Applied Thermodynamics for Marine Systems

Prof. P. K. Das

Department of Mechanical Engineering

Indian Institute of Technology, Kharagpur

Lecture - 14

Comparison of Different Staging Arrangement

Good afternoon. If we recall, we have introduced reaction turbine and then I have told that in reaction turbine there will be rows of fixed blade and moving blade one after another. That means one row of moving blade, then one row of fixed blade and then one row of moving blade like this. I had told you that in case of reaction turbine we will have pressure drop, both in the moving blade rows and in the fixed blade rows.

Earlier in case of impulse turbine, we had a pressure drop only in the nozzle which is equivalent to fixed blade, but, here we will have pressure drop both in the moving blade rows and in the fixed blade rows. That is the main difference between the reaction turbine and the impulse turbine. Then we defined some sort of degree of reaction; again I like to start from that point.

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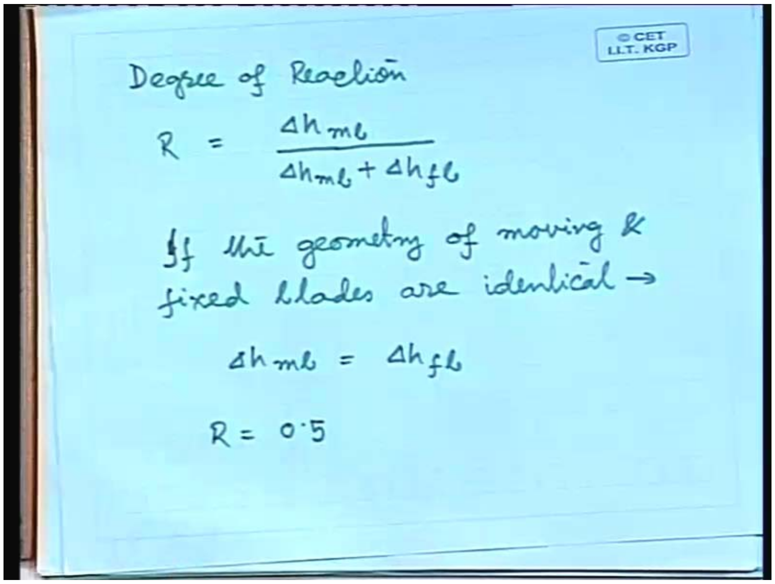

The degree of reaction is defined as R. R we will call as delta $h_{mb,}$ mb is the subscript used for moving blade divided by total enthalpy drop that comes from delta h moving blade plus delta h fixed blade. This is for a particular stage. In a stage, there will be one row of moving blade and one row of fixed blade.

Basically, it is for a particular stage that we are defining degrees of reaction. In our last class, if you remember, we have drawn a schematic diagram of these two rows of blades: row of moving blade and row of fixed blade. I have also shown how the pressure is changing from one row to another or in between a row and how the velocity is varying with different rows of blades. Then, I have told you probably that the nozzles also look like blades. We use the same type of configuration or construction for making the moving blade and making the fixed blade or making the nozzle.

Due to the ease of manufacturing, due to the ease of fabrication and inventory etc., we do not differentiate between the moving blades and the fixed blades. They are made of same geometry. If we make them of the same geometry then it is expected that the same amount of enthalpy drop will take place in the moving blade and in the fixed blade. If that is so, then we can write, if the geometry of moving and fixed blades are identical then we get delta h_{mb} is equal to delta h fixed blade fb; R is equal to 0.5 or degree of reaction is 50 %. This is a very commonly used design feature, the blades are of the same design and we have got a reaction turbine with a degree of reaction equal to 50% or 0.5.

With this, we can now have the construction of velocity triangle.

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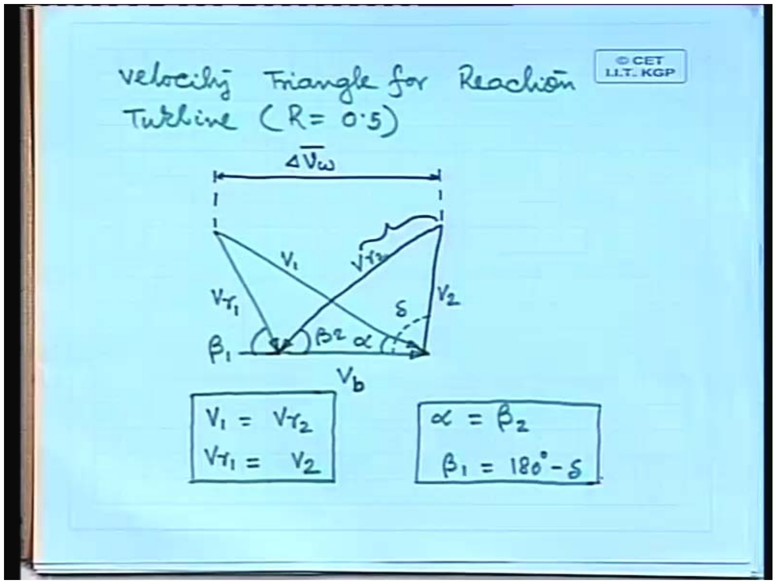

If we write the velocity triangle for reaction turbine and we can write R is equal to 0.5, then we will have the velocity triangle like this. Let us use another color for denoting, some thing like this. We can show the different direction of different velocities. This we know from our earlier knowledge is V_{r1} - that is the relative velocity at the inlet of the blade. This is V_1 absolute velocity at the inlet of the blade. This is your V_{r2} - relative velocity at the blade exit; then this is V_2 - that is absolute velocity at the blade exit. This one is V_b - that is tangential velocity of the blade due to the rotation of the turbine.

We can define different angles just like before. We have got $beta_1$, which is the blade inlet angle and here again as I have told you number of times earlier, the design is such that, the steam enters smoothly without any shock or collision into the blade. It glides into the blade. This is $beta_1$ and then this angle we call alpha, this angle is $beta_2$ and if you remember, we have defined this angle as delta.

I am not drawing the generalized velocity diagram for a reaction turbine. I am drawing the velocity diagram for a special case when R is equal to 0.5. That means there is equal enthalpy drop in the row of fixed blade and in the row of moving blade. If we do that then, we will get a very interesting relationship. We will get $V_1 = V_{r2}$ and $Vr_1 = V_2$. This is relationship we will get. We have to remember that this is a relationship which we do not get for all the reaction turbines, but this is the relationship we get for the special case when degree of reaction is 0.5. Similarly, we will get another relationship; that relationship is also equally important. That is alpha is equal to $beta_2$. This relationship we will get. Now, you can see the difference between your impulse turbine and reaction turbine.

In case of impulse turbine, I have told you that generally symmetric blades are used. What does it mean? $Beta_1$ = $beta_2$. In most of the design we will have $beta_1$ = $beta_{2;}$ but here $beta_1$ need not be equal to $beta_2$; but alpha, that will be equal to $beta_2$. The reason is quite obvious because from one row of blade the steam has to come out and it has to enter the next row of blade smoothly. That is why this type of relationship we will get. From this diagram, also we will get this type of a relationship.

Then we can get another relationship. that is $beta_1$. What is $beta_1$? $Beta_1$ we will get as 180 degrees minus delta. This relationship also we will get. See this angle and this angle, they are same. Maybe my diagram is not that good, but these two angles are the same. This angle and this angle are same. From there we will get $beta_1$ is equal to 180 degree minus delta. These are the relationships we will get for angle and the different velocity components.

Actually, some people also like to show that this v_{r2} there is some contribution from the impulse point of view and some contribution from the reaction point of view. Generally, some people want to show that this is made up of two parts and maybe this is a contribution from the reaction of the turbine. Then just like previous analysis what we can do is, we can determine what is del V_{omega}, [….] component of velocity.

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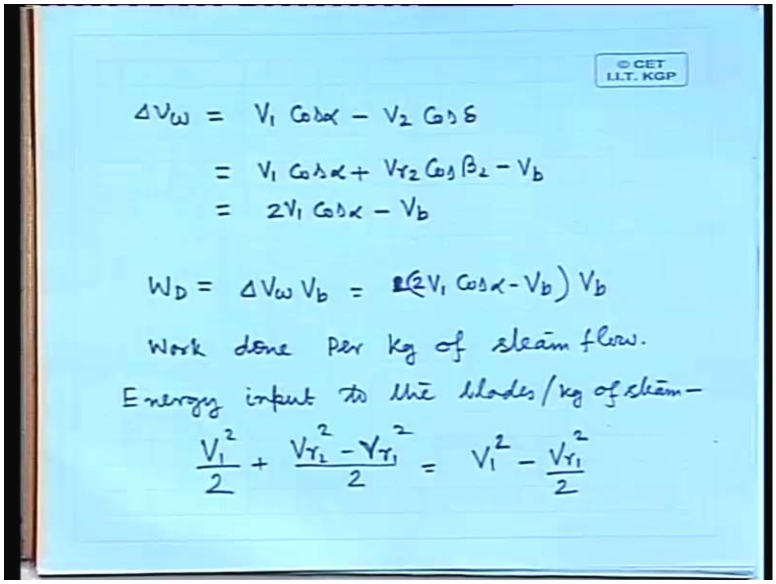

Keeping this diagram in mind, one can write, del V_{omega} that is equal to v_1 cos of alpha minus V_2 cos of delta. Just let us see what is del V_{omega}? Del V_{omega} is this quantity. Del V_{omega}, I have shown here and that is V_1 cos of alpha minus V_2 cos of delta and from there we can get basically V_1 cos of alpha plus V_{r2} cos of beta$_2$ minus $V_{b.}$ Then we can use the relationship between V_1 and V_{r2} and we can ultimately write twice V_1 cos of alpha minus V_b; this we can write.

Then work done we can write as W_D; this subscript D comes from diagram. From the diagram, we are determining all these different components of velocity, different component of force, etc. That is delta V_w into V_b that is equal to twice V_1, this 2 is inside, cos of alpha minus V_b multiplied by $V_{b.}$ Remember or please note down, that this particular expression is for unit mass flow rate of steam. If we multiply it with omega S, which we have used earlier that will give you the total amount of work done. This is work done per unit mass flow of steam. This is work done per kg of steam flow. Similarly, we can determine what the energy input to the blades per kg of steam is. We can write energy input to the blades per kg of steam.

What is this quantity? One has to be bit careful. Here, initially steam is entering the blade passage with the velocity V_1, so that kinetic energy will be there. So, per kg steam that kinetic energy will be V_1 square by 2. Then in the moving blade, there will be increase of velocity because there is expansion of steam. The blade passage is such that there is a pressure drop. So, we will have an increase of steam velocity. Which velocity increase we will get? Let us say there is no increase of steam velocity, then what happens? Whatever is the relative velocity at the entry we will have same relative velocity at the exit. Here the blade passage is such that some amount of velocity increase is there, as there is expansion. So, we will have also increase in kinetic energy while the steam flows through the blade passage. Basically, we will have v_1 square by 2, this is the same as it was in impulse blading, plus we will have V_{r2} square minus Vr_1 square divided by 2. This we will have. Now, if we remember that V_{r2} is equal to V_1 for 50% reaction. So, we can have from here V_1 square minus Vr_1 square by 2. That is the energy input to the blade.

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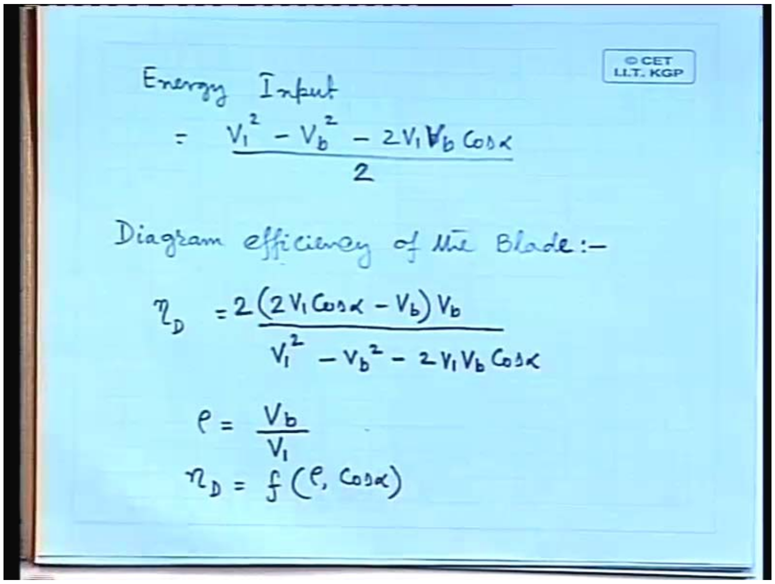

Again, if we utilize the geometry then we can get, energy input is equal to V_1 square minus V_b square minus twice V_1V_b cos of alpha divided by 2. So, if we use the geometry of the velocity triangle and the relationship which I have given for 50% reaction, if we use this, then we will get this relationship. Why we are doing this exercise is because instead of number of different velocity components, we want to express all the relationships in terms of V_1 and $V_{b.}$ V_1 is the input velocity to the blade passage and V_b is the velocity in the tangential direction. These two we want to have in all our expression. Also, we want to have one angle that is the inlet nozzle angle or nozzle angle that is alpha. That is why replacing all the other velocity components I have given the expression in terms of $V_{1,}$ $V_{b,}$ alpha etc. With this, what one can do? One can define the stage efficiency or diagram efficiency of the blades.

Diagram efficiency of the blade, it is defined just like before. That means what is the work we are deriving from the blade and the energy in terms of kinetic energy that is input to the blade. Whatever we have done, if we write that, we will have eta$_D$ that is equal to twice V_1 cos of alpha minus V_b multiplied by V_b, this divided by V_1 square minus V_b square minus twice V_1 V_b cos of alpha. I think this divided by 2. So, at the top there will be this 2 that will come here.

We have got the diagram efficiency in terms of V_1, V_b and alpha. Just like before we can introduce one particular parameter that is rho. Rho is the velocity ratio and we define it as V_b by V_1. Once we introduce that, we will get a complex expression in terms of rho and in terms of alpha. That expression one can get. That means I can write that eta$_D$ now will be a function of rho and alpha that means rho and cos of alpha. From here, one can get just like our previous exercise, the expression for rho for the maximum efficiency. That means one can do this exercise d eta$_D$ by d rho that is equal to 0 for maximum efficiency, that one can write.

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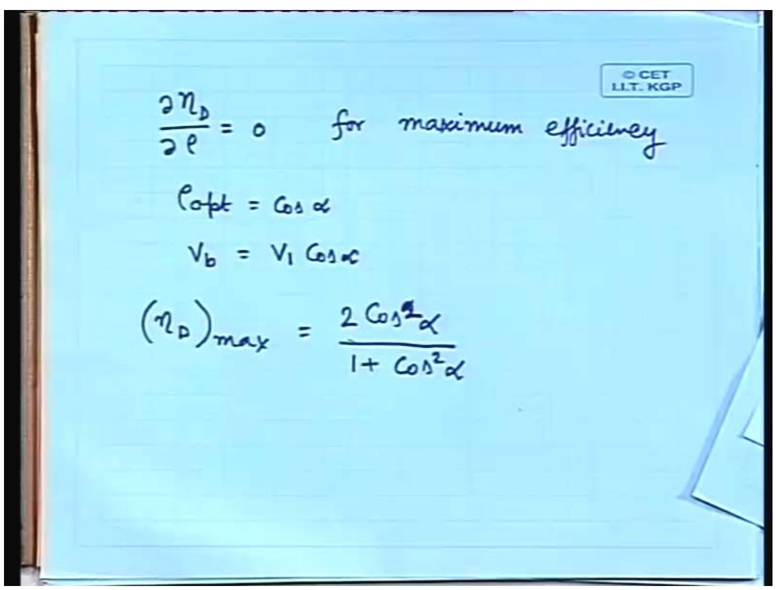

Then this will give you rho optimal is equal to cos of alpha. This is the value of optimum velocity ratio, we will get. Then V_b is equal to V_1 cos of alpha; not for all the cases, for 50% reaction turbine and when we are looking for maximum efficiency.

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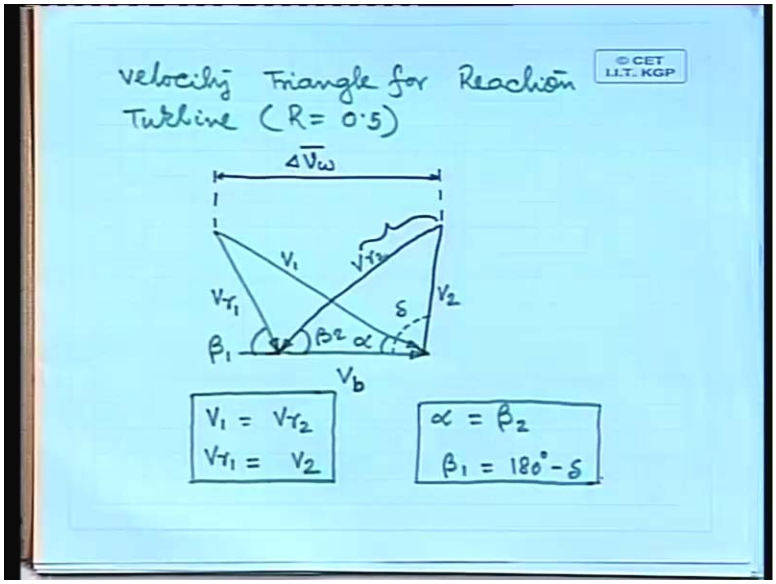

V_b will be V_1 cos of alpha. Does it give you some sort of hints as to what will be the shape of the velocity triangle? Then V_1 cos alpha means this Vr_1 has to be at 90 degree with V_b.

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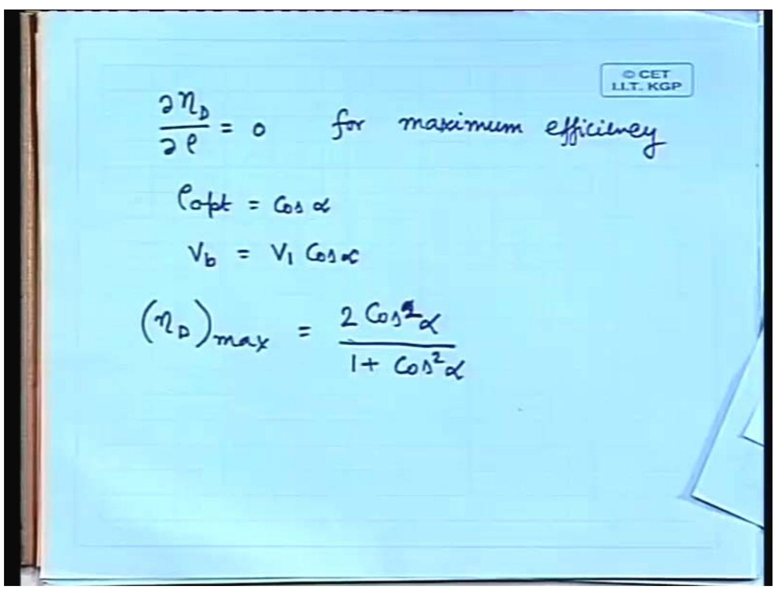

We will have eta$_D$, diagram efficiency maximum is equal to twice cos square alpha divided by 1 plus cos square alpha. This will be the efficiency of a particular stage, for the 50% reaction turbine and when our efficiency is maximum this is the maximum value of efficiency that one can get. If we draw the diagram, we will get something like this.

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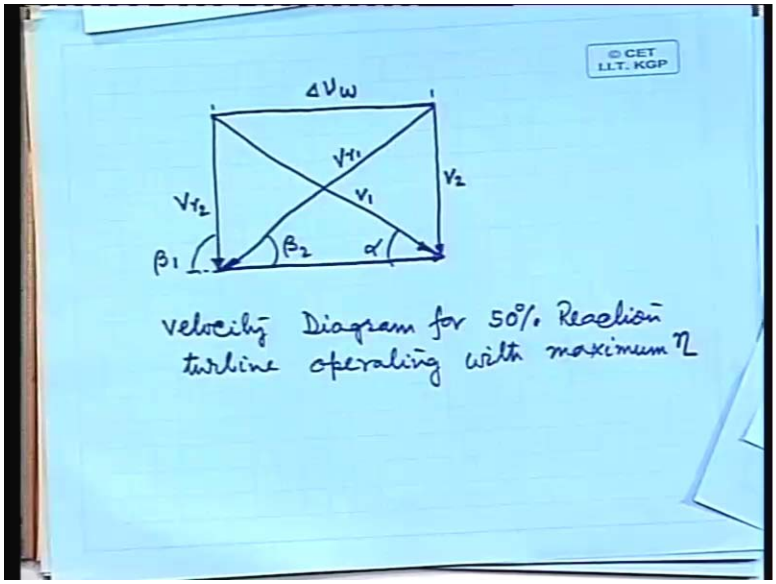

This angle is your beta, what it is? Beta$_2$ and this angle is alpha, this is V_{r2}, this is V_1, this is Vr_1, this is V_2 and this angle will be your beta$_1$. This quantity is nothing but delta V_w ….. component of velocity. This is what we will get in case of velocity diagram for 50% reaction turbine and operating with maximum efficiency. This will be the representation of the velocity diagram. Now, we will have equal enthalpy drop in all the stages. That is why the design of a reaction turbine is guided by this particular principle - if it is 50% reaction turbine and most of the cases it is 50% reaction turbine; we can decide upon the number of stages by fixing what the enthalpy drop in a particular stage will be. That we can decide upon and then accordingly we apportion the amount of enthalpy drop for each of the stages.

We do not differentiate between the nozzle and blade, we have got rows of blades, alternate rows of blades; we call them rows of moving blades and rows of fixed blades. Some other name also is given - because the moving blades are mounted over the rotor, they are called rotor blades and the fixed blade they are mounted on the casing, so they are sometimes called stator blades. We will have alternate rows of rotor blades and stator blades. In each of the blade row there will be delta h amount of enthalpy drop. I think we can have some sort of a comparison when we have made these studies of impulse turbine and reaction turbine. If we do some analysis, we have seen basically three types of arrangement and this is the basic arrangement for any turbine.

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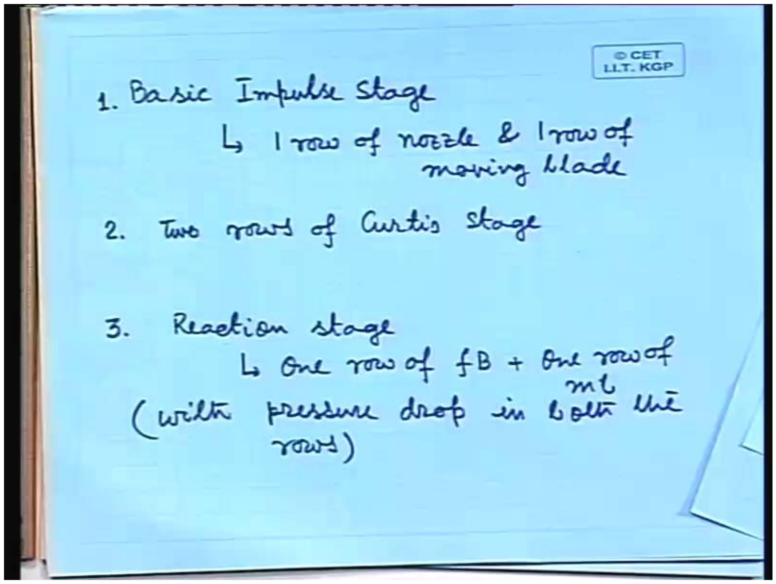

In one arrangement, let me call it basic impulse stage. What is a basic impulse stage? Basic impulse stage is like this; we have got 1 row of nozzle and 1 row of moving blade. One can call this basic impulse stage also as a pressure stage. It means that if we repeat this time and again then, we will have pressure compounding or Rateau compounding of the impulse turbine. One row of nozzle - there pressure drop will take place, velocity will increase, then it will go to the moving impulse blading and there will be decrease in velocity.

Again, it will go to one row of nozzle and its pressure will decrease, velocity will increase. This can be called as basic impulse stage or one can look this stage as a Rateau stage. This is 1, then one can have two rows of Curtis stage. Here you will have one row of fixed blade, one row of moving blade, one row of fixed blade, one row of moving blade like this. This is another arrangement.

Then third you can have that a reaction stage, that means, one row of fixed blade plus one row of moving blade, within bracket let me write, with pressure drop in both the rows. These are the three basic arrangements that one can get.

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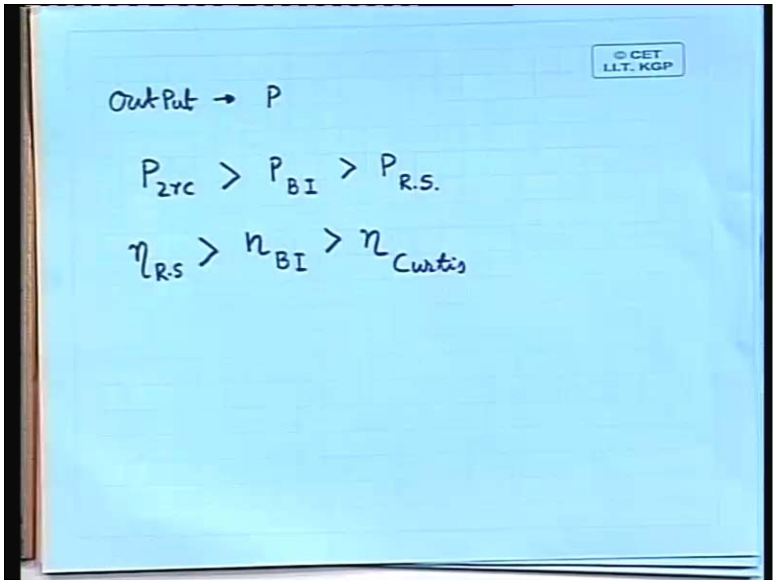

Now, if we make a comparison then we will see that output, the output we call it P. Let us denote output by P. We will have P_2 row of Curtis stage that will be greater than P basic impulse stage and that will be greater than P that is reaction stage. If we see the output for similar conditions then we will have the largest output in a Curtis stage; we will have some intermediate output in the basic impulse stage and then we will have the lowest or the minimum output in the reaction stage. Whereas if we consider the efficiency, let us have a comparison of efficiency.

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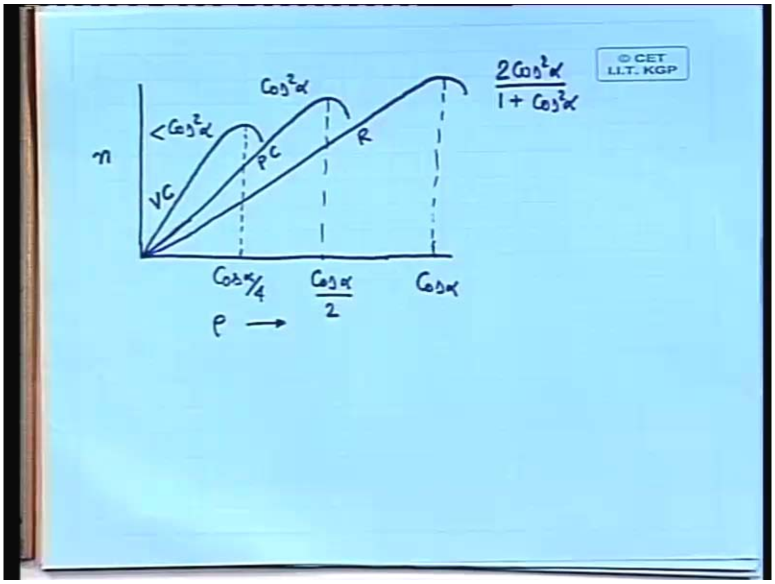

Now, if we have efficiency in this direction, can you tell me what is the maximum efficiency we have got? Let us say this is rho, in this direction we have rho. In the basic impulse stage what is the maximum efficiency we have got? Can you tell me? That was less than cos square alpha. This efficiency was less than cos square alpha. We have got two stages of Curtis. The value of rho was cos alpha by 4. Then if you have considered the basic impulse stage or the Rateau stage, efficiency was cos square alpha and this was cos of alpha divided by 2. This we have derived earlier. Just now, we have derived for reaction stage. For reaction stage, what did we derive? Rho was cos of alpha and the efficiency was 2 cos square alpha by 1 plus cos square alpha. This will be higher compared to the previous values because cos alpha has got a value lower than 1. It has a value less than 1.

This is the efficiency curve for different arrangement of steam turbine. Let me write, this is VC - velocity compounding, this is PC - pressure compounding and this is R - reaction turbine. Let us go back to our earlier diagram or earlier discussion.

If we see, if we compare output then we have got P_{2rc} means two stages of Curtis it was better, output wise it is more than 1 basic impulse stage and again the basic impulse stage is better than the reaction stage. What does it mean?

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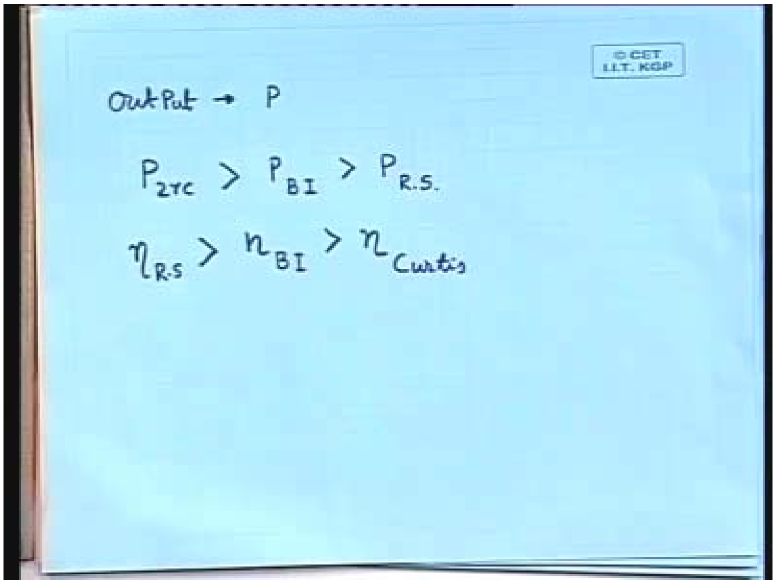

With two stages of Curtis whatever output we can get we need much more stages of reaction turbine if we have to get same output. What does it mean? More rows of blade will be there if we go for only reaction stage, whereas with less number of blades we can have same output if we have got velocity compounding in the impulse turbine. Similarly, we can write the other information just now we have got. That is reaction stage, that will be greater than efficiency of basic impulse turbine or pressure stage that will be greater than the efficiency of velocity compounding or Curtis stage. You see that these two information are opposite to each other. That is why in a steam turbine design, particularly if it is a large steam turbine, then we should have combination of all the three stages to have the maximum benefit out of the supplied steam. It is like this. To start with, we will have Curtis stage or velocity compounding, then we can have this pressure compounding and then for the last stages we can have the reaction stage. That is what is done in case of steam turbine. That is how the different stages are allocated in a particular turbine.

This almost brings us to the end of our discussion. We do not have much time to discuss other aspects of steam turbine. I have given the basic outline, how does it work and mathematical equations etc. But what I like to discuss more is that there are certain losses, which I like to discuss. What are the different types of losses which will occur in a steam turbine?

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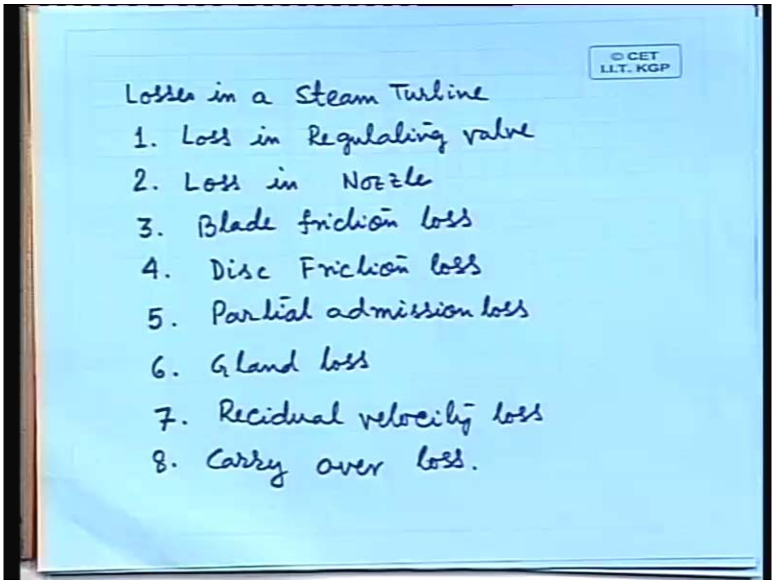

Different losses which we will come across in a steam turbine are like this: loss in the regulating valve, then we will have loss in the nozzle, I will explain; blade friction loss, disc friction loss, partial admission loss, gland loss, residual velocity loss and carry over loss. Let us discuss the different losses, one by one.

Loss in the regulating valve, that is, from the boiler the steam will be supplied to the turbine and there will be some sort of a regulating valve. We know regulating valve or any valve for that matter is a throttling device. In the throttling device, we will have loss in pressure; there will be a pressure drop. While pressure drop is taking place the steam has to flow through a narrow passage and that is why there will be certain amount of loss.

Loss in the nozzle; though nozzle is a small component, its length is not large, it is not a very long passage but even then the steam has to pass and when the steam is coming out of the nozzle then it will have sufficient amount of velocity. One thing, when it is passing through the passage of the nozzle there will be frictional loss and there could be certain amount of heat loss also.

Blade frictional loss - this is also the same type of thing. That means when the steam is passing through the blade passage then there will be friction and we will have certain amount of loss in energy.

Disc friction loss - the turbine, we have seen that we have to maintain certain ratio between V_1 and V_b. We have seen, for the optimum operation of the turbine, we have to maintain certain ratio between V_b and V_1 that is inlet velocity and the tangential velocity. What is the tangential velocity? The tangential velocity is again a function of RPM and diameter. Diameter is the mean diameter of the blade. The blade cannot be made very long; they are mounted over some disc or drum. So, that is also rotating in a passage which is built up with steam. There will be some amount of churning action and we will have certain amount of loss.

Then comes the partial admission loss. This we have to understand and we have to visualize the phenomenon inside the steam turbine. It is like this: the blades are mounted over the periphery of the rotor drum or disk; there are large of number of blades, small blades and they are uniformly located over the rotor drum or disk. This steam should enter and approach all the blades. There are nozzles or slots. Now generally these nozzles and slots they are not throughout the periphery, just before the entrance to the blade. There are slots, part of the periphery and part of the peripheral passage is blocked. Due to that, you will have steam flow through the slotted portion only and where there is no slot there will not be any steam flow. This induces a certain amount of loss and this is known as partial admission loss.

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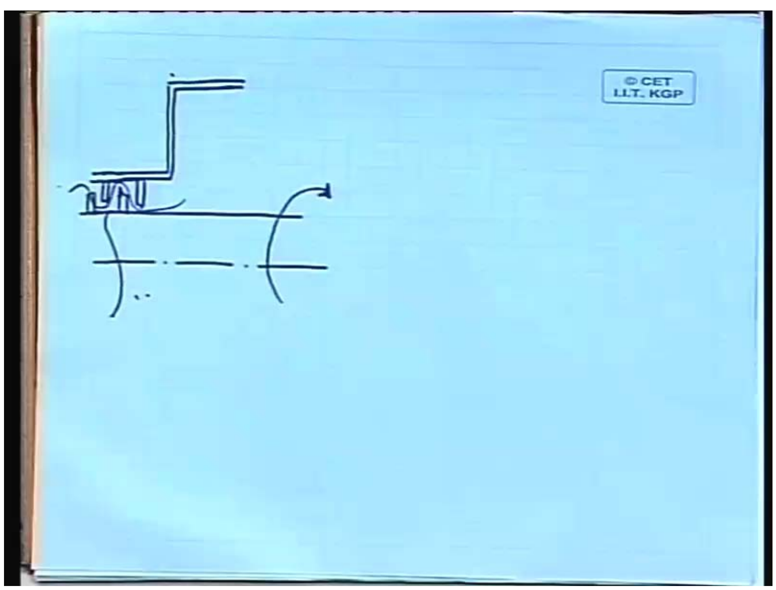

Then, gland loss. Actually, if we see, there is a casing. Let us say this is the casing. I am drawing a very rough sketch and very schematic representation. This is the casing and this is the shaft; this is the shaft on which turbine blades are mounted. This is a rotating component. These blades are mounted on this and this is a rotating component and this is a fixed component. This cannot be securely fixed on the moving element. There should be some sort of a gap between these two, but the gaps should not be such that it allows lot of steam leakage. That is why there are glands.

There are different designs of glands. One can go for details of it but it can be something like this. That means there are elements like, a number of elements like this, let us project it. That means if this steam, this is the inside of the turbine, here this steam is at a high pressure and this is the outside where the pressure is almost atmospheric pressure. Between this point to this point there is a pressure difference but if the steam has to flow then it has to flow through this zigzag passage and as there is a large pressure drop, the leakage will be minimized due to this particular design. This is known as gland or glands ceiling; there are other type of designs also. Whatever we may do for the design, there will be certain amount of pressure drop due to this gland leakage and that loss will be there. That is the gland loss.

Then we will have residual velocity loss. What is that? We know at the last stage the steam is coming out with some velocity; it cannot come out with zero velocity. It has to come with some amount of velocity. If it is coming out with some amount of velocity, it is carrying certain amount of kinetic energy and that we cannot recover. That is the residual velocity loss. Then we have got carry over loss. That means steam has to go from one stage to another stage and during that time there will be certain amount of loss and that is known as the carry over loss.

These are the different type of losses which we will have in a steam turbine. That is why what is done, in between what we can do is that we can have different stages of steam turbine and in between the stages, we can have different stages of reheat also. Maximum two reheats are used. There are some losses; to take care of these losses, the steam will be taken back to the boiler itself and it will be again heated, the pressure will be low but the temperature will be high enough so that it has got higher enthalpy and then it will be passed to the later stages of turbine where those are also known as LP stages, low pressure stages, where again expansion of high enthalpy steam will take place. That is all what we like to say about steam turbine.

I think we will start now this steam generator. As some time is there let us make a small start regarding steam generator.

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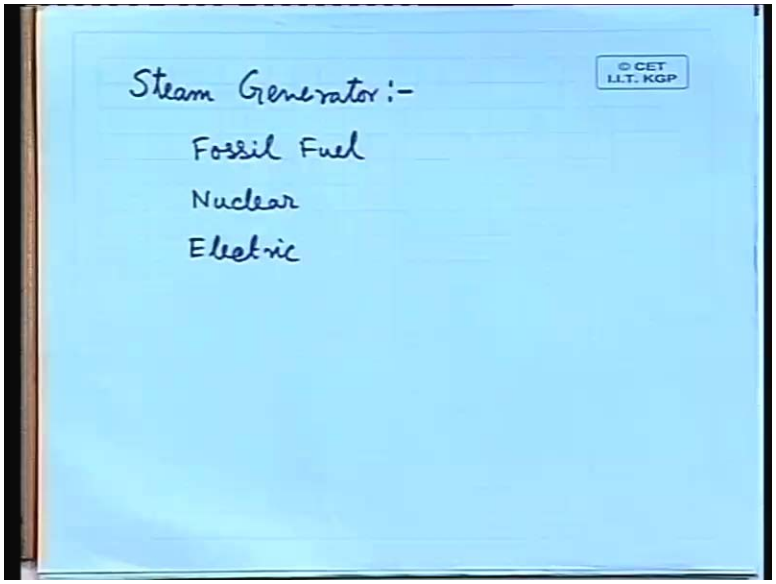

As you people are from a particular field of trade, we do not have to discuss very elaborately regarding steam generator. Our discussion will be based on marine type of boiler, but before that let me today give little bit of introduction to steam generator.

A steam generator is the device where utilizing thermal energy we generate steam for our further use safely, effectively, and economically, so that we can get the steam at required pressure and temperature. These are important: economy is important, safety is important and in certain application the compactness of the steam generator that is also important. Compactness means both, compactness in terms of volume and in terms of weight. Particularly for moving systems, weight is a consideration and also volume is a consideration. The thermal energy what is used for generating steam from liquid water that can be obtained from different sources. It can be obtained from different types of fossil fuel like coal, oil, etc., and that can be obtained even from nuclear source. For some industrial use where steam is directly used that means it is not used for power production, but it is used for some sort of process requirement, one can use electrical energy also to produce steam.

That is how one can have a classification of steam generator or boiler depending on the source of energy which is used for the generation of steam. That means you can have fossil fuel, you can have nuclear, you can have electric. Among fossil fuel, again, you can have coal, you can have oil, or you can have mixture of fuel; two different types of fuel that can be burnt to have the steam generator.

Again, there are boilers even in marine systems, these types of boilers are there where ….. is used for generation of steam. Those are known as OST boilers or recovery boilers. Depending on the type of arrangement of the tubes, we can have fire tube boilers and water tube boilers. There are other classifications which I will take in our next class.

Thank you.