Applied Thermodynamics for Marine Systems

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Lecture --11

Basic Concept of Turbine, Velocity Diagram

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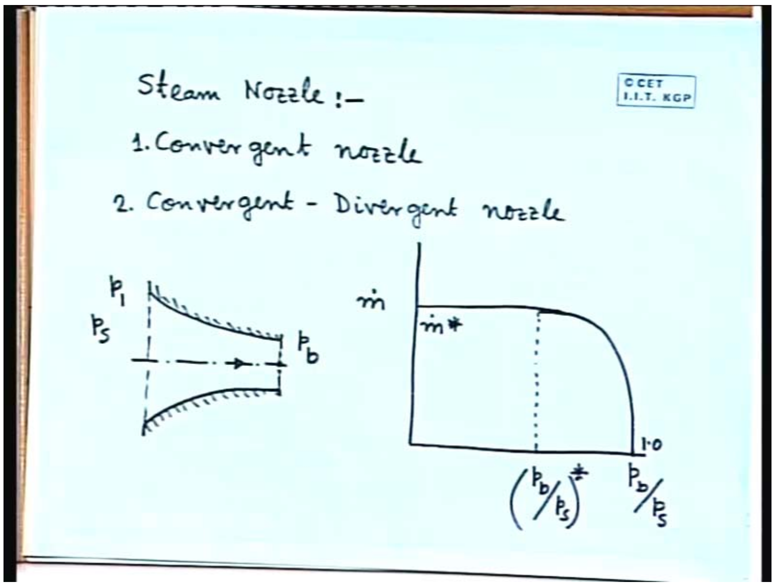

See steam nozzle can be of two different types depending on its geometry and mode of operation, one is convergent nozzle and another is convergent - divergent nozzle. Let us first understand the working principle of a convergent nozzle. In a convergent nozzle, the area of the nozzle reduces gradually in the direction of flow. As the area reduces, then, the flow velocity will increase and from Bernoulli's principle, we will have a decrease in pressure. The lowest pressure will be at the exit of the nozzle and at the same time, we will have the highest velocity at the exit of the nozzle. At the inlet of the nozzle, we are having a pressure which is denoted by p_1. Generally, the velocity of the fluid is negligibly small at the inlet of the nozzle. That is why, sometimes this p_1 is also denoted as p_s or stagnation pressure, whereas the pressure at the exit of the nozzle is called back pressure.

When a compressible fluid passes through the nozzle, we find a very unique phenomenon which is shown in this curve or graph. Here, what we have done is, we have used the mass flow rate through the nozzle as one ordinate and in another ordinate, we are having the back pressure and the back pressure we have expressed in a non-dimensional form where, we have used the ratio of back pressure to this stagnation pressure. The back pressure can be lower than the stagnation pressure or at the best it could be equal to the stagnation pressure. The maximum possible value of back pressure could be 1; that is what I have shown here. The value of back pressure can never be more than 1 in case of a nozzle.

When the back pressure value, that means this non-dimensionalized back pressure value is 1 or the back pressure is equal to this stagnation pressure then, there is no flow through the nozzle, because at the inlet of the nozzle you are having a pressure equal to p_s and at the outlet of the nozzle, you are having the same pressure equal to p_s. That is why, there is no flow through the nozzle; mass flow rate through the nozzle is equal to 0. Then, what you are doing is, you are decreasing the back pressure or you are decreasing the ratio p_b by p_s. You are moving in this direction of the coordinate. As the back pressure is reducing, keeping p_s the same value, you will have some flow rate through this nozzle. That is what you can see. As you go on decreasing the back pressure you are having higher and higher rate of mass flow through the nozzle.

But, in case of compressible flow what will happen is that this mass flow rate will go on increasing, it will come to a high value at some point and after that there is no change in the mass flow rate. It seems as if the nozzle has got chocked and this condition is known as chocking condition because beyond this, whatever may be the decrease of back pressure, suppose at this point you have made your back pressure equal to 0, even then you do not get any increase in the mass flow rate. This is known as the chocked condition of the nozzle or critical condition of the nozzle.

This ratio is the critical pressure ratio p_b by p_s star; that is the critical pressure ratio. This m dot at this corresponding condition denoted by m dot star is the critical mass flow rate through the nozzle. Physically what happens is, at this condition when you attain this critical pressure ratio, the velocity at the exit plane of the nozzle is the local sonic velocity or velocity of sound. You cannot increase the fluid velocity beyond that, if you have nozzle geometry like this. Here, you are having velocity of sound that is the maximum velocity in the nozzle and you cannot increase this velocity. As you cannot increase this velocity, in the upstream point also this velocity remains fixed and the mass flow rate through the nozzle remains fixed. In other words, once you reach the critical condition, at every point, the state of the fluid and the velocity remains fixed.

You cannot change it by changing the back pressure. At critical point and beyond critical point you are having the fixed value of flow rate and fixed value of fluid velocity.

Why do we use a nozzle? We use a nozzle to create high velocity flow or high velocity jet. We can see that, this nozzle has got a limitation. Also, we want to have nozzle through which high mass flow rate is possible. In that, regard also, we find that this nozzle has a limitation. With respect to mass flow rate and with respect to fluid velocity, we have got limitation in this nozzle. That is why other designs of nozzles are looked into.

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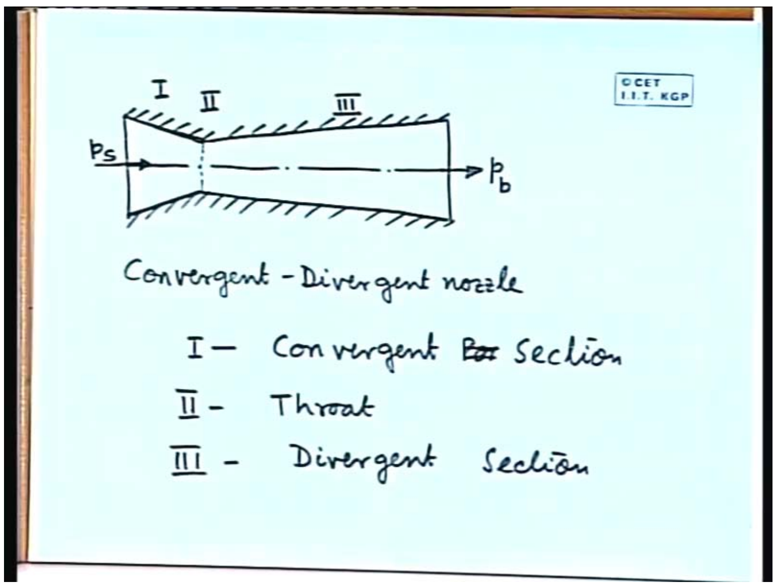

If we go for convergent - divergent type of nozzle, let us say our design is something like this. This is a convergent - divergent type of nozzle. This is the nozzle axis. Here, again you are having stagnation pressure and here you are having the back pressure. This is your convergent-divergent nozzle. In this case what will happen? The phenomenon in the convergent portion is the same as we have discussed earlier. That means the pressure at the inlet of the nozzle which is denoted as p_s, this is the stagnation pressure. You are keeping this pressure constant and you are changing the back pressure. You are gradually reducing the back pressure. So the phenomenon, just like before will take place. That means, you will have higher and higher flow rate through the nozzle and the velocity will also increase. Where the velocity will increase? The velocity will increase in the convergent portion. If we see the nozzle, there are three portions of the nozzle. First one is the convergent portion; I is the convergent portion. II is called the throat of the nozzle and III, is the divergent portion of the nozzle.

One can write, I is the convergent portion or section, then II throat and III is divergent section. If we see the velocity, we are going on reducing back pressure, so velocity will go on increasing in the convergent section, pressure will go on decreasing in the convergent section. In the divergent section what will happen? Again pressure will increase and velocity will fall and maximum velocity in the nozzle where we will get? We will get it at the throat. We will get at the throat the maximum amount of velocity. This will continue as we go on decreasing back pressure. So, the throat velocity will go on increasing. At one point it will be equal to the velocity of sound. Once it is equal to the velocity of sound, whatever decrease you may do in p_b, whatever smaller may be the value of p_b, no change will occur in the convergent section of the nozzle.

In the convergent section of the nozzle you will not have any change but then, you can find some unique changes in the divergent section of the nozzle. It can be shown by simple fluid mechanics that, once the velocity is sonic velocity at the throat after that, if you reduce the back pressure then, expansion will continue even in the divergent section and in the divergent section you will have further reduction in pressure and you will have further increase in velocity. That means you will have supersonic velocity in the divergent section.

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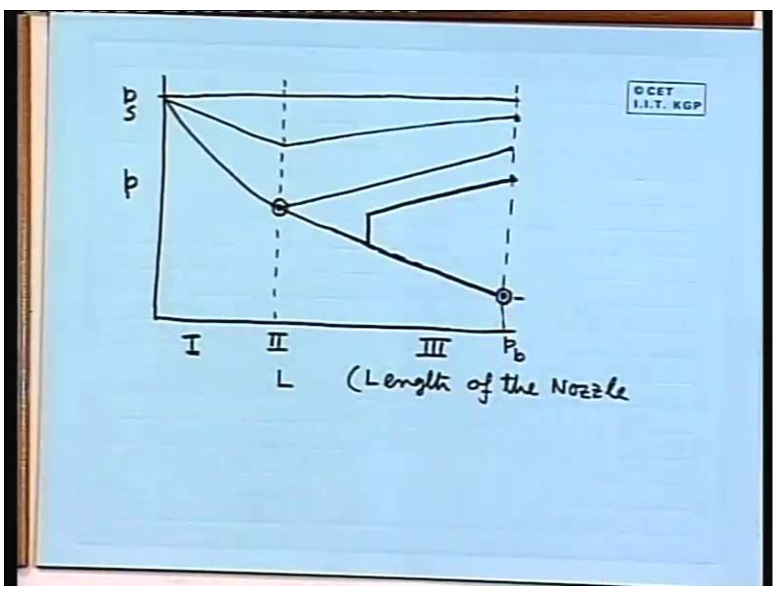

It is like this, if we represent it graphically. Let us say this side we are representing the pressure and this is the length of the nozzle L. This is II, this is I and this is III; convergent section, throat and divergent section and let us say this is the exit plane where the pressure is back pressure. Initially, you have the stagnation pressure and this pressure you are keeping constant. Initially the back pressure is also equal to this stagnation pressure, so there will not be any flow through the nozzle and everywhere in the nozzle you have the same constant pressure. Then you have reduced the back pressure to this value. This is the plane for back pressure. Let me call it p_b, then you have reduced it here. What you will find is up to throat there will be reduction of pressure; but beyond throat there will be increase in pressure. Up to throat there will be increase in velocity but beyond throat up to the exit there will be decrease in velocity. This will continue till you have sonic velocity at the throat. After that, again, here you will find that the pressure is increasing and velocity is decreasing. But, let us say your back pressure is somewhere here. Once you have reached the sonic velocity at the throat, after that if you reduce the back pressure further, there will not be any change in section I and you will continue about the same line of expansion even in the divergent section III. But you see, if you proceed along this line, you are going somewhere here. You have kept the pressure here so you cannot go here. What will happen? You will go up to certain distance then there will be a shockwave and you will come back here.

This process will continue only if you put your back pressure at some value here then, you can proceed along this line. The advantage you get then is you are coming out of the nozzle with supersonic velocity. This point is known as the design back pressure of the convergent - divergent nozzle and we want to operate it at this point only. What do we get if we operate at this point? We get a maximum flow rate, through the nozzle because at the throat you are having sonic velocity; we are having maximum velocity of the fluid at the outlet of the nozzle because, in the divergent section the flow is supersonic. It is fulfilling both the purposes. Steam nozzle which are convergent - divergent nozzle, we will try to operate those nozzle at this operating range. Our mass flow rate through the nozzle will be maximum and velocity at the outlet of the nozzle will be also maximum possible that is at supersonic range. In this steam turbine mostly this convergent - divergent type of nozzles will be used. We have already done the analysis of the nozzle; that is not very difficult to do.

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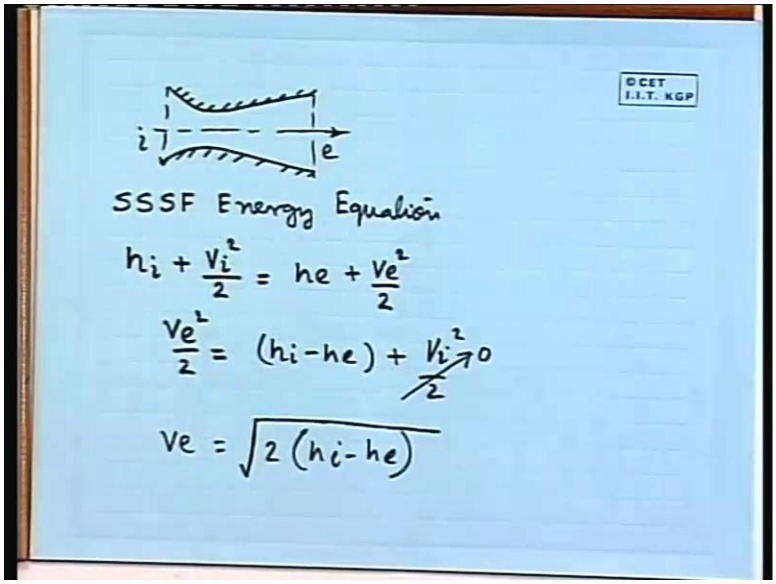

Whether it is a convergent - divergent nozzle or it is a simple convergent nozzle, let us say this is inlet i and this is exit e. For the nozzle, we can write down the steady state steady flow energy equation. The nozzle is well insulated, so there is no heat transfer; there is no work transfer also. With all these things, we can write: h_i plus V_i square by 2 is equal to h_e plus V_e square by 2 or in other words, V_e square by 2 is equal to h_i minus h_e plus V_i square by 2. Generally, (Refer Slide Time: 20:17) this is small compared to the exit velocity, compared to the change of enthalpy. V_e is equal to twice h_i minus h_e and then this is under root. This is how we can determine the velocity through the nozzle.

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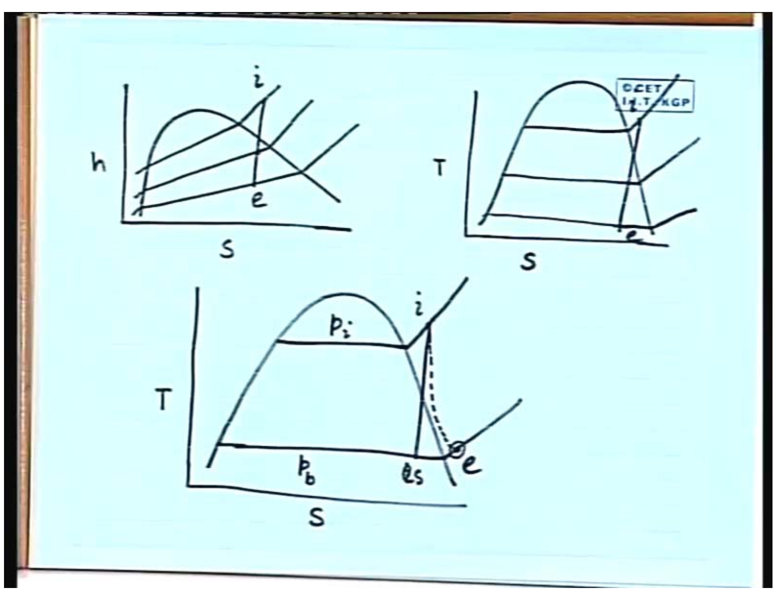

If we see the process either on a TS plane or on an h-S plane, it is like this. Let us say this is h-S plane. This is i and this is e and basically we have shown three different pressures because, this is the inlet or stagnation pressure, this is the back pressure and this could be the pressure at the throat. The TS diagram will also be equally simple, something like this. This is i and this is e. That is how the steam expansion through a nozzle will be represented. This is ideal expansion of steam through the nozzle where we are assuming that the process is isentropic, but actually the process will not be isentropic. The first thing is that, there are some dissipative processes like there is friction. When steam will flow through the nozzle, as it is a fluid and it is flowing through some sort of a solid passage there will be friction at the valve of the nozzle and however good may be the insulation of the nozzle, there will be transfer of heat from the expanding steam to the ambient atmosphere.

Mainly these two will render the process irreversible and there will be change in entropy during the process due to these two effects. If there is a change of entropy, how can we represent the process? We will try to represent it on a TS plane itself. (Refer Slide Time: 23:50) This is your actual isentropic process. This is p_i, inlet pressure, this is p_b and this is the condition from which steam is expanding. This is i and I am denoting it as i_s because it is a process through which s or entropy remains constant. Due to irreversibility there will be increase in entropy. While the same steam is expanding from the same pressure, same inlet pressure to the same back pressure, there will be increase in entropy, so the exit point will be somewhere here. This is e_s and this is e. e_s represents the exit point, if s remains a constant or entropy remains constant throughout the process and e is the exit point if there is irreversibility. The actual expansion will take along this dotted line. We generally give this dotted line, because we do not know the actual path. We know the initial point, we know the final point and by guess, we have drawn the path between initial and final points. That is why this is denoted by dotted line. Depending on the exit condition, it may be inside the two phase dome, it may be outside the two phase dome. But always there is an increase in entropy. That is why there is a tendency to go to the superheated region. But it is not necessary that always it will be in the superheated region. As we can see that, ideally the exit point is here but, practically the exit point is here, which is having higher entropy; one can define nozzle efficiency.

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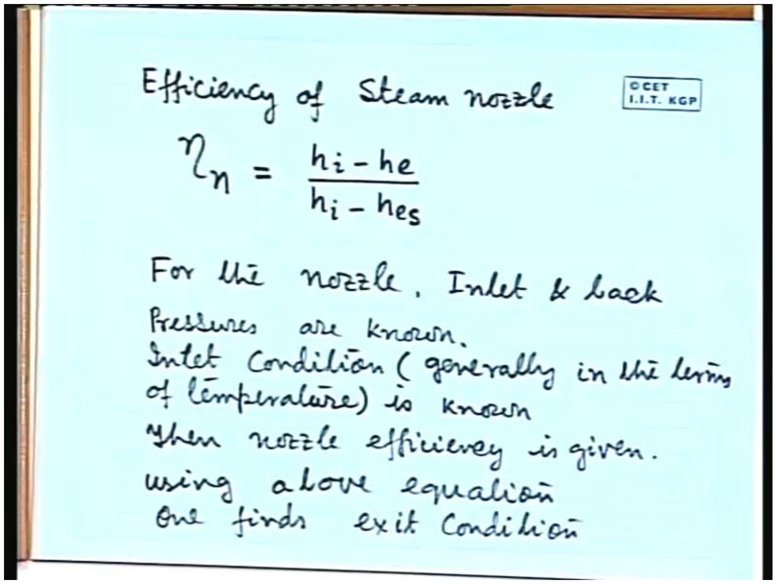

We can define nozzle efficiency. The efficiency of steam nozzle, eta_n can be defined in different ways. One can take the ratio of actual velocity divided by the ideal velocity as your nozzle efficiency. If we do that we will get h_i minus h_e divided by h_i minus h_{es} and that becomes the nozzle efficiency. h_i is known and probably the nozzle efficiency value will be provided. Taking the water generally supplied from the nozzle, design point of view is like this. For the nozzle, inlet and back pressures are known; so these two are known. The inlet condition, generally in the terms of temperature, is known. Then, the nozzle efficiency is given.

Using the above equation, one can find out the exit condition of the nozzle that will be in the same pressure line. But that will have a higher entropy value compared to the inlet of the nozzle. This is how we can find out the efficiency of the steam nozzle and this is applicable or the previous equation, where we have determined the outlet velocity from the nozzle. The same equations are applicable for both convergent nozzle and convergent - divergent nozzle. We do not have different equations for them. It is important to know that, convergent nozzle has got some limitations and these limitations can be extended in case of convergent-divergent nozzle. In a steam turbine, we will see that in number of places this convergent-divergent nozzle is used to increase the mass flow rate and to have high velocity at the outlet of the nozzle. That is all for steam nozzle. We we will be able to analyze the nozzle or solve some problem on the nozzle using the formula which we have given. With this we can go to the basic types of steam turbine.

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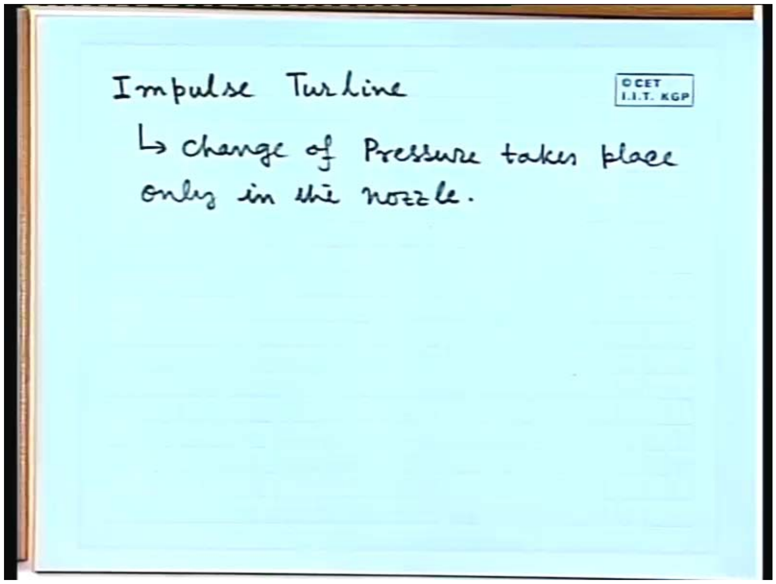

One of them or the most basic type of them is known as impulse turbine. Which type of turbine we will call impulse turbine? We have seen that, in a turbine basically, energy conservation takes place in two different stages. One is the nozzle and another is the blade passages or bladings. If the turbine design is such that, change of pressure of the steam takes place only in the nozzle then, we will call it an impulse turbine. So, we can say that change of pressure takes place only in the nozzle; steam pressure changes only in the nozzle and then in the blade passage what happens? There is change of momentum. Let us see what the working principle of an impulse turbine is.

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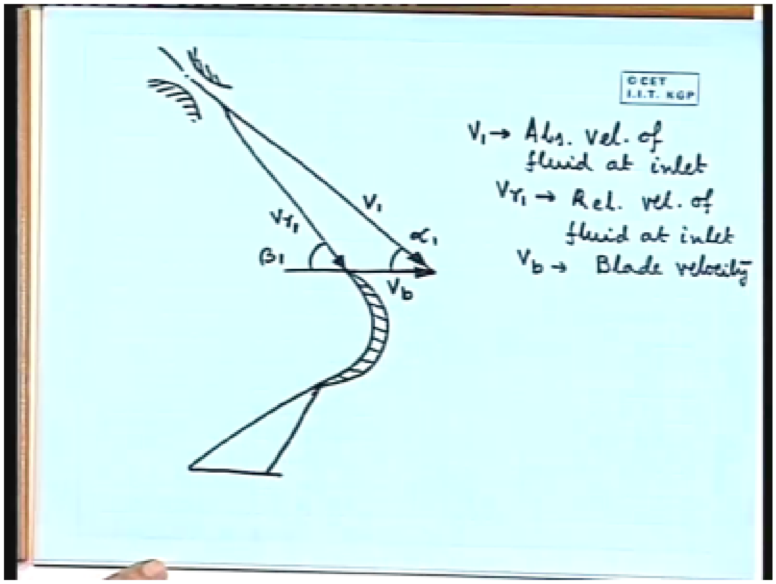

If we want to understand the basic working principle of an impulse turbine, let us think of a nozzle and a blade. This is a blade and we have a nozzle like this; let us keep the names. The blade is moving in this direction. The nozzle is fixed and the blades, we are just showing a cross section of it; there will be a large number of blades and they will be mounted on a disk or a drum. Then, as the drum is rotating the blade will also move along with the drum. This is the velocity of the fluid, relative velocity; this is the absolute velocity of the fluid and this is V_b, the linear velocity of the blade. That is how we will have relationship between different velocities. This diagram, this is a triangle, this is known as velocity triangle. There are different angles, this angle is denoted as alpha$_1$ and this angle is denoted as beta$_1$. We can write, V_1 is absolute velocity of fluid at inlet, V_{r1} is relative velocity of fluid at inlet and V_b is the blade velocity.

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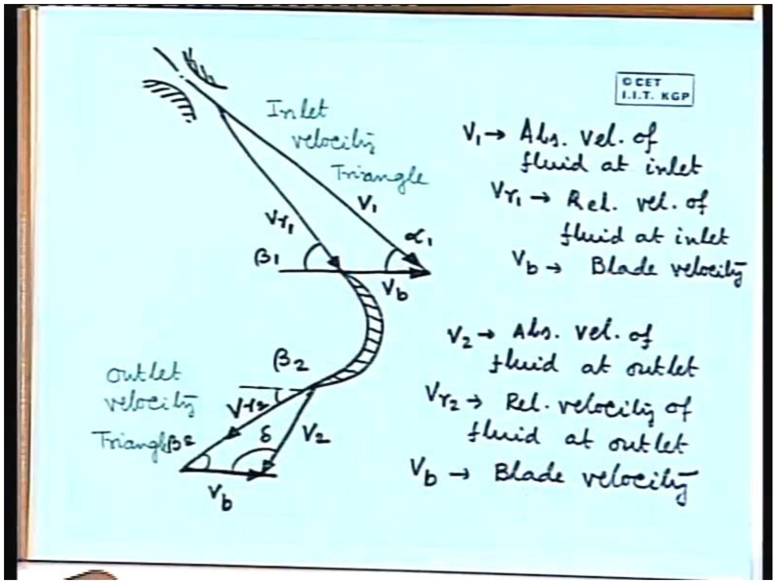

Similarly on the exit side if we see, the fluid is entering like this; it is gliding over or moving over the blade surface like this. As it is doing like this, there is a change of momentum. Either only the direction of the fluid or both the magnitude and direction of the fluid are changing, so there is a change of momentum. The fluid is coming out like this; this is your V_{r2}, relative velocity at the exit of the blade. This angle we call as beta$_2$. If this angle is beta$_2$, this angle will also be beta$_2$. This is again V_b, this is also V_b that is the blade velocity and then this velocity is V_2 that is the absolute velocity of the fluid at the exit and this angle let us denote it by delta. We can write V_2 is absolute velocity of fluid at outlet, V_{r2} is relative velocity of fluid at outlet, and V_b is blade velocity. I think one should be very much conversant with this figure because, this is the basis of our understanding and analysis of the working principle of a turbine. The arrangement is like this; let me tell it once again.

In a steam turbine, we will have alternate arrangements of steam nozzle and blades. Here, I have shown only one nozzle and one blade that too, the cross section. So, only one blade has been shown but, there will be large number of blades mounted over the drum or disc which will be connected on a shaft. Steam will pass through the nozzle. When it comes out of the nozzle, it will come out as a high velocity jet. That is what we have discussed so far. That is the sole purpose of using the nozzle and then this high velocity jet will impinge on the blade. When it is impinging on a blade it will move over the blade passage and there is change of momentum. The fluid momentum will be transmitted to the blade passage or some amount of force will be exerted on the blade passage and the blade will move. Then another blade will come and that will get then the supply of steam; again that will move and a third one will come. This continuous rotation will go on and ultimately from the blade the motion will be transmitted to the disc and shaft; from the shaft we will get the output. That is how it works and if we have to do some analysis, we have to see how the fluid velocities are changing and what are the different components of fluid velocity? Here, that is what we have drawn.

We have drawn the section of the nozzle. Through the nozzle with some velocity the fluid is coming. That is as the nozzle is fixed, the velocity with which fluid is coming out of the nozzle that is the absolute velocity of the fluid at the inlet. This is denoted by V_1 and it makes an angle alpha$_1$ to the tangential direction. This direction, if we call it the tangential direction, it makes an angle alpha$_1$ with the tangential direction or with the direction of blade motion. Though the blades move in a circular path for this small amount of time with which it is in contact with the fluid, we will assume that it is having a linear motion in the direction given by the arrow V_b. It is not having linear motion. But for the small amount of time during which the fluid jet or this steam jet is impinging on it, it is having a linear motion and the direction of motion is in the arrow direction of V_b. The absolute velocity V_1 at the inlet makes an angle alpha$_1$ with the direction of motion or with the linear direction of motion of the blade. This is also called the tangential direction.

From this diagram, we get V_{r1} is the relative velocity of the fluid. That means, with this velocity it comes inside the blade passage and moves through the blade passage. In the blade passage there could be frictional resistance. Due to that, when the fluid will come out of the blade passage it may have a different relative velocity which is V_{r2}. With V_{r2} is coming out and then in this direction, this is the motion of the blade V_b. So, V_{r2} plus V_b will give the absolute velocity of the fluid from the blade. This will be V_2. This beta$_1$ is known as the inlet blade angle and beta$_2$ is the outlet blade angle. What are the inlet blade angles and outlet blade angles? Inlet blade angle is the angle between the tangential velocity and relative velocity at the inlet of the blade. Similarly, outlet blade angle is the angle between the relative velocity and the tangential velocity at the outlet. These are beta$_1$ and beta$_2$. In most of the impulse bladings, you will have identical values of beta$_1$ and beta$_2$. Though it is not mandatory it is a common practice to have identical values of beta$_1$ and beta$_2$ for impulse turbine or impulse blading.

From these two velocity triangles, this is known as inlet velocity triangle and the other one is known as outlet velocity triangle, we can get lot of other useful information. What we do is we go for a composite diagram of this inlet and outlet velocity triangle like this. If we see these two velocity triangles, one thing is common between them that is, the V_b. So keeping V_b same we can super impose these two diagrams.

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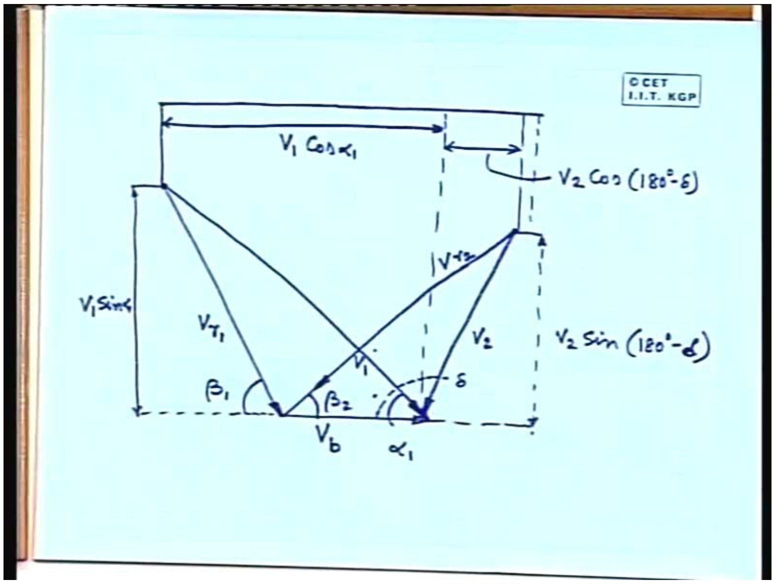

This is V_b. This is your $beta_1$, this is your V_{r1}, this is V_1, this is $alpha_1$ and this is V_b. Then, we can have the other diagram. This is V_{r2}, this is V_b and this is V_2. We have got this angle; this angle is delta, so here also we can have this angle as delta. We can have this as $beta_2$. This is the inlet blade angle and this is the outlet blade angle. Then, we can have different components of the velocities projected on both. If we project this V_1 along this line, what will it be? This is V_1 cos of $alpha_1$. This one is your V_1 cos of $alpha_1$. Similarly, this quantity will be V_2 cos of 180 degrees minus delta. This can be written as V_2 cos of 180 degrees minus delta. We can have on this plane, this is V_1 sin of $alpha_1$ and here we can have V_2 sin of 180 degree minus delta. All these quantities which I have denoted have some physical significance and they are important in the analysis of the performance of this blade. I think, we have to continue this in the next lecture and I think, we will preserve these few diagrams and will continue with this diagram in our next lecture.