Applied Thermodynamics for Marine Systems

Prof. P. K. Das

Department of Mechanical Engineering

Indian Institute of Technology, Kharagpur

Lecture – 13

Reaction Turbine Compounding

Today we will continue with our earlier discussion on steam turbines. We were discussing impulse steam turbines and I told you that the basic impulse turbine contains two components. One, there will be a row of nozzles and followed by this row of nozzles will be row of blades.

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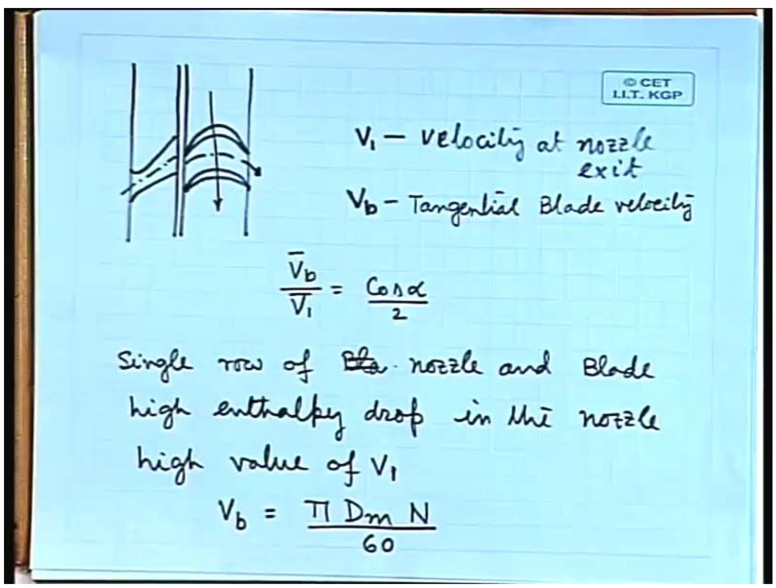

The row of nozzles is a stationary component. This is one nozzle, let us say. Steam will be passing through this nozzle and then it will be directed to the row of blades which are moving blades and the steam will pass ultimately through this moving blade passage where it will impart motion to the blades so that blade movement is possible. We have seen what could be the thrust, what could be the work done and what the efficiency is. We have done all this from the geometry of the blade and knowing the velocity at the exit of the nozzle. Here, you see, we get two very important velocities. One is V_1, that is, the velocity at the nozzle exit; another is V_b, which is the tangential blade velocity. We have derived that there is a relationship between V_1 and V_b for maximum efficiency of the turbine and we have got V_b by V_1 that is equal to cos of alpha by 2. If this is the direction of V_b, then the nozzle makes an angle alpha with the direction of V_b. That is what we have got.

Let us say that we have designed the turbine so that there is one row of nozzles and one row of bladings like this. What are we getting? I said that there will not be any pressure drop in the blade passage if it is an impulse turbine. The entire pressure drop is taking place in the nozzle itself. What does it mean? It means that if we have got a steam power plant, I will ask you to recall the diagram of this steam power plant or the arrangement of this steam power plant, we can see that there is enthalpy drop in the turbine. So, the entire enthalpy drop of the turbine is taking place in the nozzle itself. That means, the steam is being supplied at super heated condition at high pressure to the turbine inlet and it goes out of the turbine at the condenser pressure. The enthalpy corresponding to the boiler pressure and enthalpy corresponding to the condenser pressure, the entire amount of enthalpy drop is taking place in the nozzle. Then, we will get a very high value of V_1.

Let me write it, single row of nozzle and blade. After the high enthalpy drop in the nozzle, then we will get high value of V_1. This is what we are getting. Again, I have told you that there is some sort of a limitation. Arbitrarily, we cannot take the value of cos alpha; there is a certain value fixed for it. We can see that the significance of that is if we have got large value of V_1 we have to go for a large value of V_b. What is V_b? We can write V_b is equal to pi D_m into N by 60, where D_m is the mean diameter. Why mean diameter? Because the blade will have some height, we will not take the root diameter of the blade, we will not take the tip diameter of the blade; but the mean diameter at the midpoint of the blade, if we take then we will get D_m. So this is the mean diameter of the blade, N is the RPM.

If we have a very large value of V_b, either we have to go for a large value of Dm or we have to go for a large value of RPM. Both of these have got practical limitations. We cannot arbitrarily increase D_m or N. That is why we can see that if the total enthalpy drop takes place in one nozzle, then there will be a very large value of V_1 and if there is one stage of or one row of moving blades, then the ratio between V_1 and V_b becomes impracticably high. That is why we have to go for some sort of an arrangement where either we will have a lower value of V_1 or we can do something so that V_1 V_b ratio can be lowered. That is what is done in impulse turbine by staging of turbine. We can have multistaging of the turbine. Now, we are going for multistaging of turbine or in other words, it is known as compounding of turbine.

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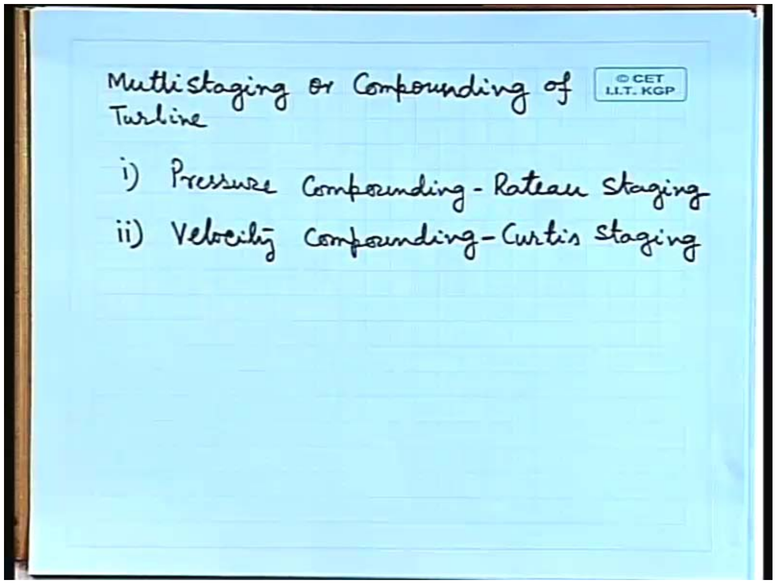

In case of impulse turbine, if it is a pure impulse turbine, then we have two options for multistaging or compounding. One, we can go for pressure compounding; after the name of the inventor this is called Rateau staging. Or we can go for velocity compounding. Again, after the name of the inventor, this is called Curtis staging. Either we can go for pressure compounding or we can go for velocity compounding. Let me explain what pressure compounding is and what velocity compounding is.

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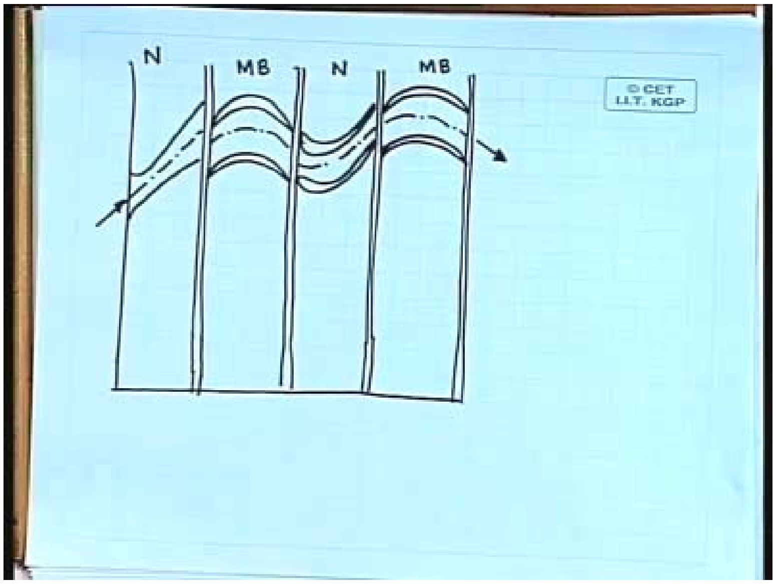

In pressure compounding we will have pressure drop at different stages. Let me draw it and then I will explain how it is done. Basically we need to have, initially one nozzle. Through this nozzle steam will flow and there will be pressure drop in this nozzle. Then, there will be impulse blading and we will have a change of direction of the velocity so that the impulse will be imparted on the blade and the blade can move. After this blade passage there will be another row of nozzle. This one which I am drawing now is one row of nozzle. This is the nozzle and this we can call as moving blade; this is again the nozzle. Why am I writing the moving blade? Because this also looks something like a blade but these are fixed, they are working as nozzles; they are fixed. Then again, we will have another row of impulse blading. This will be the arrangement for your pressure compounding. Steam is entering here and steam is coming out of here.

I have shown one row of moving blade, one intermediate row of nozzle, another row of moving blades, but it is not necessary that there should be only two rows of moving blade. There could be more rows of moving blade if necessary; if the design is such, we can have more rows of moving blades. What we can see is that there will be a pressure drop initially. In this moving blade there will not be any pressure drop as it is impulse staging. Again, there will be a pressure drop and here there will not be any pressure drop. The picture will be clear if we draw how the pressure and velocity varies along all these elements of the turbine stage.

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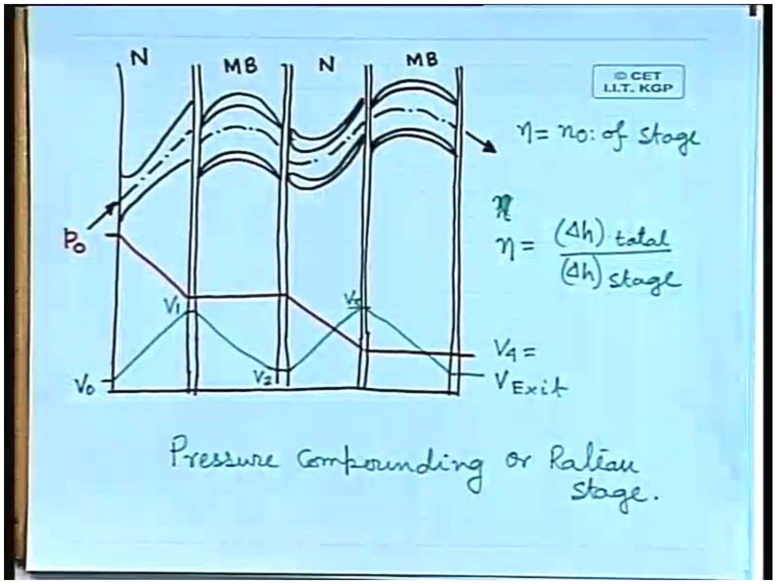

Let us use another colour. So, we will have steam entering at a high pressure. Let us say we call it p_0. Then, there will be pressure drop; here, there is no pressure drop. Again, there will be pressure drop. In the moving blade row, there will not be any pressure drop. What about velocity? For velocity, we can have steam is entering with a very small velocity. As there is decrease in pressure in the nozzle there will be an increase in velocity. Through the moving row of blade there will be a decrease of velocity and here there is a pressure drop so there will be increase of velocity. Again, there will be decrease of velocity like this. So this is our V_0 and this is V_{exit}. We can call this as absolute velocity V_1, then V_2 and then here, we can call V_3 and this is V_{exit}; V_4 is equal to V_{exit}. This is what we will get in case of pressure compounding of impulse turbine. So, let me write, this is pressure compounding or Rateau stage.

In general, what we do is that the turbines are designed in such a way so that in every nozzle there is almost equal amount of enthalpy drop. In general it is designed that way. If n is the number of stages, then one can write delta h total, the total enthalpy drop through the turbine, divided by delta h stage. The number of stages can be obtained from here. n is the number of stages because in the impulse turbine inside the blade or in the blade passage there will not be any drop in enthalpy. The enthalpy drop will be there only in the nozzle. One can do the analysis, accordingly and now we can see or calculate what the stage efficiency will be. Before, I have done for a particular stage taking only one nozzle and one blade. Here, one can do the same analysis for a particular stage. The only thing is that there are a number of stages so that analysis has to be done as many times as the number of stages and we can get the total amount of thrust, total amount of work done and the total efficiency of the turbine. One can calculate the stage efficiency. One can calculate also the total efficiency if required. That is what we can do here.

We go for the next arrangement of compounding that is called velocity compounding.

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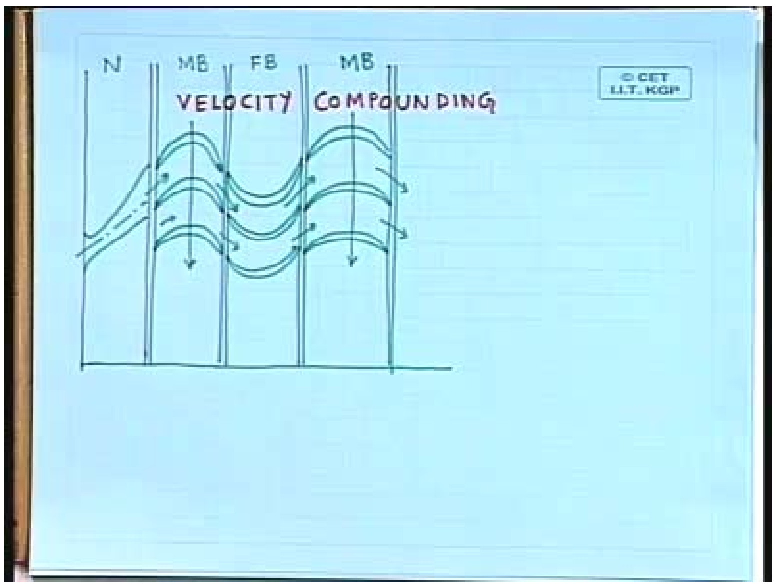

Velocity compounding is like this. Here also, we will have one nozzle to start with. Let us draw one nozzle; then, there will be a blade. Instead of the second row of nozzle that we had in the earlier arrangement we have got another row of blade here. Let us put the name. This is the nozzle; we can call this as moving blade, this we call fixed blade. So we have got initially one nozzle where there will be pressure drop and then we can have row of moving blade. After the row of moving blades we have got another row of blades, which are fixed and look similar to the moving blades, but these are fixed. This row is a row of fixed blades and then after this row of fixed blades, we will have another row of moving blades. We can write, again, this is another row of moving blade. Basically steam is going like this, coming back and then is moving like this and this one. We can show this as a row of moving blades. This is another row of moving blades. So this is how we can represent the velocity compounding of the impulse turbine.

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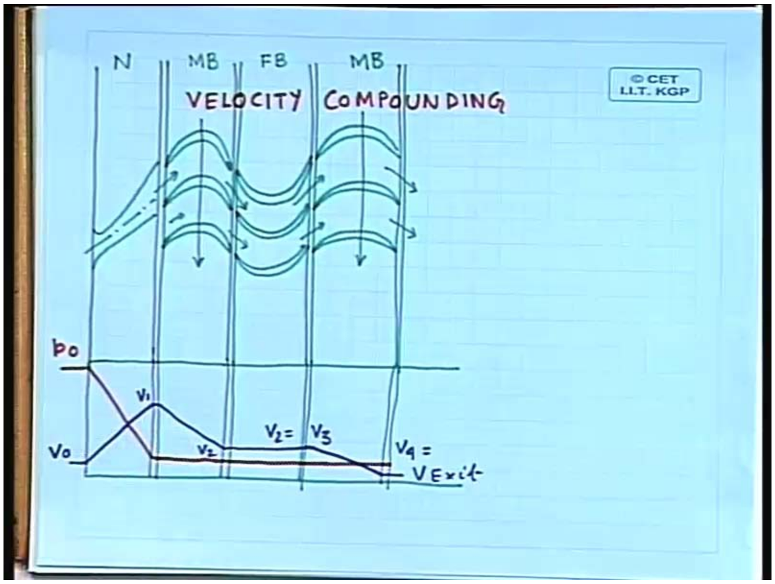

Now, let us draw how the pressure and velocity changes. Here, let us note down the difference with the previous stage or previous method of compounding. We will have a pressure drop only in the fixed nozzle which is at the beginning of the turbine. Let us say this is the value of p_0 and pressure drop will take place here only. After that, throughout these stages the pressure will remain constant. You can compare the diagram which we have drawn for the previous compounding. What about velocity? Velocity will increase in the nozzle. Let us say steam is entering with a very low velocity and then there is an increase in velocity. There will be a decrease in velocity when it is passing through the moving blades. Then, when it is passing through the fixed blade there will not be any change in velocity. The fixed blades are only changing the direction of the steam flow but there is no change of the velocity. If the blade passage width remains constant then, there is negligible frictional drop. These are only passages through which a fluid is flowing; so, there will not be any change in velocity. We are showing here that there will not be any change in velocity through the fixed blade. It is only deflecting the steam, so that again it can smoothly enter the row of the moving blade in the next stage.

Again there will be decrease in velocity as it is passing through the moving blades, so this is your V_{exit}. What we can write here? Let us say this is V_1, this will be V_2.V_2 will remain as it is; so, we can write V_2 is equal to V_3 and then V_4 that is equal to V_{exit}. We can have this type of a diagram in case of velocity compounding or Curtis compounding. What we can see is that we will have a particular velocity diagram or compound velocity diagram what we have drawn earlier for the first stage; similarly, we can have another velocity diagram for the second stage, a third velocity diagram for the third stage and so on. For each and every stage, we will have different velocity diagrams because the magnitude of the velocity is changing throughout these stages. Only one particular velocity that remains constant is the blade velocity component or tangential velocity component pv; that remains constant in each and every stage. Other components of velocity or other velocities will change from stage to stage.

We are considering a two stage compounding and two stage velocity compounding. What will we have?

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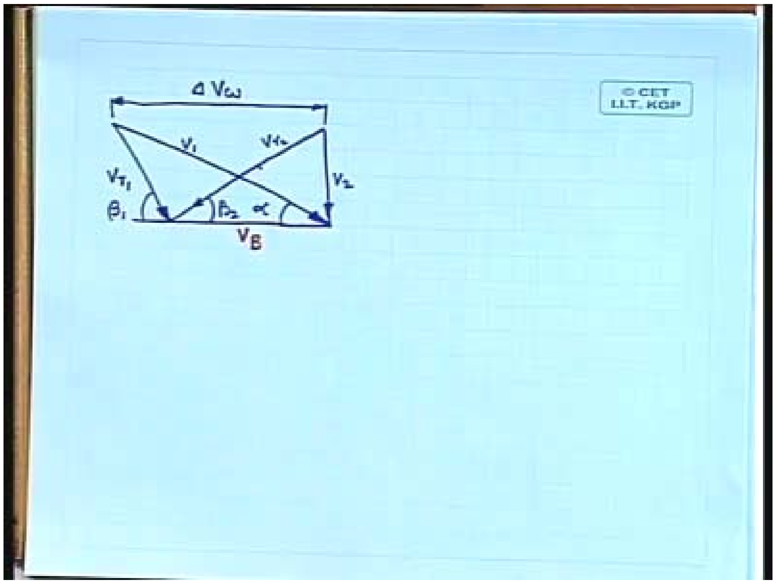

We will have two velocity diagrams. Let us say this is the diagram for the first stage. We got this one as V_{r1}, this as V_1 and this angle as beta$_1$- blade inlet angle for the first stage and this angle alpha is the angle of the stationary nozzle at the beginning of all the stages or at the entry of the turbine. Then we will have something like this. This is your V_{r2} and this is your V_2. This angle is beta$_2$. This we have denoted as gamma or delta; probably, we can have denoted it as delta. What is important is this quantity. This quantity is the component of ….. velocity. We have denoted it as delta V_w. Similarly, we can have the velocity diagram for the second stage. Let me write what will remain constant. This is actually important; this is your V_B, blade velocity.

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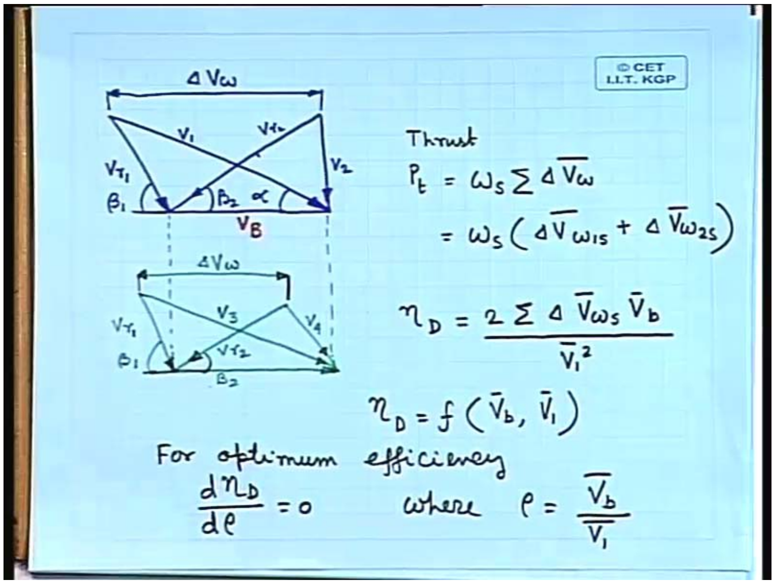

What will remain constant is the blade velocity. Here, again, we will have this diagram which will be something like this. Let me write down the names; let us use different colours for different stages; V_{r1} is the relative velocity at the blade inlet for stage I and this green colour is for stage II. So, I am writing this as V_{r1} itself but this green colour shows stage II and again this will be V. This we have denoted with a different velocity, we called it V_3. Let us say this is V_3 and this will be V_{r2}. We have to remember that this is the relative velocity at the exit of the second stage of blade and then this will be V_4. Again we will have $beta_1$ here. These two $beta_1$'s need not be the same. It depends on the design and then this angle is $beta_2$; they may or may not be the same; should not confuse that these two are identical. Actually alpha we denote for the nozzle angle.

Generally, if we see the diagram (Refer Slide Time 33:12), in case of impulse turbine we use symmetric blades. If these blades are symmetric, then these blades are to be also made symmetric. Maybe, if we take up some problem, then the numerical values of these components will be clear.

Again, this is called delta V_w or omega, the ….. component of velocity. Similarly, we can have the velocity diagram for the third stage. What will be the thrust? The thrust P_t, we can write is equal to $omega_s$. We know this is the steam flow rate then summation of all the ….. component of velocity. This one and this one (Refer Slide Time: 34:42) are the …. component of velocity. For two stage we can write it is like this; for this particular diagram we can write, this is delta $V_{omega1s}$, first stage that is why I am writing 1s, plus delta $V_{omega2s}$, the second stage. This is only for this diagram.

What will be the efficiency of the turbine, total efficiency? We can determine the stage efficiency. The diagram efficiency considering all these diagrams will be 2 into sigma delta V_{omegas}, or omega stage we can write, all these stages are to be considered; multiplied by V_b blade velocity. What is the energy supplied? That is, the kinetic energy at the entry. So, this is V_1 square. This is half V_1 square; that 2 has gone up. For the two stages, I am taking care by this summation sign; as many as possible. This will be the efficiency of the total turbine. Again what we can do is, I can express it using the velocity triangles and then I can keep only two variables. That means eta_D can be expressed as a function of V_b and V_1. That is what I can do. Just as I have done earlier in this case also, we can do this particular exercise. If we do that, then for optimum efficiency, we can write $deta_D$ by drho is equal to 0, where rho is equal to V_b by V_1. Again we can do this exercise.

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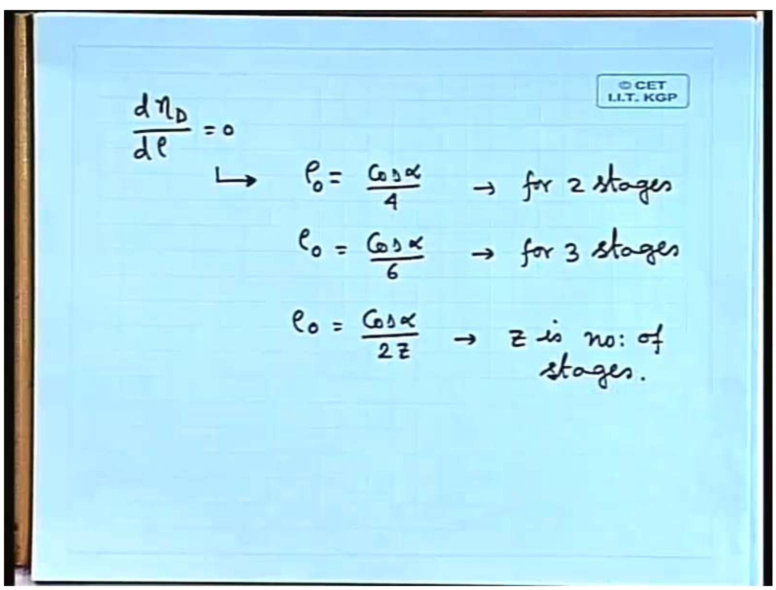

What we have got is $deta_D$ by drho is equal to 0. That will give rho is equal to or $rho_{optimum}$ is equal to cos alpha by 4 for two stages; $rho_{optimum}$ is equal to cos alpha by 6 for 3 stages; the 2 and then the number of stage will come. Then $\rho_{optimum}$ is equal to cos of alpha by 2z, where z is the number of stages. At the beginning, when I started discussing the compounding of turbines, I have told you one thing that somehow we have to decrease the ratio of V_b by V_1. That is what we have to do or we have to decrease V_1. If we have taken number of nozzles, then initially we can start with a small V_1. That is what we have done in pressure compounding. We will not consume the entire enthalpy available for this steam in a single nozzle and we will not have a very large V_1. We can have a smaller value of V_1 to start with. In between, we can have a number of nozzles and accordingly we can again have different velocities at the beginning of different stages. That is what we can do. Another thing we can do is that at the beginning itself we will have a large velocity as we have done in case of velocity compounding.

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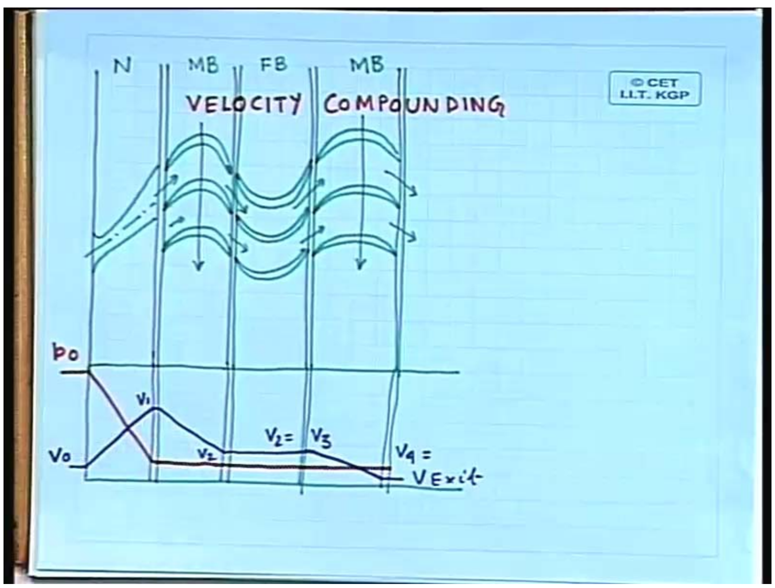

The decrease in velocity in a particular stage will not be very large. It will be at different steps. Here some decrease in velocity is there or decrease in kinetic energy is there which is getting converted into the useful work. Again, some amount of decrease in kinetic energy is there in another stage and it is getting converted into useful work or mechanical work; like that we can do. In practice, both velocity compounding and pressure compounding are used. That means not that we will use only velocity compounding or only pressure compounding, in practice there is a mixture of both, unless the turbine is a very small turbine. In certain cases, it can be like this demonstration turbine or something like that. But, otherwise if it is a turbine for power generation plant where the generated power is used for the downstream, for running something or for the generation of electricity, there we will have both pressure compounding and velocity compounding. So a combination of these two will be there.

Now after this, we can go for reaction turbine. I think we will start reaction turbine also today. Let us see what is reaction turbine? The difference between the impulse turbine and reaction turbine lies in the fact that, in the impulse turbine through the passage of the moving blade there will not be any change in pressure. But, in case of a reaction turbine, what will we get is that when the steam is passing through the moving blade passage there will be also expansion of steam or pressure drop of steam. In the reaction turbine or through the reaction blading, whenever there is flow of steam it is creating useful work by two different mechanisms. One is there is a change of direction of motion; another is, there is expansion of steam. As there is expansion of steam, pressure is decreasing; so, there will be increase in kinetic energy or increase in velocity. The second effect is called the reaction effect. Due to the combination of these two effects, we will have the motive power of the turbine.

Let me first draw the figure. Then certain things regarding the working principle will be clear.

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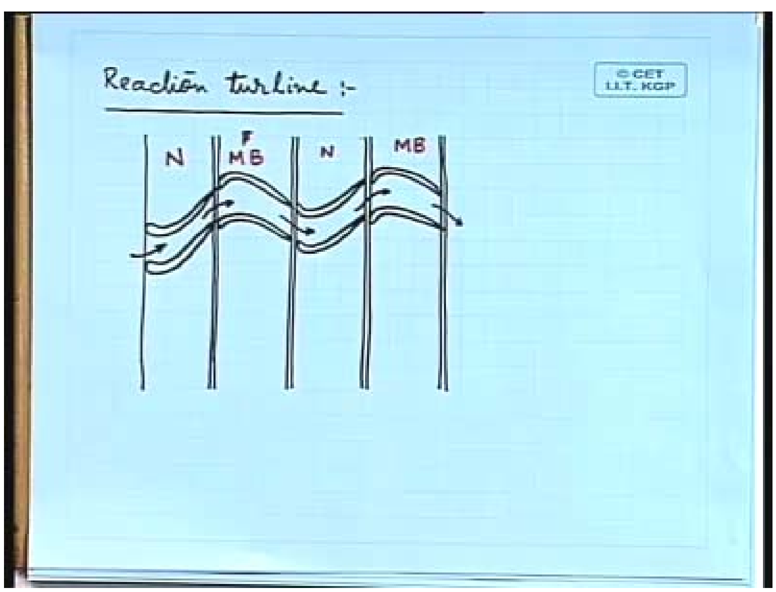

Here, again, we will have different components in series. First, we have to start with some sort of a nozzle and let us say the nozzles are like this. Then, there will be blades and they look like this.

There will be another row of nozzle; when I am calling nozzle, they are fixed and there will be a row of moving blade. The steam path will be something like this. Let me write; this is nozzle, this is moving blade, then again nozzle and this is moving blade. The nozzles and moving blade, there may be some small difference but we will come to those things afterwards. They look almost similar. That is why, sometimes these are called fixed blades but basically they serve the purpose of the nozzle. If you compare it with any of the earlier diagram, here also we have got a moving blade, a fixed blade, a moving blade and fixed blade like this.

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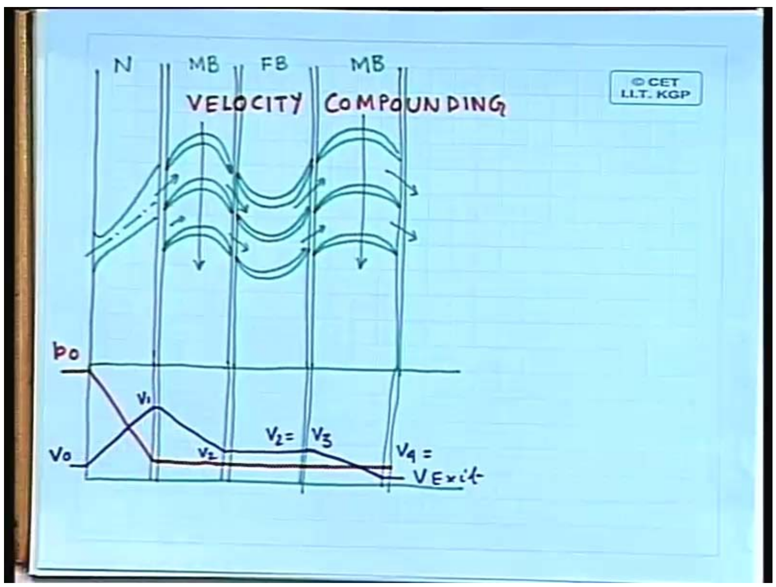

If we compare this thing with the diagram just now we have drawn, the changes that we can see is like this. The first thing here you see is these blades are symmetric blades and the passage width does not change as we move from this leading edge to the trailing edge of the blade. Here, it is entering and here it is moving so the passage width does not change as the steam moves through the blade. As this passage width does not change, there will not be any change in the pressure. In the second case, where we have gone for the reaction stage, in the moving blade itself we can see that the passage width is changing from point to point. In fact, the passage design is such that there will be expansion of steam. If we see the moving blade here, not only the direction of steam flow is changing but also the magnitude of relative velocity is changing because the passage width is changing from point to point.

If we go to the fixed blade (Refer Slide Time 48:30), here also the passage width is such that it does not change. The fixed blades are such that it only deflects the steam, so that in the next stage it enters smoothly in the moving blade rows but there is no change in velocity. That is what we have got. The velocity remains constant. But if we go for reaction stage, here we see that it is basically a nozzle. It serves two purposes. One purpose is, it will direct this steam so that it can smoothly enter the next stage of moving blade but at the same time there will be drop in pressure so that there will be increase in velocity. We shall take some other diagram, which we have drawn. Let us see this diagram.

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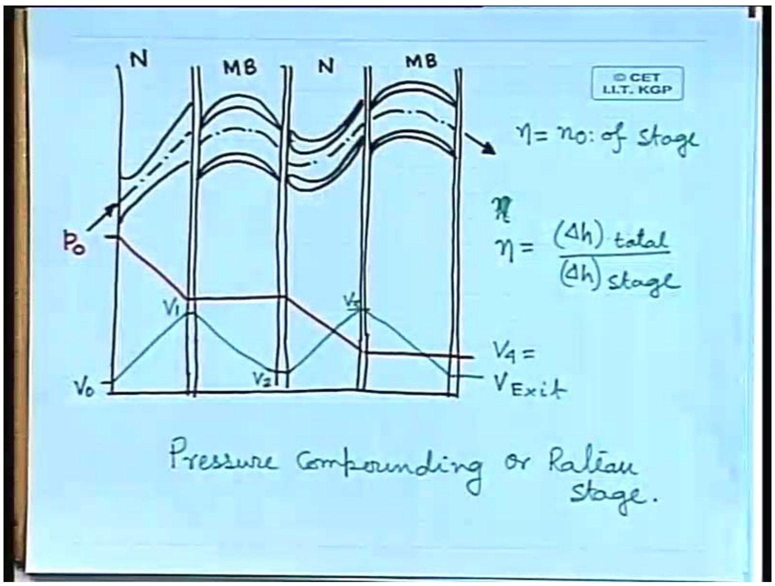

What can we see here? We can see another very important difference. Here, there is a pressure drop only in the nozzle. In the moving blade passage there is no pressure drop but here in the last diagram when I will draw the pressure difference or pressure change, we will see throughout all the rows of nozzle and moving blade we will have pressure drop. Let us complete it.

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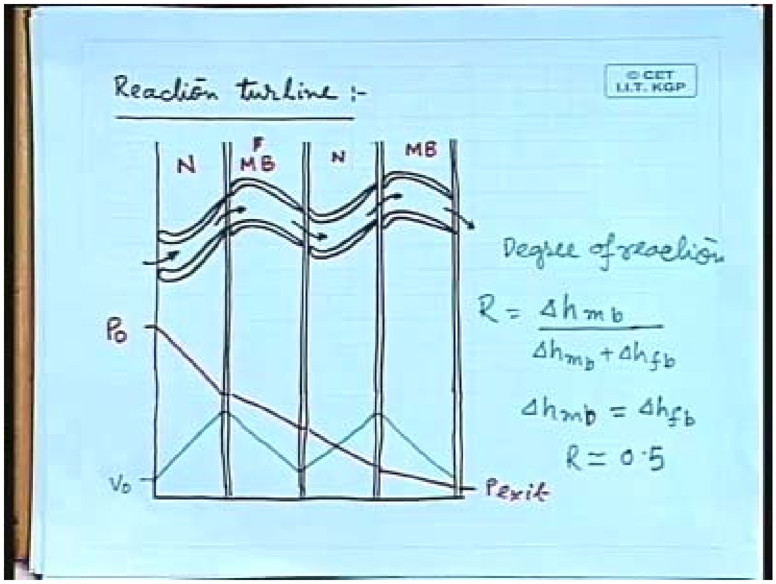

There will be pressure drop, again there will be pressure drop, there will be pressure drop, there will be pressure drop, like this and you will have like this. In case of fixed blade, this is P_0. Let us say this is P_{exit}. In case of fixed blade or nozzle, whatever you may call it, let us say it is entering with a small velocity. There will be increase in velocity, then there is a decrease in velocity and then again there is increase in velocity. Again, in the moving blade, there is decrease in velocity like this. This is how our velocity will change from stage to stage. As we can see, there is pressure drop in both the moving blade rows and the fixed blade rows; there will be enthalpy drop also both in the moving blade rows and in the fixed blade rows; one row of moving blade and one row of fixed blade will constitute one stage.

We can define degree of reaction R as delta h moving blade; what is the enthalpy drop in the moving blade rho; divided by total delta h, that means, delta h moving blade plus delta h fixed blade. This is how we will get the degree of reaction and generally the blade design is made such that, due to manufacturing, we have got identical blade now for the moving blade and the fixed blade. So we will have delta h moving blade is equal to, approximately, delta h fixed blade and the degree of reaction generally is 0.5. I think I will stop here and next class we will start from this point.