the velocity that is tangential to the shaft or to the shaft axis. If we try to imagine the turbine, then these are the physical directions of these two components of velocity that is …. component of velocity and axial component of velocity. The geometry is basically there are two triangles. We can use the basic laws of geometry and can get the relationship between different components of velocity. We can do this in a minute. Let us see what type of relationship we will get.

In this diagram, I would like to make a small change. Generally this is a difference. We want to put this as delta V_w or the difference between V_{omega1} and V_{omega2}. Let us see how we get these quantities.

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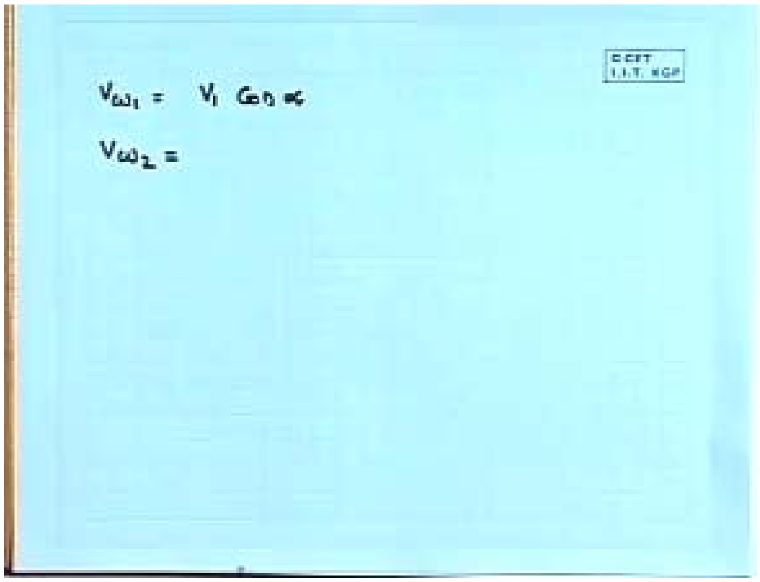

Let us see V_{omega1}. What is V_{omega1}? If we see this, V_{omega1} is nothing but… If we see V_1 and project it on this plane then we get V_{omega1} and this angle is alpha. So, V_{omega1} will be V_1 cos of alpha. Now, let us determine V_{omega2}.

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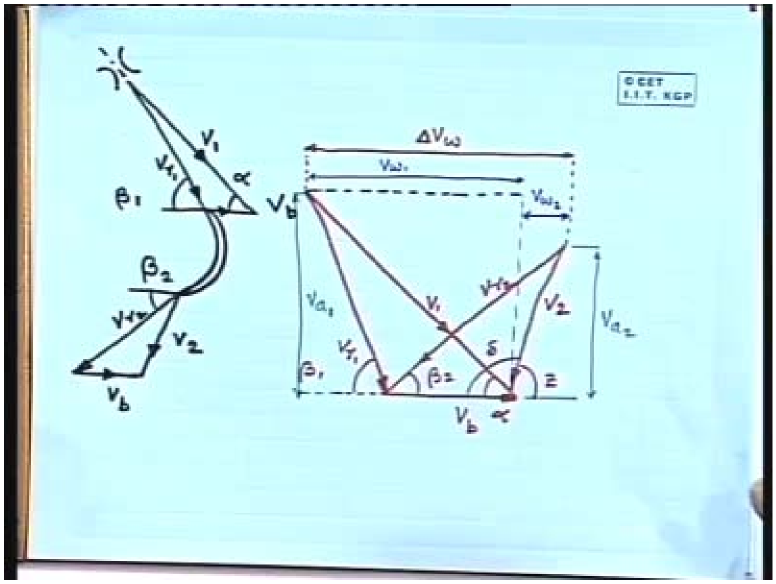

What is V_{omega2}? If we see this is V_2. This angle let us call it any name, let us say it is Z. If we take V_2 cos Z then we get $V_{omega\ 2}$. V_2 cos Z, if we write… this is V_2 cos of Z.

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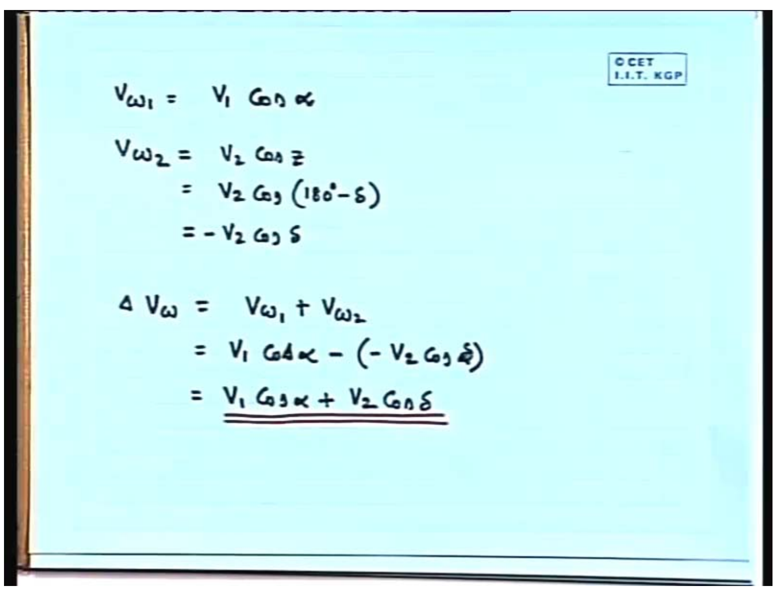

We can write V_2 cos of, from this relationship, 180 degree minus delta, cos 180 degree minus delta. So, what we will get? We will get minus V_2 cos of delta. The magnitude of V_{omega2} will be V_2 cos delta. And then what can we get? We can get delta V_{omega} is equal to V_{omega1} plus, magnitude wise it will be plus, V_{omega2} and then we can write it will be V_1 cos of alpha, then minus of minus V_2 cos of alpha. According to this diagram, which I have drawn it is like this. Basically we can put V_1 cos of alpha plus V_2cos of delta.

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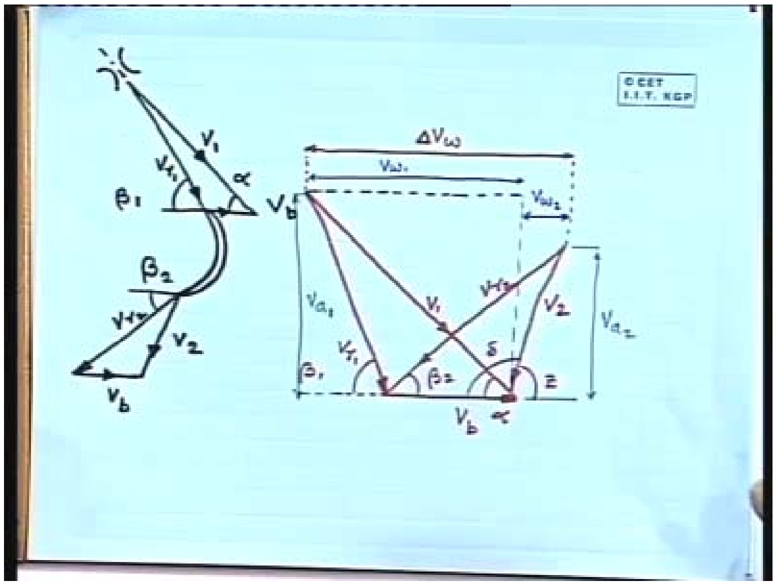

Here, I like to tell you, that we have drawn a particular diagram where delta is an obtuse angle. It need not be an obtuse angle always. Delta need not be an obtuse angle always. The value of delta depends on the value of the relative velocity, the blade velocity and the blade angle, outlet blade angle. In some cases, it can be an acute angle or in some cases, it can be 90 degree also. But, this relationship we can use always; irrespective of the magnitude of delta you can use this relationship always.

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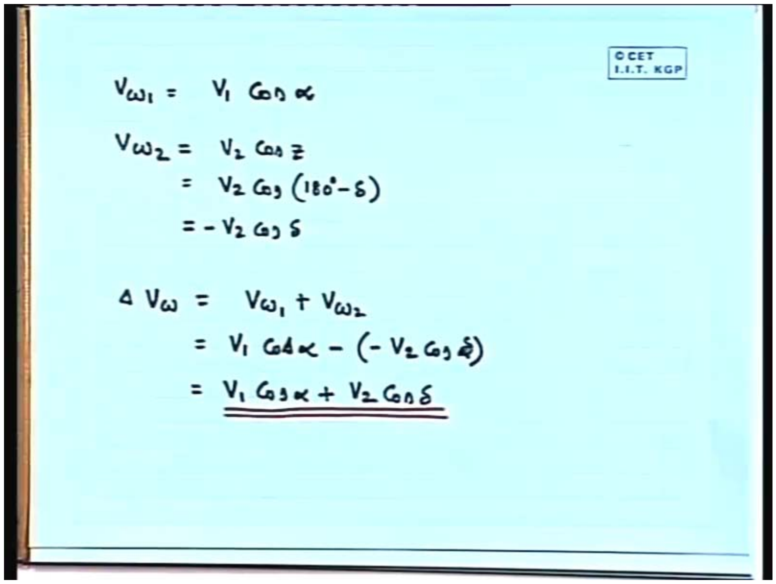

Basically, delta V_{omega} is equal to V_1 cos alpha plus V_2 cos delta; the way I have drawn the delta. If we draw or if we denote delta in the same manner then we can use this relationship. We can determine also the inlet blade angle.

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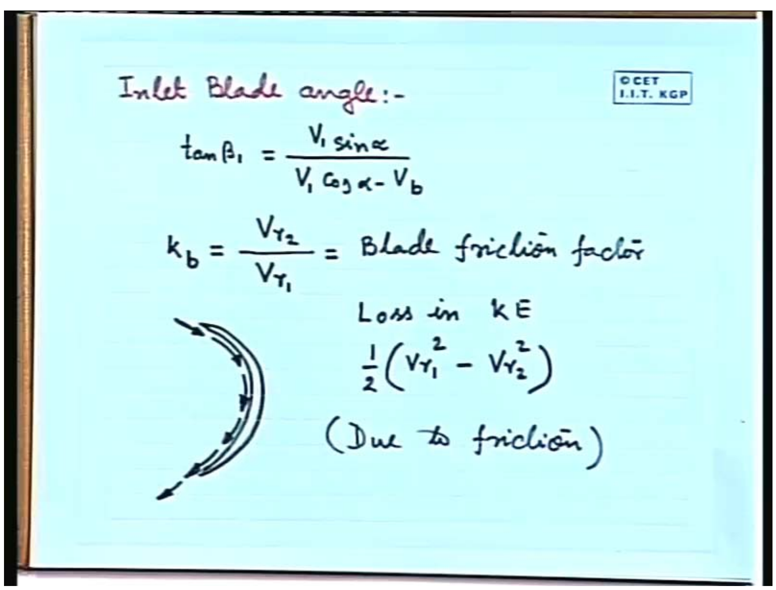

The inlet blade angle if we see, the inlet blade the angle is given by β_1. We can get a relationship like this - tan beta 1 is equal to… How we can get? This is V_1 sin alpha is this one and then V_1 cos alpha is this length minus V_b. So we can write V_1 sin of alpha, V_1 cos of alpha minus V_b. So, the inlet blade angle, if I have to determine, what do I have to know? I have to know the velocity or absolute velocity with which this steam is coming out of the nozzle. How do I determine that – the absolute velocity of steam coming out of the nozzle? This I have told earlier; we have to know what the incoming enthalpy is. What is the enthalpy with which steam is entering the nozzle and what is the enthalpy with which steam is coming out of the nozzle? When we have done the nozzle analysis in the previous class, I have discussed this. From there I will get $V_{1;}$ the nozzle angle should be known to me and V_b the blade velocity or blade velocity due to rotation of the disc should be known to me.

Why is it important to determine tan beta_1 or beta_1? Because, the blading should be designed in such a way so that this steam enters the blading tangentially without any shock or collision. If there is any shock or collision, if tan beta_1 is something different from the blade inlet angle, then when this steam is entering it will make some sort of collision with the blading or with the edge of the blade and some of the momentum will get lost. We do not want that. We want the steam to smoothly glide when it is entering the blading. That is why it is important to know and we can see that the inlet angle for shockless entry - this is called a shockless entry - that is a function of the absolute steam velocity, nozzle angle and the blade velocity.

Then we define another quantity, we define a quantity K_b. K_b is defined as V_{r2} divided by V_{r1}. This is the relative velocity of steam at the blade exit and this is the relative velocity of steam at blade inlet. K_b is conventionally known as the blade friction factor. The concept is like this. The blade is something like this. Let me draw the blade here. This is one impulse blading. The steam is entering something like this; it is moving along the blade surface and coming out of this blade. This is a cross section of the blade. Steam is entering like this. It is a horizontal plane and steam is going out like this. If steam is entering like this and going out like this and I have told in impulse blading, there is no change in pressure. The pressure is not changing. The height at which this steam is entering almost at the same height it is going out. There is no change in pressure; there is no change in this static head. So, the velocity at the inlet and outlet can be different only if there is a frictional dissipation. Otherwise, there will not be any change in velocity.

In other words, the relative velocity here V_{r1} will be equal to V_{r2} if there is no friction in the blade passage or the blade passage is smooth. If there is friction in the blade passage, then V_{r1} is not equal to V_{r2}. In general, there can be some friction. So, that is why we defined a factor $K_{b,}$ which is V_{r2} divided by V_{r1}. If this is 1, then there is no friction and inlet relative velocity is equal to the relative velocity at the exit. If there is friction then the relative velocity at the inlet and exit are different. From here, we can also determine what the frictional dissipation is. The frictional dissipation, the kinetic energy which will be lost due to friction, that is equal to 1/2 V_{r1} square minus V_{r2} square. This is per unit mass flow of steam. Let me write loss in kinetic energy due to friction. Due to friction, this will be the loss in kinetic energy.

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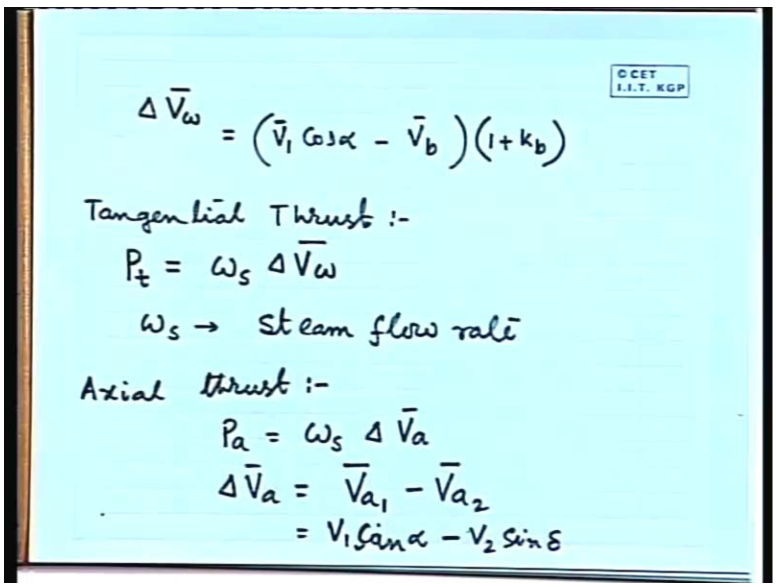

Once we have introduced this K_b we can write delta V_{omega} - this is a vector quantity, it has got a direction. This quantity can be written like this: V_1 cos of alpha minus V_b. All are vector quantities, these velocities, 1 plus K_b.

Now, this needs a little bit of derivation but that derivation is easy and I am leaving this derivation to you. If you try with the combined velocity triangle diagram, what one has to do is this V_1 one has to change it to V_{r1} and V_2 to $V_{r2.}$ Then one can introduce the relationship between V_{r1} and $V_{r2,}$ bringing this $K_{b.}$ Then one can get this relationship. This I am leaving to you. This derivation you can do easily.

Then comes the important parameters. Next, we want to determine what the tangential thrust is. The tangential thrust this is generally thrust. It is nothing but a momentum and it is denoted by P; as it is in the tangential direction we call it P_t and this P_t is change of momentum in tangential direction.

A change of momentum in the tangential direction means, again, let us go back to this basic diagram. Here, steam is entering with a velocity V_1. It will have a component in the tangential direction. This is the tangential direction; so, V_1 into cos of alpha in this direction. Similarly, when it goes out it will have a component in the tangential direction and if we take the difference between them then we will see what the change in velocity along the tangential direction is. That multiplied by the mass flow will give you the momentum or change of momentum in the tangential direction. We will have P_t that is omega_s into delta V_{omega}. This is a vector quantity.

Omega_s is the steam flow rate. This is the thrust which is responsible for doing the work. From the turbine, we get the mechanical work or we get the external work. This thrust, the tangential thrust, is responsible for that. This thrust is responsible for the movement of the turbine. That is why this is very important and we can determine it. We have to determine delta V_w or V_{omega}. V_{omega}, I have given two formulae; this formula and initially I have given another formula in terms of V_1 and V_2. So, either of these we can use and can determine the tangential thrust. Then comes the axial thrust. Axial thrust again in the direction of the axis, if we see what the change of velocity is, we can determine it. In the inlet we have got V_{a1} that is in the direction of axis and in the exit, we have got V_{a2}.

We can write P axial is equal to omega_s delta V_a. Delta V_a is equal to V_{a1} minus $V_{a2.}$ Again V_{a1} we can write V_1 sin of alpha. V_1 sin of alpha, we can write minus this is V_2 sin of z that means sin of 180 degree minus delta, that is, V_2 sin delta. This is how we can get the axial thrust. Now, axial thrust does not do the useful work. Rather, it is not desirable to have a very large axial thrust. Though we cannot avoid it, there will be some amount of axial thrust and that is taken care of by bearings in a turbine shaft. This is the axial thrust. So tangential and axial thrust we could determine.

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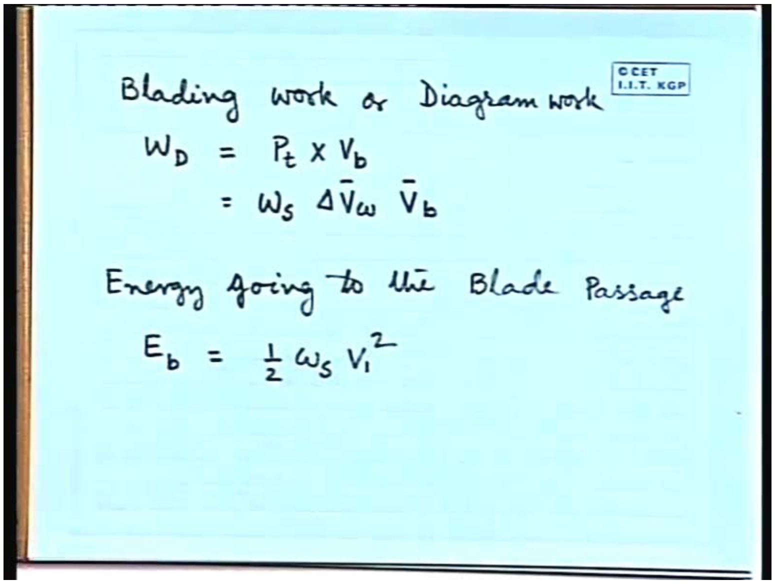

Next, we can determine the blading work or diagram work. This blading work or diagram work, we know that the useful component of force which is doing the work, that is, P_t. So P_t due to this force there is a movement in the direction of V_b or there is a rotation of the blade; rotation of the blade and in the same direction we have got the tangential velocity V_b. Using these two we can determine the blading work, let us say we call it W_D diagram work, that is why it is called $W_{D;}$ that is equal to P_t into V_b. That means we will have this is the steam flow rate into delta V_{omega} into $V_{b.}$ This will be the blading work or diagram work. This is the amount of energy which is coming out as external work or as the useful work out of a turbine.

What is the energy being supplied to the turbine? The energy that is being supplied to the turbine, if we do not consider the nozzle, but if we consider only the blade, then energy going to the blade passage that will be equal to let us say E blade, that is equal to half into $omega_s$ into V_1 square. That is the kinetic energy. With this, we can define the blade efficiency or stage efficiency or sometimes it is called diagram efficiency. Let us go to another page.

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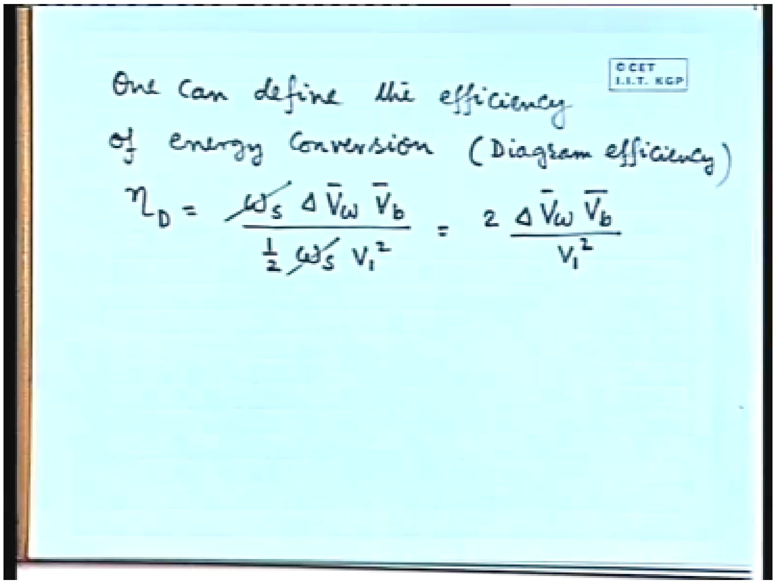

One can define the efficiency of energy conversion, eta$_D$. Again sometimes, it is called diagram efficiency. That is why I have denoted it as eta$_D$. So, what will it be? We will have omega$_s$, delta V$_{omega}$ to V$_b$ divided by 1/2 omega$_s$ V$_1$ square. Omega$_s$ can be cancelled from both the sides. So, basically we will get twice delta V$_{omega}$ V$_b$ divided by V$_1$ square. We see if we go back to the initial diagram which we have drawn or maybe we can go to the first diagram.

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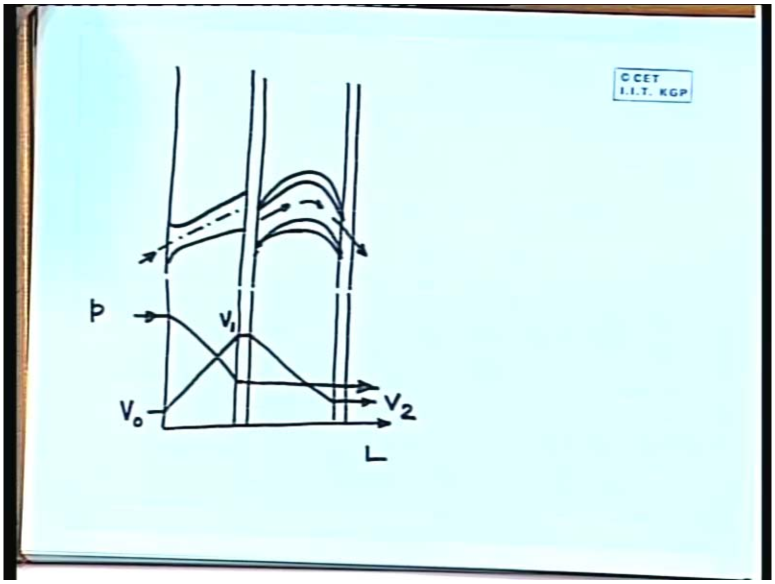

What we can see in this diagram is that steam is supplied at certain pressure, at a certain enthalpy and there is a nozzle and there is a blade. In the nozzle, there is a change in pressure. There is a loss in pressure or drop in pressure and velocity is increasing. When the steam is passing through the blade passage, then there is a drop in velocity. Basically, there are a number of conversions and how much will be the inlet velocity and outlet velocity that depends on nozzle design and blade design. At this point, I mean a very logical question will arise: Are these values arbitrary? Can we choose these values arbitrarily? Or is there some sort of a guideline we should follow to get the maximum out of this design?

If we go to the next diagram, we can see how the different components of velocities are changing from inlet to outlet.

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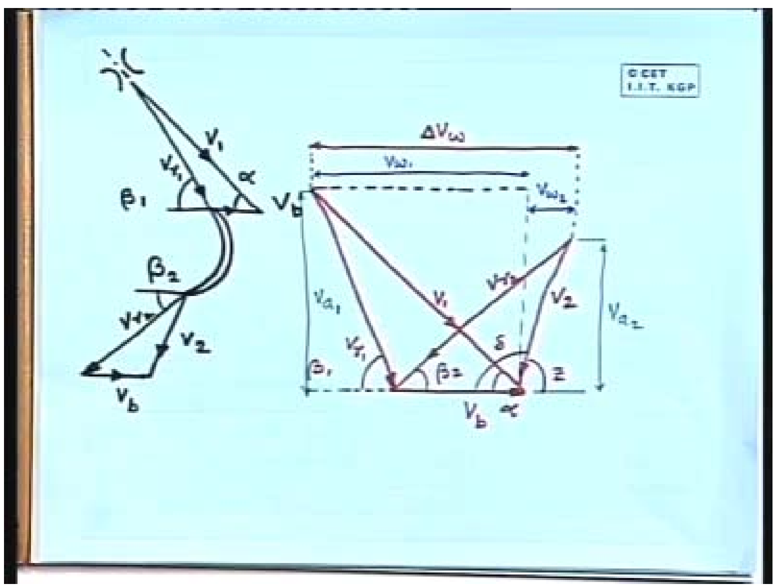

You see quite a few things can be selected. One can select the nozzle angle; one can select the tangential component of velocity for the blade which is V_b. How? Because we know that, it is a function of rotational speed RPM and the diameter of the turbine, one can select that; or if we see from the other perspective, let us say that the power generated is torque into RPM. We have some sort of independence of selecting torque and RPM separately, so that we get a product that is torque into RPM or power. So, if power also remains constant, one has some independence of selecting torque and RPM.

The question is how these design parameters can be selected so that we get maximum efficiency out of our design turbine. Probably at this point, we are in a position to decide that at least partially.

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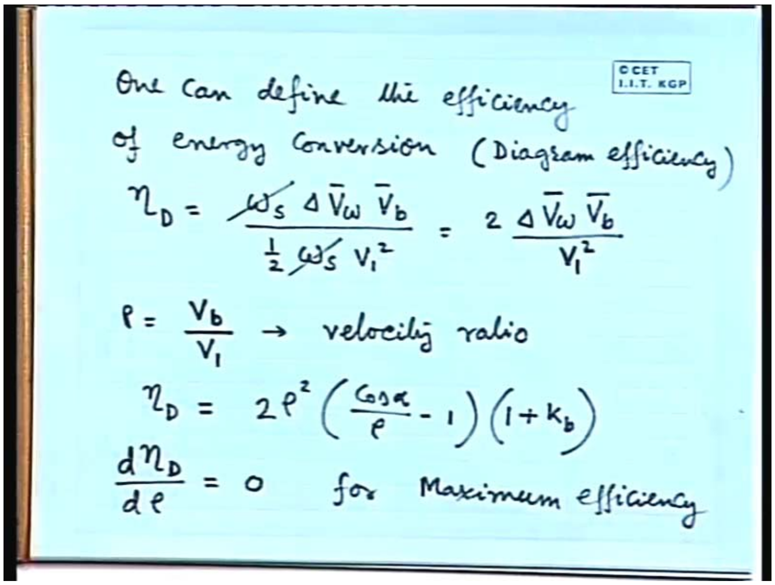

Here you see that we are getting two velocity components, one is V_1 and another is V_b. Apparently these two can be selected independently but let us see whether there is some sort of a relationship or not. What we can do is, let us define a ratio rho that is V_b by V_1. Again, here we have to remember that V_1 that is the velocity at the nozzle outlet and that depends how much enthalpy drop we are going to allow in a nozzle.

Let us see how V_b depends on V_1. If I define this as rho and we call it velocity ratio then one can show eta$_D$ is equal to twice rho square cos of alpha by rho minus 1 into 1 plus K_b. K_b that friction ratio or blade friction factor we already have. One can do a little bit analysis like d eta$_D$ by d rho that should be equal to 0 for maximum efficiency. For maximum efficiency, this quantity should be made equal to 0.

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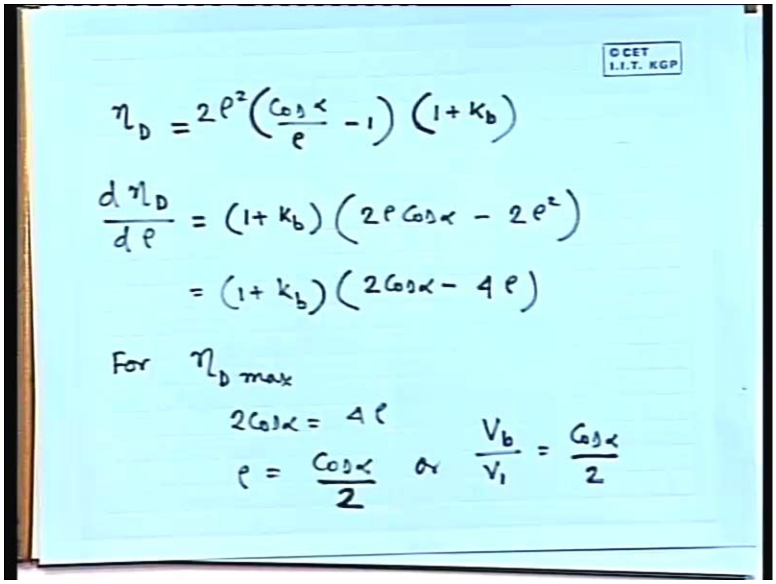

Let me write it once again, eta_D is equal to twice rho square cos of alpha by rho minus 1 and this is 1 plus K_b. d eta_D by d rho that is equal to how much will be this quantity? If we break it 1 plus K_b, that will be a constant term. Then rho will cancel, so we will have 2 rho cos of alpha minus 2 rho square. This is equal to 1 plus K_b and 2 cos alpha minus 4 rho and for maximum efficiency this is equal to 0. For maximum efficiency, for eta_D max, we will have twice cos of alpha is equal to 4 rho or rho is equal to cos of alpha by 2. We can see we have defined rho as or V_b by V_1 is equal to cos of alpha by 2. We can see that if we want to run the turbine at maximum efficiency then we cannot arbitrarily select V_b. I said that V_1 comes from how much enthalpy drop we are going to allow in the nozzle; from their V_1 comes. So if V_1 we select arbitrarily or V_1 is selected independently, then V_b bears a relationship with it for maximum efficiency and this is the relationship.

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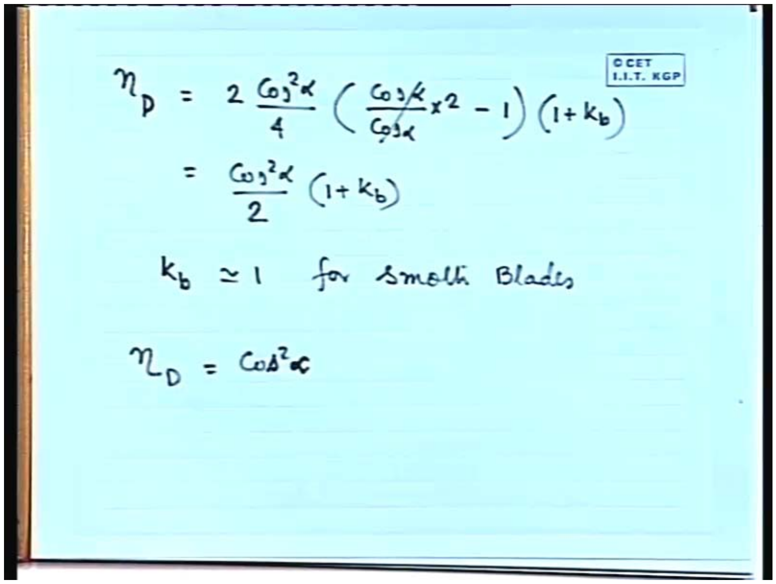

If we put that we will get eta$_D$ is equal to, rho is equal to cos alpha by 2. So, twice cos square alpha by 4, then cos of alpha; this is cos alpha by 2, cos of alpha by 2 means this is 2 minus 1 and 1 plus K_b. We will get cos alpha, cos alpha will cancel 2 minus 1 is 1 and here it is cos square alpha by 2, 1 plus K_b. If the blade is assumed to be more or less smooth, then K_b is equal to 1; K_b is 1 for smooth blade. In that case eta$_D$ is equal to cos square alpha. This will be the efficiency of the blade passage or optimum efficiency of the blade passage. Let us go back to the diagram.

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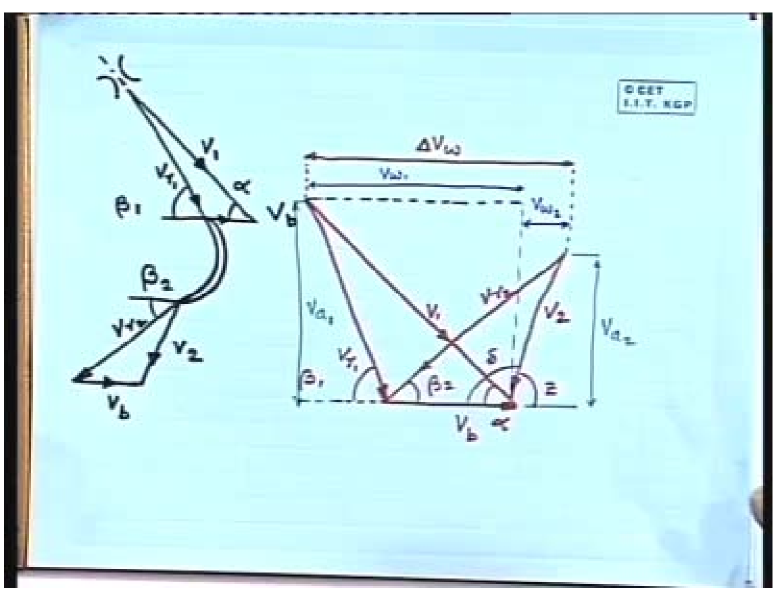

We see that efficiency of the blade passage depends on the nozzle angle. That is what I said at the beginning that there are number of parameters. At the beginning it appears that they are independent of each other. We can select them bit arbitrarily but it is not so. We can see that the blade angle determines what the efficiency of the turbine will be. From here again it is interesting to see that eta_D will have a high value, if cos alpha is high. Now, if cos alpha value has to be high, then this angle has to be very small, but we cannot make it very small due to the mechanical construction. We cannot make it very small, it will slant then and the blade passage will be very obscured, so we cannot do it. There are some limitations. Generally, this angle is kept 12 degrees, 14 degrees, like that. We generally do not go to a smaller angle than this, may be 12 degrees or 14 degrees or 16 degrees like this. These are the typical values of the nozzle for the impulse turbine.

This analysis is the basic analysis and it is applicable for impulse staging. We will see what the different ways of compounding impulse turbine are and that we will do in the next class.