# Thermal Engineering: Basic and Applied

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## Lecture - 37
## Compounding of Steam Turbine

I welcome you all to the session of thermal engineering basic and applied and today we shall discuss about the compounding of steam turbines. So, before going to discuss this topic let us first review the flow analysis through a nozzle. So, if we try to recall then basically nozzles and blades together from the steam turbine. What is done in practice is that the steam which is produced in the boiler is having high pressure high temperature and that steam is allowed to flow through the nozzles and while steam is passing through a nozzle, at the expense of pressure drop, the velocity of steam at the exit of the nozzle is increased. And it is because of this increase in flow velocity, the jets of steam which is coming out from the nozzle increases. Rather the velocity of steam Jets increases and that high velocity Jets of steam impinges upon the turbine blades. And while that steam Jets impinge upon the blades, there is a deflection of the steam Jets because of the blade angle and that Jets suffer a loss of momentum and that momentum is absorbed by the wheel of the turbine and it produces torque. So, basically the flow nozzles and Blades together form the steam turbine.

So, before going to discuss about the compounding and then of course about different types of compounding, at least it would be important to know why this particular aspect is needed for the smooth and efficient operation of the turbine.

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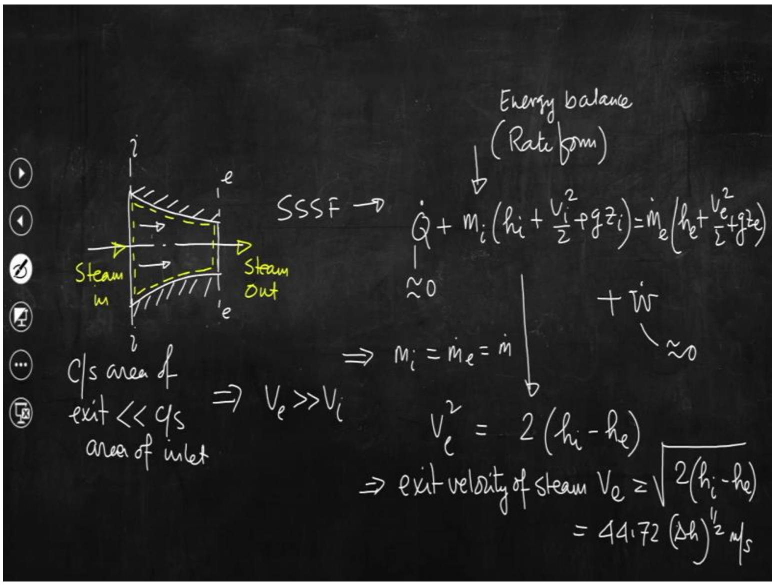


So, let us consider a flow nozzle and the direction of steam flow is as shown in the slide. The nozzle is insulated. So, let us assume this as the control volume because we are going to apply first law for our flow process. This is steam in and this is steam out as drawn in the slide. So, if you apply the steady state steady flow equation for the flow process across the control volume then we can write the generic equation that is

$$\dot{Q} + m_i\left(h_i + \frac{V_i^2}{2} + gz_i\right) = m_e\left(h_e + \frac{V_e^2}{2} + gz_e\right) + \dot{W}$$

Since the process is steady state steady flow, so $\frac{dE_{cv}}{dt} = 0$

Now we can see from this particular depiction that there is a flow of steam through a nozzle where nozzle is insulated essentially to prevent any heat loss from the flowing steam to the ambience. So $\dot{Q} = 0$ and mind it, we have written this equation steady state steady flow in the rate form and we are also not going to extract any work from the control volume. So $\dot{W} = 0$ and we have discussed that this is the energy balance for the flow process. And energy balance is not a balance in an isolated manner rather mass balance has to be coupled with the energy balance equation. So, basically if we apply mass balance then we can write

$$\dot{m}_i = \dot{m}_e = \dot{m}$$

Now as shown in the slide, we are assuming that the section e e is exit and i i is the inlet. So, the cross sectional area of exit is much less than cross sectional area of inlet. Hence we can write $V_e \gg V_i$. So, basically if that is the case, then from this particular SFEE equation, we can write that

$$V_e^2 = 2(h_i - h_e)$$

$$\Rightarrow \text{Exit velocity of steam, } V_e = \sqrt{2(h_i - h_e)}$$

So, try to understand the velocity of staying at the exit of the nozzle is nothing but the total enthalpy drop across the flow nozzle. Next if we express this enthalpy drop in kJ/kg then this exit velocity would be

$$V_e = 44.72\ (\Delta h)^{\frac{1}{2}}\ \text{m/s}$$

So, if we measure $h_i$ and $h_e$ in kJ/kg, then the velocity of steam at the exit of the nozzle is $44.72\ (\Delta h)^{\frac{1}{2}}$. So, here we utilized 1 nozzle to have the pressure drop from boiler pressure to the condenser pressure. So, basically we have studied in impulse turbine that there is no pressure drop when steam flows through the passage between the blades. So, the total pressure drop takes place inside the nozzle only.

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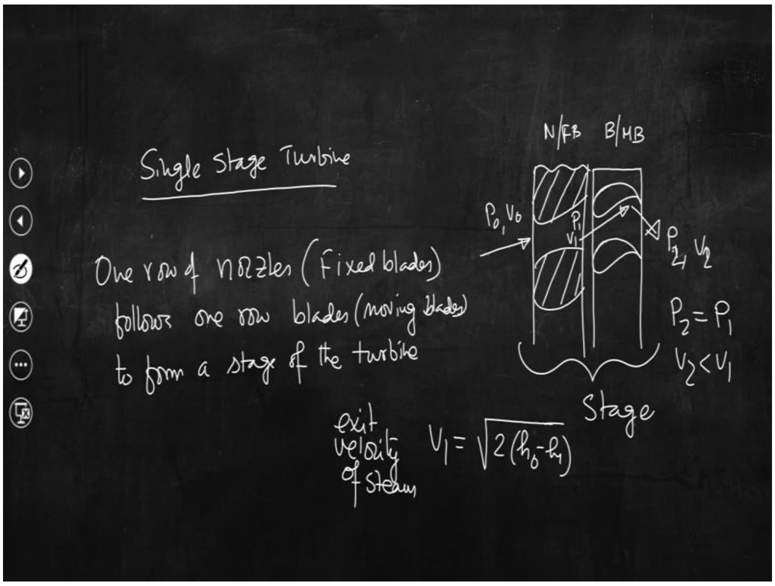


So, let us now consider a single stage turbine. Single stage turbine means this consists of 1 row of nozzles or fixed blades followed by 1 row of blades or moving blades. Now the stream which has come out from the boiler is entering into the flow nozzle and while passing through the nozzle, it expands and at the cost of the pressure drop velocity increases. Then that steam Jets strike the turbine blades. After striking, the steam is coming out from the first row of blades or moving blades and because of the blade angle, we can see that the jets suffer a loss of momentum and that momentum is absorbed by the wheel of the turbine and it produces torque.

So, basically you know that steam which is coming out from the boiler is now entering into the first row of fixed blades with pressure $P_0$ and velocity $V_0$. Then we can understand that at the exit of the nozzle, the pressure is $P_1$ and theoretically there is no pressure drop when steam is passing through the passage between 2 consecutive rows of moving blades. So, at the exit of nozzle, pressure is $P_1$ and velocity is $V_1$. So $P_2$ and $V_2$ are the pressure and velocity of steam at the exit of the first row of moving blades.

Now $P_2 = P_1$ and certainly $V_2 < V_1$ because a part of the kinetic energy would be observed by the first row moving blades. So, now try to understand if you would like to have the pressure drop from $P_0$ to $P_1$ or $P_2$ and if you would like to have the total enthalpy drop in single stage of turbine then you know that the velocity would be very high. So $V_1$ is the velocity of steam at the exit of the nozzle. So, if you are applying the equation for exit velocity between State 0 and 1 then of course

$$\text{Velocity of steam at the exit of Nozzle}, V_1 = \sqrt{2(h_0 - h_1)}$$

We have derived this is the expression in the previous slide. So, we can understand that if we design the turbine in such a way that the total enthalpy drop will be there in a single stage then the exit velocity of steam would be very high.

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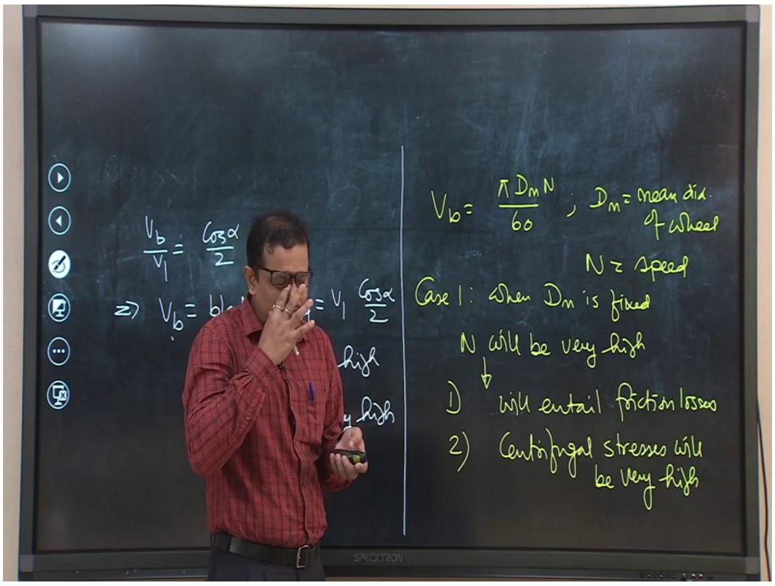


Now we know that $V_1$ is directly related to the blade velocity as

$$\frac{V_b}{V_1} = \frac{\cos\alpha}{2} \;\Rightarrow \text{Blade velocity} = V_b = V_1 \frac{\cos\alpha}{2}$$

Here $\alpha$ is the flow angle at the inlet. So, now if $V_1$ increases then we can see that the blade velocity will also increase. So, that means if you would like to have total enthalpy drop in a single stage turbine, then the speed at which the blades in the first row (because it is a single stage turbine) will be excessively high. So, that means when $V_1$ is very high which is obvious because you would like to have the total enthalpy drop in the first stage then $V_b$ will be very high as well. So, now let us discuss what happens when $V_b$ is very high.

$$V_b = \frac{\pi D_m N}{60}$$

Here $D_m$ is the mean diameter of the wheel and $N$ is the speed of the wheel. So, you can understand that there are 2 possibilities to accommodate such a high $V_b$.

Case 1: when $D_m$ is fixed.

We cannot increase $D_m$ beyond a particular value to meet the space constraint requirement because when you are installing turbine in a power plant, then for the turbine house we are also having space constraint. So $D_m$ cannot be increased beyond a particular value. So, if we keep $D_m$ fixed then to accommodate such high $V_b$, $N$ will be very high that means the turbine will rotate with a very high velocity. If it is the case then it has 2 consequences.

1) Such a high speed of the wheel will entail frictional losses
2) If $N$ is very high then the centrifugal stresses will be very high.

So, these 2 are not desirable for the efficient or smooth operation of the turbine unit in a power plant. So, that means we can understand that allowing total enthalpy drop in a single stage turbine will lead to these problematic issues.

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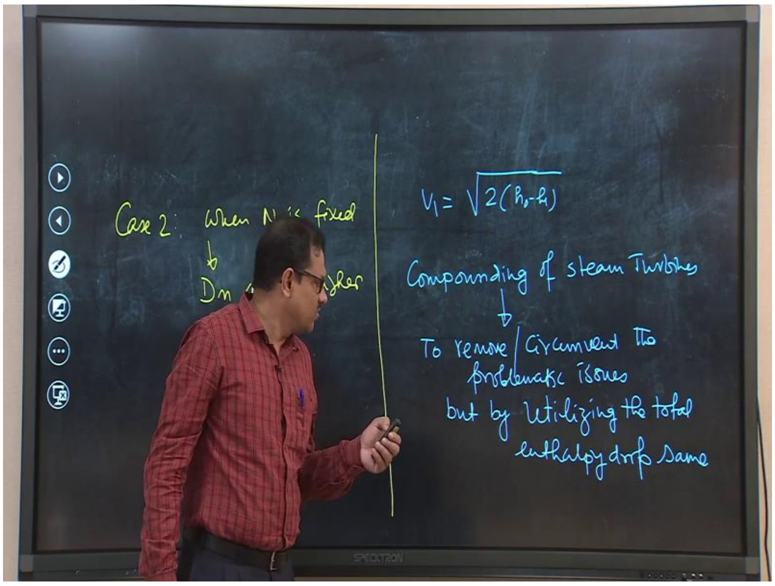


Case 2: when $N$ is kept fixed.

Then to accommodate such a high $V_b, D_m$ will be higher. Again this is not a kind of desirable situation as I said that increasing the wheel diameter beyond a particular value is not allowed because we are having space limitation. The entire turbine unit which is there in a power plant, so we cannot go beyond a particular value to increase the diameter of the wheel. So, this is also not possible.

So, try to understand that we would like to have drop of pressure from boiler pressure to the condenser pressure because at the exit of the turbine steam pressure is the condenser pressure or back pressure. So, basically if you like to have it then we have understood the problematic issues which are associated with this particular arrangement. We all know that a single stage impulse turbine is also known as De laval turbine, which is having very high speed and if the speed of the wheel is very high then we have discussed about the difficulties and all these are not kind of desirable, of course for the smooth operation of the turbine unit.

So, basically we have understood that 2 things. First of all $V_1 = \sqrt{2(h_0 - h_1)}$ and the total enthalpy drop is $h_0 - h_1$. So, that means we can reduce $V_1$. If we can reduce $V_1$ then the problematic issues that we have discussed will not be there but to reduce $V_1$, we have to have very less enthalpy drop but again it is not desirable.

So, basically if we allow more enthalpy, more work output will be there. Now we are trying that the total enthalpy drop would remain same, and at the same time we are trying not to invite all these problematic issues. So, that means we need to design the unit in such a way that all these issues will be circumvented but securing the total enthalpy drop will be the same and that is what is done by the compounding of steam turbine. So, basically compounding of steam turbine is basically a kind of arrangement by which we can utilize the total enthalpy drop but by eliminating all these problematic issues.

So, compounding of steam turbine basically allows us to remove or circumvent the problematic issues but securing the same total enthalpy drop. So, that means we are not going to compromise this enthalpy drop but at the same time we can eliminate the problematic issues which are associated with high speed of the wheel as well as larger diameter of the wheel.

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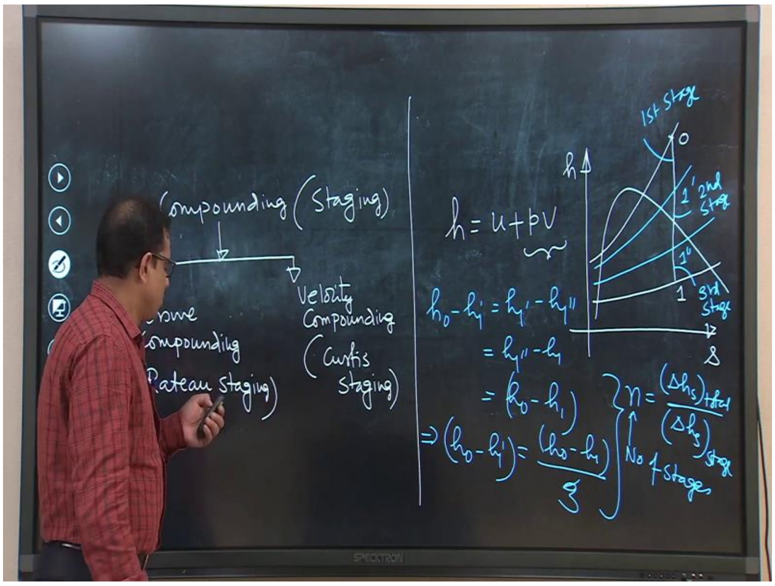


Basically compounding is also known as staging. There are 2 types of compounding, one is pressure compounding or Rateau staging and second one is velocity compounding or Curtis staging. So, now let us discuss about these 2 different types.

So, we know that total enthalpy is basically $h = u + pv$. So, internal energy of steam is not going to be disturbed. So, what we can do is that this enthalpy drop can be divided just by altering the drop in pressure inside the nozzle. So, basically you can that by changing pressure and velocity we can play with the enthalpy that will drop in a particular stage. So, $u$ being a representative measure of temperature, this internal energy will remain same. But only thing that can be done here is that by altering the pressure drop and change in velocity while steam is passing through the nozzle, we can have the change in $h$ such that the total enthalpy drop will remain same without all these difficulties.

So, the let us discuss about the pressure compounding first. So, basically you know that enthalpy will drop. So, let us look at the h-s diagram in the slide where State 0 and the total state 1 are shown. So, you can understand that we would like to have this total enthalpy drop but if the pressure and velocity these 2 are compounded such that we can have the total enthalpy drop in a number of stages, then instead of having the total enthalpy drop in a given stage, we can split that enthalpy drop equally among number of stages then we can have total utilization of the enthalpy drop and at the same time we can eliminate the problem associated with the high speed of the wheel as well as the larger diameter of the wheel.

So, basically you know that we can split the total enthalpy drop into a few stages. So, you can understand that in the h-s diagram 1', 1" are marked. So, basically we can write that

$$h_0 - h_{1'} = h_{1'} - h_{1''} = h_{1''} - h_{1'}$$

So, that means when we have the enthalpy drop in a number of stages, the total enthalpy drop will remain same that is$= h_0 - h_1$. So, we can understand that enthalpy drop in a given stage

$$h_0 - h_{1'} = \frac{h_0 - h_1}{3}$$

So, we are going to have 3 different stages this is the first stage, second stage and third stage. So, basically you are having 3 different stages and total enthalpy drop is $h_0 - h_1$. And that total enthalpy drop is now splitted equally among the number of stages. So, basically we can understand from this expression that

$$\text{Total number of stages} = \frac{(\Delta h_s)_{total}}{(\Delta h_s)_{stage}}$$

Here $\Delta h$ has suffix s because this is isentropic enthalpy drop. So, the above expression is for number of stages. So, basically it is very important to know that number of stages which is needed I mean how many stages are needed to utilize the total enthalpy drop but at the same time eliminating all these problematic issues and that can be calculated from this expression. So, you can understand that basically you would like to have enthalpy drop in a number of stages and since we should utilize the total enthalpy drop, accordingly the total number of stages would be determined.

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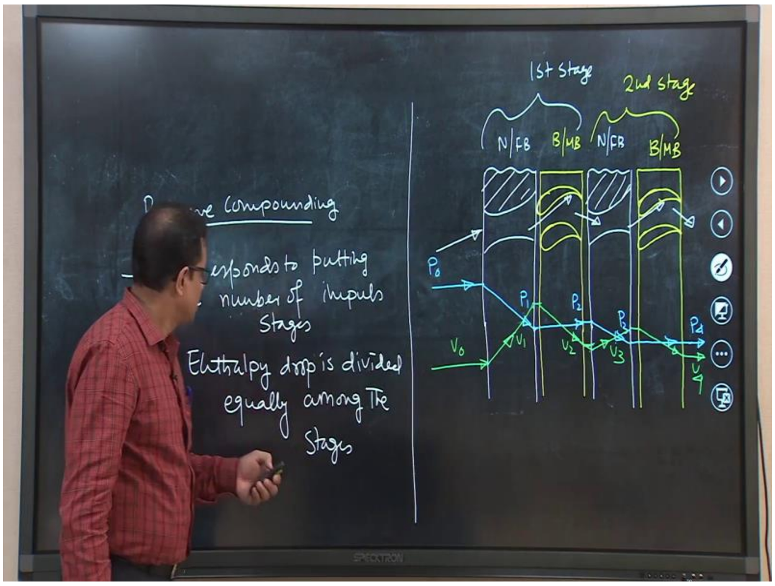


So, for the pressure compounding we are splitting the total enthalpy drop equally among a few stages. So, that means from the particular expression $h = u + pv$, you can understand that $u$ is the internal energy and we cannot change because *u* being a representative measure of temperature. So, basically what we can do from this particular expression is that we can change pressure and volume such that the enthalpy drop in a given stage can be altered. So, we can have compounding of pressure and we can alter total enthalpy drop from 0 to 1 that is from boiler pressure to condenser pressure. Now if the total pressure can be compounded such that the total drop will remain same but because of the drop in pressure in nozzle, the velocity should not be very high. So, that means we are going to have the total drop in pressure in a number of stages instead of utilizing as given stage.

So, basically pressure compounding corresponds to putting a number of simple impulse stages and total enthalpy drop is divided equally among the number of stages that means we will be having total pressure drop but the pressure drop will be compounded such that the enthalpy drop in a given stage can be calculated. And if we can multiply the pressure drop in a given stage with the number of stages that will be the total pressure drop and that would be corresponding to total enthalpy drop.

So, pressure compounding corresponds to putting a number of impulse stages and enthalpy drop is divided equally among the stages. So, now let us see how this particular configuration works. So we know the total enthalpy drop that is basically due to a change in pressure from boiler pressure to the condenser pressure. Now if you would like to have total pressure drop in a single stage then we have seen that velocity of steam at the exit of the nozzle will be very high. And to accumulate such a high velocity, either blade speed will be very high or diameter of the wheel will be very high. Now instead if we can use a number of stages and the total enthalpy drop will be divided equally among the stages, then in such a case we would be utilizing the total enthalpy drop but at the same time the velocity of steam leaving 1 stage would not be very high.

So, let us try to draw the pressure compounding in the schematic depiction which will help us to understand this particular arrangement in a more convenient way. So, in the slide, basically blade or first row moving blade with nozzle or fixed blade is drawn. Then there is again another nozzle or fixed blade and finally we can have the blade or moving blades. So, try to understand there are 2 stages and first and 2$^{nd}$ stages are marked in the schematic diagram.

Now steam which is coming out from the boiler enters to this first row of nozzles or fixed blades then it comes out from the first row of fixed blades or nozzle and strike the first raw blades.

And then again it enters into the second row of fixed blades or nozzles and finally it comes out from the second row of fixed blades or nozzle and strikes the second row of blades or moving blades and then it comes out from the second stage. So, try to understand we may have further stages that is third stage, 4th stage, and fifth stage depending upon the requirement. So, the number of stages required is highly dependent on the total enthalpy drop that will be there while steam is passing through the turbine unit.

Now, let us try to draw the pressure velocity diagram. So, here we are talking about pressure compounding. So, if we go back to the definition of enthalpy that is $h = u + pv$, here we are not going to have any alteration of $u$. So, what we are trying to do? We are trying to alter pressure and velocity in such a way that the drop in enthalpy in a given stage can be altered keeping in mind that the total enthalpy drop will remain same such that the enthalpy drop in each stage will be equal and the total enthalpy drop in all stages will be equal to the enthalpy drop that we need to have when steam is passing through the turbine.

So, basically when steam is passing through the nozzle or fixed blades we know that at the expense of pressure drop velocity will increase. So, the pressure will drop and when stream is passing through the moving blades or blades theoretically there is no pressure drop. So, that pressure will remain same. So, accordingly $p_0, p_1$ and $p_2$ has been marked in the diagram. And again when it is passing through the second row of nozzle or fixed blade pressure drop will be there and then finally it will remain constant when it will come out from the second stage. So $p_3$ & $p_4$ has been shown in the diagram.

Now at the cost of this pressure drop, there will be change in velocity. So, the velocity of steam which is entering into the nozzle is $v_0$ and this velocity will increase to $v_1$ when steam is passing through the first row of nozzles. So, basically our sole purpose was to increase the velocity of steam which is now going into the first row of blades or moving blades. So, if we know the mass flow rate of steam, that kinetic energy will be partly absorbed by the first row moving blades. Hence the velocity will drop to $v_2$. And when the steam is passing through the second row of nozzles and fixed blade then again velocity will increase because of this pressure drop. So, this velocity will again increase to $v_3$.

So, basically you can understand it is because of the compounding of pressure. So, we are going to have total pressure drop in a compounded manner that means it is not in a drop in a given stage. So because of this pressure drop further in the second stage of nozzle or second row of nozzles or fixed blades, velocity increases from $v_2$ to $v_3$. And when that particular steam jet is again entering into the second row of blades and moving blades, kinetic energy will be absorbed by this row and velocity will drop and finally the steam will come out from the second row of blades or moving blades with velocity $v_4$.

So, you can understand that when you allowed steam to expand only in the first row of nozzle, then the velocity would have been much more and if we had tried to utilize that in the first row of moving blades then as we have discussed in the beginning of this class that the speed would have been much more and the requirement of diameter of the wheel would have been even larger. So, now instead of doing this we are utilizing a few number of stages and the drop in pressure is compounded in such way that the total pressure drop $p_0 - p_4$ is remaining same.

But the total pressure drop is now compounded in a number of stages and hence the name pressure compounding is there. It is because of this pressure compounding, the increase in velocity of steam in the first row of fixed blades or nozzle is not very high, so that those problems will not be there. So, this is basically pressure compounding or Rotor staging.

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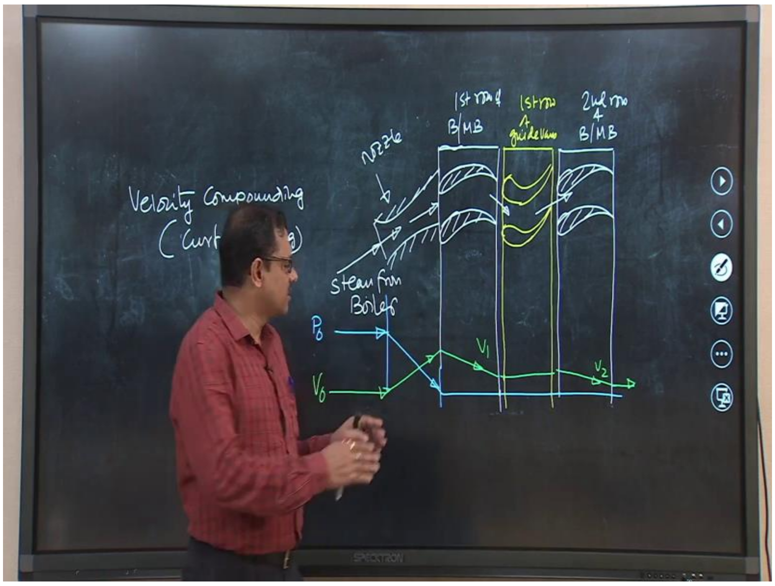


We shall be discussing about the second type of compounding that is velocity compounding or Curtis staging. So, try to understand again here velocity would be compounded. So, it would be possible to have the total drop of pressure in a first row of nozzles. And then the increase in kinetic energy due to increase in velocity of steam would be very high. So, instead of using the total kinetic energy in a single row, it would be again convenient and we can also eliminate all those problem, if we can utilize that kinetic energy in a number of stages. So, we are now trying to utilize that high velocity of steam not just in a single row of blades but in a multiple rows of blades that means we are trying to have compounding of velocity.

So, velocity of steam would be very high at the end of the first row of nozzle wherein we have utilized the total pressure drop. If you are trying to utilize such high velocity in a first row of blades or moving blades, then either speed would be very high or the requirement of diameter of the wheel would be very high. So, those are not again desirable. So instead of doing this, we can utilize the total kinetic energy that would be available at the exit of the nozzle in a multiple rows of moving blades. So, this is called compounding of the velocity. So, the high velocity of steam at the exit of the nozzle will not be utilized in a single row instead that velocity would be utilized in a number of stages so that we are compounding the velocity in such way that the problem associated with the utilization of high velocity in a single stage will not be there.

So, let us draw the schematic again which is very important. In the schematic drawn in the slide, the nozzle and the steam flow is shown. Then the nozzle, the first row of blades or moving blades and the first row of guide vanes are also marked. Then there is the second row of blades or moving blades. So, let me discuss here what is done.

So, the steam from boiler is taken through the first row of nozzle wherein the stream is allowed to expand totally. So, the total pressure drop will takes place in this nozzle only and the velocity of steam that would be there is high. A part of that velocity would be utilized in the first row of moving blades or blades. And the velocity of the steam which is coming out after doing some work on the first row of blades or moving blades is still having some velocity and that velocity is again guided by the first row of guide vanes to direct the steam to the second row blades or moving blades.

So, try to understand, it is the nozzle here in total pressure drop occurs. It is because of this total pressure drop, the velocity of steam leaving the nozzle will be very high and kinetic energy of steam will be very high too. That kinetic energy is partly utilized in the first row of blades or moving blades and remaining kinetic energy that means the velocity of steam will be very high even at the exit of the first row of blades or moving blades.

Then that steam is taken through the first row of guide vanes and these are stationary. The sole purpose of the guide vanes is to direct that steam to the second row of blades and moving blades, there also a part of the kinetic energy will be utilized and it will rotate. Then it will again go into the second row of guide vanes or stationary blades and then again third row of moving blades of blades and like this it will continue.

So I have discussed that nozzles are also known as fixed blades stationary blades. So, the first row of nozzle and first row of blades or moving blades, these two rows form the first stage. The first row of guide vanes placed in between 2 rows of moving blades and the second row of blades form another stage. So, basically this is a two stage turbine.

Now let us draw the pressure velocity diagram. So, pressure of the steam which is coming out from the boiler and entering into the nozzle is very high and the total pressure drop will occur inside the nozzle only and the pressure will remain constant thereafter. So, at the expense of this total pressure drop the velocity of the stream will increase. So, basically the steam pressure at the inlet to the nozzle is $p_0$ because this is the inlet, so it is the boiler pressure and pressure will drop drastically inside the nozzle and thereafter pressure will remain constant as the steam passes through.

Now let us try to draw the velocity. So, basically the velocity of steam at the inlet of the nozzle will increase in the nozzle and as I said that when that steam is entering into the first row of blades or moving blades, a part of that velocity would be utilized. So, there will be again velocity drop and while the steam is passing through the guide vanes or stationary blades, there is again little drop in velocity. But this is remaining more or less constant and when stream is again entering into the second row blades or moving blades, velocity will further drop. So, the velocity $v_1, v_2$ is marked in the diagram and then the steam is coming out. So, this is the 2 stage turbine diagram that we have drawn here. And you can see that the guide vanes are designed in such a way that there will not be any drop in velocity theoretically.

So, you can understand that the total rise in velocity is now partly utilized in the first row and remaining velocity is utilized in the second row like this. So, that means had we tried to utilize the total velocity only in the first row of blades then the speed would have been much more and also the requirement of wheel diameter would have been even larger.

So, this is known as velocity compounding as if the pressure is remaining constant but we are trying to utilize the total velocity in a number of stages as if the velocity is compounded. So, what we can see is that steam with high kinetic energy enters into the first row of blades or moving blades and the steam jet work on the first row of blades and moving blades. Leaving the first row of blades and moving blades, it enters into the first row of guide vanes and there is no change in kinetic energy theoretically. Then that steam jets leave the first row of guide vanes and steam jets enter into the second row of blades or moving blades and again that steam jets work on the second row moving blades and so on. So, the process will continue depending on the number of stages which is needed for the turbine unit.

So, if we try to summarize then today we have discussed about compounding. We have discussed that why this particular arrangement is needed for the efficient operation of the steam turbine. Then we have discussed about the types of compounding and we had seen how pressure and velocity compounding work essentially for the efficient operation of the steam turbine unit. So, with this I stop here today and we shall continue our discussion in the next class. Thank you.