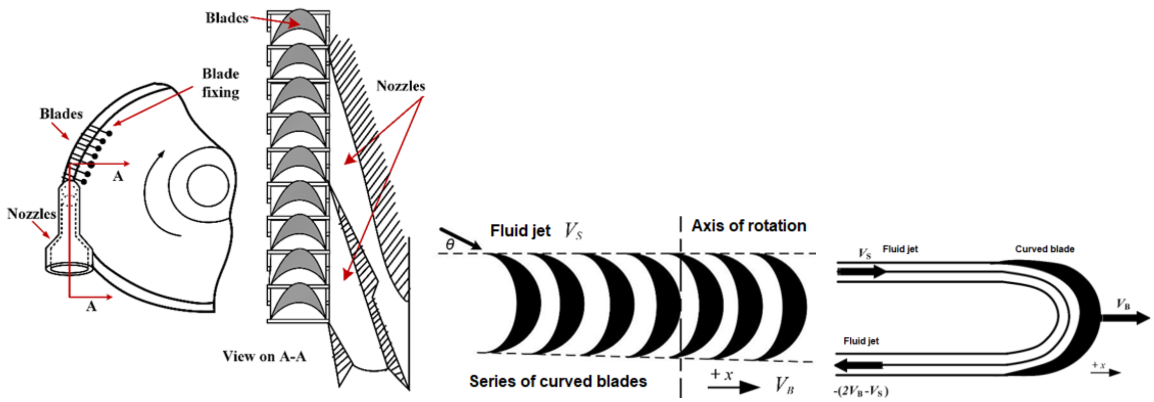
**POWER PLANT SYSTEM ENGINEERING**

**Lec 8: Impulse Turbine**

Dear learners, greetings from IIT, Guwahati. We are in the MOOCs course Power Plant System Engineering, module 2 and the title of this module is Vapor Power System part 2. And we are in the lecture number 6 in which we are going to discuss the following topics. First one is impulse turbines and in fact, prior to this lecture we have given elaborate discussion on impulse principles and subsequently how that principle was used, starting from a flat plate to a curved blades and subsequently through velocity diagram how power output can be derived. So, in terms of practical utility we will try to see the realistic version of impulse turbine how it looks like. So, basically there are two categories of turbines one is single stage type, other is compounded type.

The reason behind this two categories is that many a times in large power plants where we have stream available at very high pressure and temperature, we normally do the compounding because in a single stage power extraction through impulsive mode, it gives lots of losses. For that reason compounding is being done. This compounding is addressed by two configurations- one is through velocity compounding other is pressure compounding. So, the topics of discussion for today's lecture will be mainly focused on the practical aspects of impulse turbines and subsequently how those things we are going to utilize through staging or through distribution of enthalpy drop across each stages. So, this is the overall summary of today's lectures.

Now, let us start to understand what we have studied so far in our previous lectures. We have approved in our previous lectures that we started with a flat plate in which velocity of jet which impinges, when the plate is fixed then there is no power output, but when we start moving that plate we saw that we can get 50% of power from the jet. But if we make a curved blade instead of plate we have proved that 100% power recovery from this velocity of jet is possible and this is the basic principle. But in a realistic version the single curved blade is replaced with array of blades and these array of blades are exposed to some fluid jet.




And of course, these blades are rotating and we got the velocity of the blade as $V_B$ and once you get this then, this principle we are going to adopt in some configuration or more. So, this is the realistic version show in this figure, where we have shown how that array of blades are organized. So, if you can see these arrays of blades and they are fixed with nozzles that means, there may be a single nozzle or multiple nozzles and we say that jet is being impinged through these blades and after they pass through the blade the fluid jets comes out in the manner through this passage shown in picture. In the other version as shown in the picture, this makes this rotor rotating. So, normally we call this wheel or in hydraulic term, we call it an impulse wheel, but in our term we will not use the word impulse wheel rather we will use the word impulse turbine.

So, basically what does the impulse turbine do is the rate of change of angular momentum of the fluid in the rotating passage to provide torque on the rotor. And initially the fluid enters into the rotor in tangential directions with absolute velocity, the fluid flows through the rotor at a fixed mean radius and the change in the linear momentum tangential to this wheel or rotor gives the tangential force. So, thereby these wheels continuously rotate as long as these receive the steam from the nozzles. And finally, the fluid leaves this wheel through tangential direction.

Now, just to give some insight of this impulse turbine in a realistic versions. They are recognized by their shapes that means, looking at the shape of this blades we can say it works on the impulse mode. They basically have symmetrical entrance and exit angle at 20°. Normally these impulse turbines are employed in the entrance of high pressure steam turbine when the specific volume of the steam is low or mainly in the superheated regions.

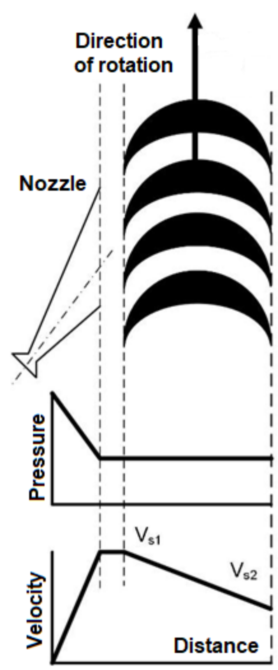
So, if you recall our Mollier diagram that is h-s diagram, we can see that when we are looking at the initial condition of the steam that is state 1, it is in the superheated region and this fluid expands from boiler pressure to the condenser pressure and typically this is about 30 bar and this is 0.007 bar. So, under this scaling difference we can see the steam is already at superheated conditions, and the point to be noted is specific volume is low. Another advantage of this turbine is it requires smaller floor areas as compared to low pressure stage condition of the steam. The blades of an impulse turbine are short, they have constant cross sections. The characteristics fixture of the impulse turbine is recognized by the fact that most of the enthalpy drop occurs in the nozzles, that is fixed blades passage that perform the nozzle actions. So, I will try to emphasize upon the point in the subsequent slides.

So, basically impulse turbines are integrated with nozzles that supplies steam to the blades and most of the enthalpy drop occurs in the nozzles only. And there is a very little pressure drop which is placed in the moving blades which mainly occurs due to the friction that gives rise to a velocity coefficient term. That is the reason we say that, since the steam is already at very high pressure and temperatures, there has to be friction if there are large number of blades comes into picture. So, hence we have to see some term like velocity coefficient that gives the losses in the power.

However, this term is quite low. We have seen in last problems that this term is quite low. So, that maximum velocity recovery can be possible because as long as you are maintaining this nozzle angle 20° and the flow deflection angle close to 180° this velocity coefficient term will be as minimum as possible. The impulse turbine or the turbine stages are very simple configurations as compared to other configuration. The impulse stages are simple configurations and there can be a single rotor or multi rotor turbine arrangements which means these blades can be connected either to a single rotor or you can have a multi rotors. When you have a single rotor we call it single stage when you have multi rotor then we may have stages.

So, that is the idea of doing the compounding. So, let us start with the first case which is called as single stage impulse turbines. Now onwards we will use the single stage impulse turbine as the benchmark because this is the simplest version of turbine that a conventional steam power plant uses. And in steam power terminology, this single stage impulse turbine is called as *de Laval turbine* & invented by a Swedish scientist. We have used the word *de Laval* nozzles. In a nozzle terminology, they are nothing, but convergent-divergent nozzles that are used for generating thrust but in turbine terminology or power generation terminology we say it is a turbine. And if we look at its arrangement we can see there are single stage array of blades and direction of the rotation, blade velocity is shown in the picture. Then we have a nozzle arranged in the manner shown in picture. So, basically in this figure there is one particular nozzle caters to at least four number of blades. So, likewise if you have large number of blades we can think of multiple number of nozzles that can supply the steam to the blades, but at a certain angle.

And typically this angle is kept within 20° to 30°. We expect 30° so that it caters as many number of blades possible. It is very difficult to align $\theta$ to 0° and if this $\theta$ is 0°, then we will have 100% or 180 ° deflection, but that is not possible in practical point of view. So, nozzle has to be arranged at certain angle $\theta$ which is typically 20° to 30° to cater some arrays of blades; this is first point. Second important point is the pressure drop and the pressure drop happens in the nozzle only because entire enthalpy is exhausted in these things after that the pressure almost theoretically it should remain constant. After this pressure drop if you look at the velocity; this velocity is increasing in this nozzle and side by side once the blade rotates that means, the fluid has transferred its kinetic energy from $V_{s1}$ at its initial state to $V_{s2}$. And through this velocity difference we have shown that the work done by the blade would be the difference in the kinetic energy at the inlet and exit. This is what we have been deriving from the velocity diagram. So, this we see that the increase in the velocity occurs in the nozzle and drop in the absolute velocity of the fluid occurs in the blades. So, these points can be summarized to the fact that *de Laval turbine* consist of a single rotor to which impulse blades are attached, the steam is fed through either one or several convergent-divergent nozzle arrangements, so that only part of the blades are impinged upon the steam at any point of time.

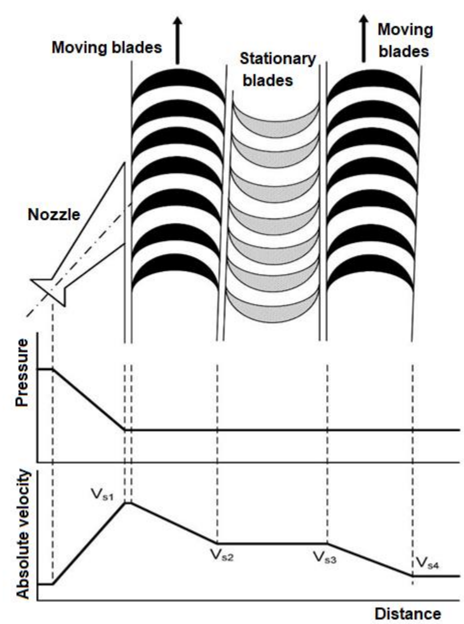



Suppose you do not want some blades to operate then we have possibility that we can shut down few nozzles to turn the power off. If you see this diagram the overall pressure and velocity of the steam change in the nozzles and the blade passages. The pressure drop mainly occurs in the nozzles, kinetic energy of the steam occurs in the nozzles exits which decreases from $V_{s1}$ to $V_{s2}$ in the blades. The overall steam pressure and absolute velocity changes are shown in this figure. So, this is about the single stage impulse turbine.

Now, we will move on to next concept. So, single stage turbine means we simply call this in a steam powered terminology as a *de Laval* turbine. But when you go for the compounding, first question arises why do you require compounding? So, normally in modern boilers that means where the steam generation takes place we used to look about the pressure availability of around 160 bar. At the same time temperature may also be very high close to 300/400/500°C.

Now, such a high pressured steam when expands to a condenser pressure of 0.07 bar or up to atmospheric pressure, what may happen is that there will be enough loss. That means if you use a single stage mode like a *de Laval* mode then there will be significant loss. That means in other words, we are not capturing maximum amount of power from the energy available in the steam. Another thing is that in terms of turbo machinery point of view, there is a limit that blades can rotate at certain speed. And typically for a steam velocity of 1640 m/s which is available at 160 bar, the optimum blade velocity is half of steam velocity which is about 820 m/s. So, rotating at 820 m/s is also a difficult task. If you use a single stage mode the system will be bulky & it will give rise to lot of losses. So, that is normally avoided. So, to overcome these difficulties two methods are normally employed- one is velocity compounding & other is pressure compounding.

So, basically the compounding word means is staging that means whatever steam or enthalpy is available to us or energy available to us, you staggered it in stages and this compounding means nothing, but different stages. So, this is the method adopted to minimize these losses. So, for that reason there are two possibilities what we can have one is velocity compounding other

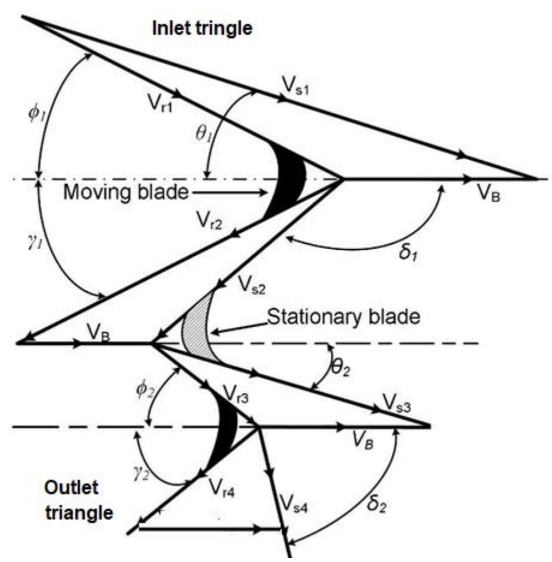


is pressure compounding. So, let us see what does they mean. So, let us stick to velocity compounding impulse turbine first.

So, typically when the compounding word comes into picture scientists tried to find out the possible regions or configurations or arrangement how we can make it, they come up with some designs. And one most important design which can be used as a practical viewpoint is the Curtis turbines. So, it was proposed by Charles G. Curtis while employing the staging of turbine through impulse principle. So, that we call as a Curtis turbine. So, when you say velocity compounded in steam power terminology we say Curtis turbine or Curtis stage. So, it is said that we can have a Curtis turbine which is composed of one stage of nozzle as a single stage turbine followed by two rows of moving blades. So, in the arrangement (as shown in picture), there are two rows of moving blades with one set of stationary blades. So the main philosophy behind this alignment is that when the fluid passes through the blades that we can reduce the velocity as low as possible. So, to do that we are adopting that same concept through rows of moving blades, but these rows of moving blades are to be fed in a particular manner. So, that is the reason the stationary blades are incorporated. So, these stationary blades are interpreted in many books as a guide vanes means they have no role, rather they redirect the exit from the first stage of moving blade will be redirected to the entry of the next stage of moving blade.

So, in many books, these are referred as guide vanes, but in our term we say these are stationary blades means they do not rotate, but these are like guide vanes. And of course, at the entry stage that entire steam or power is supplied through a single nozzle or arrays of nozzle. Same concept is applied here, but instead if you see that pressure stage, pressure drop only occurs in the nozzles, after that pressure remains constant, but if you look at velocity the drop, it happens only in moving blades. Like here from first stage of moving blade we have from $V_{s1}$ $to$ $V_{s2}$ then stationary blade does not do anything there is no change in the velocity then from second row of moving blades it changes from $V_{s3}$ to $V_{s4}$. Through this process velocity drop happens. Now, if you drop the velocity in a step by step manner or you can do in stages then thermodynamically it is proved that maximum utilization of energy is possible. So, this is how the concept of Curtis turbines employ. Curtis turbine by default is a velocity compounded impulse turbine.

Then moving further if you want to analyze this in terms of velocity diagrams, this particular figure shows the schematic diagram of inlet triangle and outlet triangle and there is the first stage of moving blades. Moving blades have same $V_b$, the first set of first stage moving blades moves at this velocity $V_b$, again in the other case also this same velocity $V_b$. Now, to have this same velocity the fluid has to be organized in this manner.




That means, you can see that blade velocity is $V_b$everywhere in the velocity diagram. Then what does this stationary blade does? It simply guides the fluid to have a smooth entry at the next stage of moving blade. Now, one more important factor we have emphasized here that there are possibilities of drop in the velocity of the fluid in this velocity diagram. Like for example, in ideal conditions, $V_{s2} = V_{s3}$. 20 50 $V_{s2}$ is that leaves from the first stage of moving blade and $V_{s3}$ is the entry velocity for the second stage moving blade.

So, we can introduce the term velocity coefficient or $k_v$ which takes care this ratio. As we say which we can quantify this as the amount of the fluid that enters. That means, we can precisely say at what velocity the steam enters in each rows of moving blade. Now, once we have everything then we can calculate the work transfer by momentum impulse principles. Then of course, we can calculate the blade efficiency and stage efficiency in the similar manner what we did in our last lecture.

Just to give the mathematical insight about the work output that we get from a Curtis stage.

Velocity coefficients in stages:

$$V_{r2} < V_{r1} \Rightarrow k_{v1} = \frac{V_{r2}}{V_{r1}}; V_{s3} < V_{s2} \Rightarrow k_{v2} = \frac{V_{s3}}{V_{s2}} \& V_{r4} < V_{r3} \Rightarrow k_{v3} = \frac{V_{r4}}{V_{r3}}$$

This is the general expressions that if you recall our previous lectures we have derived that the work output from an impulse blade is

$$\dot{W} = \frac{\dot{m}}{2}\{[(V_{s1}^2 - V_{s2}^2) + (V_{r2}^2 - V_{r1}^2)]\}$$

So, if you have only one set of blades this is the work output from the blade. But what happens that if you have a pure impulse mode the relative velocity terms will becomes 0. So, we say that this work output is only pure impulse mode. Now, in this case, since we have two sets of moving blades and each of them will have a velocity triangle. So, in the first case we have velocity triangle which involves $V_{s1}, V_{s2}, V_{r1}$ & $V_{r2}$. In the second case we have $V_{s3}, V_{s4}, V_{r3}$ & $V_{r4}$. So, this work gets added up that means we are recovering the work in a staged manner.

So, this gives a higher power output. So, this is what the Cartier stage of recovering power from the steam is all about.

Work output for Curtis stage:

$$\dot{W} = \frac{\dot{m}}{2}\{[(V_{s1}^2 - V_{s2}^2) + (V_{r2}^2 - V_{r1}^2)] + [(V_{s3}^2 - V_{s4}^2) + (V_{r4}^2 - V_{r3}^2)]\}$$

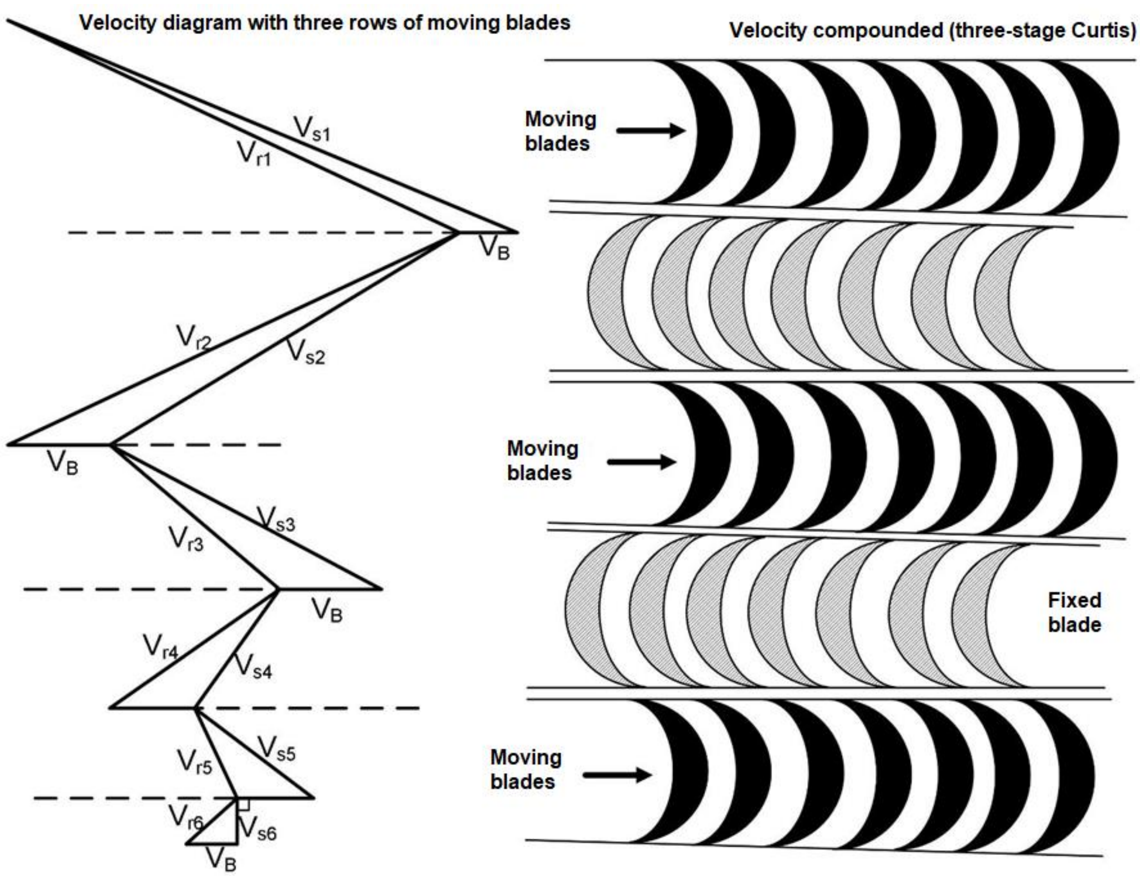
Blade efficiency: $\eta_b = \dfrac{\dot{W}}{KE}$ & $KE = \dfrac{1}{2}\dot{m}V_{s1}^2$;

Now once we have work transfer then we can find the kinetic energy and you remember that for all these cases we have used the same nozzle for all the blades. So, kinetic energy at the inlet is always, $KE = \frac{1}{2}\dot{m}V_{s1}^2$. So, once we have blade efficiency then we can find out the stage efficiency.

Stage efficiency: $\eta_s = \frac{\dot{W}}{\Delta H_s} = \frac{\dot{W}}{\dot{m}(\Delta h_s)}$ $\Delta H_s$:Total enthalpy drop of the fluid for whole stage

Stage efficiency means enthalpy drop of the fluid for the whole stage that means when the fluid enters here and leaves here, what is the drop in the enthalpy in this whole stage.

So, this is how we get the stage efficiency.




Now in same philosophy we can extend it for any number of rows. So, like there we have only two sets of moving blade and one set of stationary blade. Now here we have three sets of moving blade and two sets of fixed blades. So, same way we start with $V_{s1}, V_{r1}$ which enters and which leaves with $V_{r2}, V_{s2}$ and this gives blade velocity $V_b$. Now for the next set of moving blade it is $V_{s3}, V_{r3}$ that is entering and it gives the blade velocity $V_b$. Now and for next two we have $V_{r4}$ & $V_{s4}$ . So, this gives the velocity $V_b$ and subsequently when you go to the last one it is $V_{s5}$ & $V_{r5}$ and it gives $V_{r6}$ & $V_{s6}$. So, question is till how long we can do? We can continue till the magnitude of velocity which is impinging is very less. So, it in a realistic way if you draw the vector diagram appropriately we can see that the length of this $|V_{s6}|$ as quite low. So, that means, we have captured maximum energy from the fluid because magnitude of its velocity has reduced substantially. That means, initially we have $V_{s1}$ with length of value as shown in picture and finally, $V_{s6}$ becomes an insignificant number.

So, to think about some kind of a realistic mode basically speaking we have been using n stages to extract the power. So, ideally speaking, one can think of n number of stages and if you say if there is just one stage then the optimum velocity that gives maximum power would be

The optimum plate velocity that maximizes power: $V_{B,opt} = \frac{V_{s1} \cos \theta_1}{2n}$

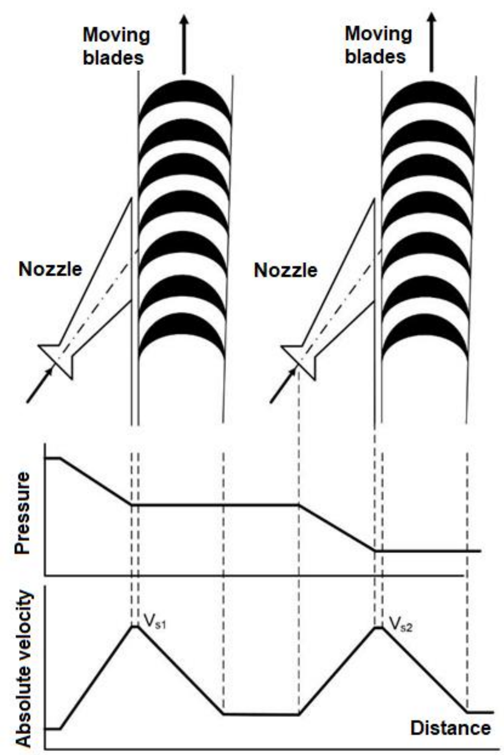
Where, $\theta$:Nozzle angle & $n$:number of stages (rows of moving blade)

Now if you have n number of stages that means, n number of rows of moving blades then optimum velocity also gets reduced. That means, for same energy extractions we can operate with a lower blade velocity; same power can be extracted at lower velocity. So, this is the advantage that we get when you do velocity compounding through Curtis.

And other advantage or maybe geometrical advantage we get are like this; when you do the staging with successive increase in the blade angle that results flatter and thinner blades. That means, when we go towards the last row of blades it becomes thinner because there is no significant steam velocity which is available at that end. So, that gives an advantage- exit blade velocity can be brought down to near 0 for ideal power generation systems. And through these staging we can say that we can extract same power with relatively less blade velocity.

Now work ratio of highest to lowest pressure stages is typically 3:1 for a two stage Curtis, it becomes 5: 3:1 for a three stage Curtis and becomes 7:5:3:1 for four stage Curtis turbine. When you go for higher number of Curtis stages practically it becomes uneconomical. That means when you go towards higher number of stages although we are trying to reduce this $V_{s6}\ to\ 0$, but towards the end side, fluid does not have sufficient momentum to drive the blade. So, Curtis staging beyond 2 is normally avoided.

So, that means at that point of time, this velocity compounding will not be an effective mode. So, you have to look for some other methods which means when you have Curtis stage more than 2, we have very high pressure steam and we are thinking of going for higher stage or four stage or five stage Curtis it becomes uneconomical. So that means velocity compounding is not a feasible option as far as its practical utility is concerned. So, then what do you do?




Then we go for the next alternative, pressure compounded impulse turbines. So, here the compounding is done in same way, that means we have availability of steam at very high pressure, as well as superheated steam and then we are going to extract its power through compounding. So the question is if you want to do through pressure compounding mode how do you do? And this velocity compounding stage that Curtis stage beyond 2 is not economical, but at that point of time there are critical requirement that your blade speed in two stage is also too high. So, this means that the issues of high blade velocity in the single stage turbine is elevated by incorporating nozzles in each stage so that the enthalpy drop is divided into many single stages. So, basically pressure compounding is a method in which each moving blade will be associated with its own respective nozzle.

That means same nozzle will not supply the fluid to all the moving blades rather will have a different nozzles for each set of moving blade. How it works then? So, this works in a same manner that means if you look at this set of moving blades the fluid starts with some pressure, there is a pressure drop in the nozzle area and across the moving blade there is no pressure drop. Then it goes to the next nozzle that means the same fluid that exits from the first moving blade is fed to another nozzle. Now, when the exit fluid is fed to the next rows of moving blade through another nozzle then you see that there is a second stage pressure drop. So, here pressure drop is done in stages and side by side if you look at the velocity plot in the first stage i.e., in nozzle the velocity increases, in the moving blades there is a drop in the velocity then till the fluid enters another nozzle there is no change in the velocity. The next rise in the velocity happens when there is a pressure drop in next nozzle.

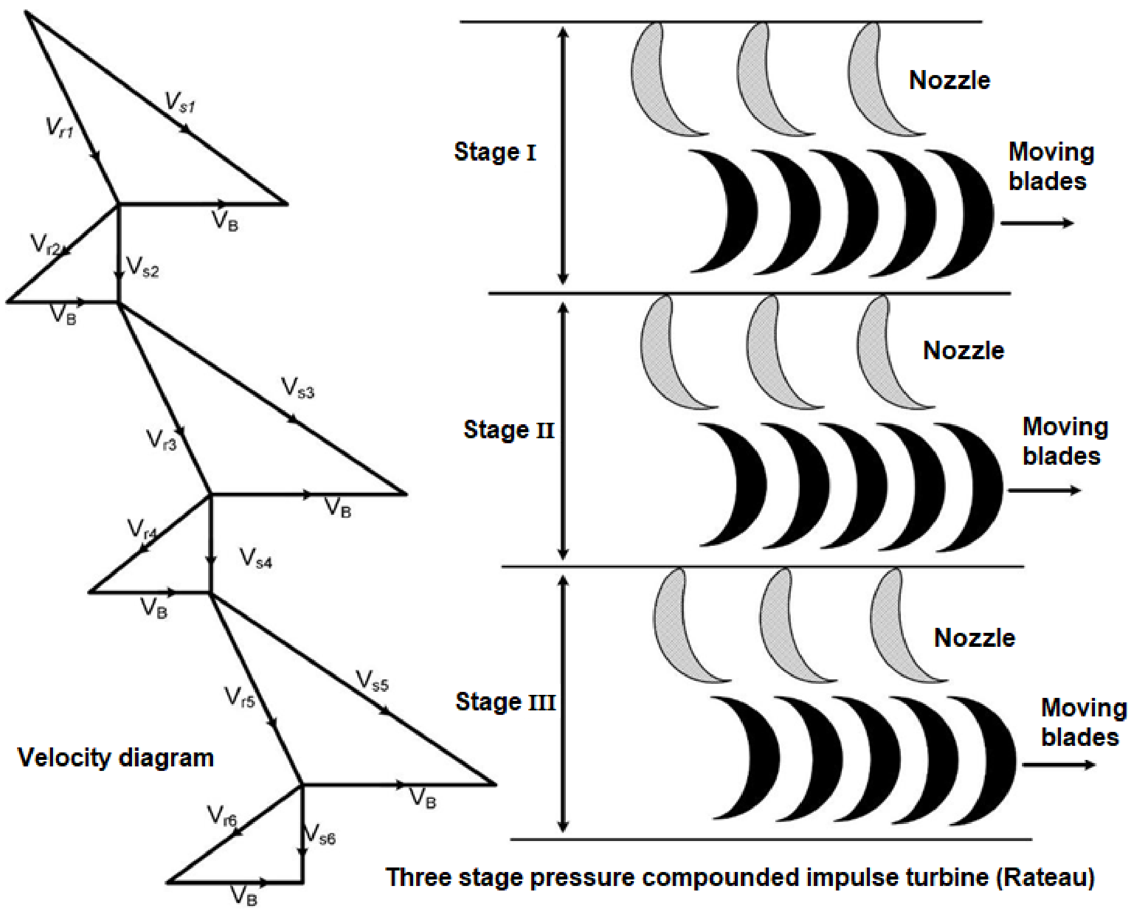
So, this keeps on happening for subsequent stages. Now, this concept of pressure compounding is normally referred with the viewpoint of steam power terminology, as Rateau turbine. So, here it is said that the total enthalpy drop is divided among many single stage impulse turbines. The inlet fluid velocity to each stage is equal with a reduced enthalpy drop. As already explained the enthalpy drop per stages is same, but not the pressure. Now, to think about in realistic numbers, let's say suppose we have availability of steam which is about 70 bar (800K) and it has to be expanded to condenser pressure of 0.07 bar and which carries about enthalpy 1350 kJ/kg. So, we can divide this enthalpy in 4 equal stages which is comes about 337.5kJ/kg, but we can think of this to happen at different pressure drops of 45, 18, 6 and 1 bar. So, that means, instead of going for 0 velocity we are going close to atmospheric pressure.

So, these are all the requirements. So, in this process, the inlet velocity to the nozzle can be calculated from the simple nozzle equation,

$$V_{s1} = V_{s2} = \cdots . = \sqrt{\frac{2(\Delta h_{tot})}{n}};$$

$n$:number of stages; $\Delta h_{tot}$:Total enthalpy drop of the turbine.

And below image gives a complete clear picture of how staging is done in a pressure compounding mode. You can see, for each rows of moving blades there are fixed set of nozzles meaning one set for stage I, one for stage II & so on. So, in other words we can say that each stage of this can be viewed as a single stage impulse turbine and correspondingly their velocity diagram is drawn and this turbine is called as Rateau turbine.




Three stage pressure compounded impulse turbine (Rateau)

And finally, the significant point that we need to emphasize here is that the exit velocity of whirl for all the stages is 0 corresponding to optimum blade velocity. The nozzle of each stage receives steam discharge from the previous stage, expands it, and then redirect it to moving blades. So, this is the main philosophy behind the pressure compounding of impulse turbine. And there are some advantages to it like we have reduced blade velocity in each stage that is because the nozzle for each moving blades will have a different entry velocity, then there will be reduced steam velocities due to friction and equal work among all stages.

But there are disadvantages too, like unavoidable steam leakage and large number of stages. So, this concept is implemented where efficiency is important; we do not go for higher stages pressure compounding rather we are satisfied with 2 stage Curtis mode of velocity compounding. So, if efficiency is more important than capital cost then probably this particular idea of pressure compounding is a better approach. So, this concludes the theory of compounding under impulse principle for steam turbines.

Now, we will try to solve some numerical problems based on our discussion today.

**Q1. An impulse steam turbine has a number of pressure stages, each having a row of nozzles and single ring of blades. The nozzle angle in the first stage is 20° and the blade exit angle is 30° with respect to plane of rotation. The mean blade velocity is 130 m/s and the velocity of steam leaving the nozzle is 330 m/s. Draw the velocity diagram and calculate the following parameters:**

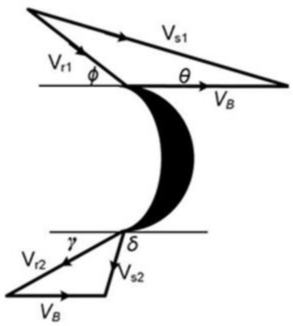
(a) **Considering the nozzle efficiency of 85% and velocity coefficient as 0.8, determine the work done per kg of the steam and blade efficiency.**

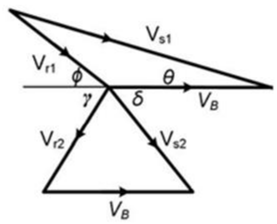
(b) **The supply of the steam to the first stage is 20 bar and 250°C and condenser pressure is 0.07 bar. Estimate the number of stages assuming equal stage efficiency and work done for all stages.**

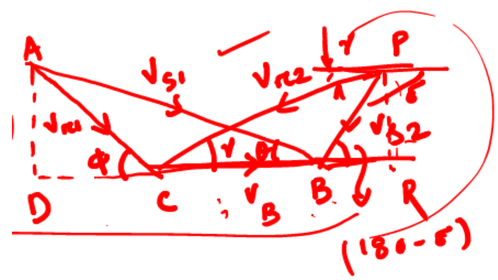
So, in our previous lecture we have similar problem, but here it is proposed to have the problem based on the stages. So, basically speaking the problem is based on impulse turbine which works on number of pressure stages. So, we mean that this is a pressure compounding type impulse turbine and that means each stage will have own sets of nozzles and moving blades and we need to concentrate on one particular stage. So, one thing we can assume while talking about number of stages is that the enthalpy drop is divided equally among the number of stages. So, basically each stage gives equal amount of work.

So, with this assumption we will proceed for solving this particular problem, but here our attention will be on one stage only and for that one stage we are going to draw this velocity diagram. And since it is an impulse turbine so, velocity diagrams are concentrated with respect to one particular blade and this particular blade will have inlet triangle & outlet triangle.

So, for this we have nozzle angle, $\theta$ ; we have the blade angle, $\emptyset$; then we have the fluid exit angle, $\delta$; and this blade angle, $\gamma$. So, before that things you have already understood what this inlet and outlet velocity triangles is. Now to solve this problem, we need to combine these two diagrams and draw with same blade velocity, $V_B$.








Combining both the velocity triangles, a single graph is drawn. So, then we can drop one vertical to make it a right angle triangle we can name this triangle such ADCBPR

So, once you have drawn this angle then we need to analyze this velocity triangles.

Data Given:

Mean velocity, $V_B = 130\ m/s$

Velocity of the steam entering the nozzle, $V_{s1} = 30\ m/s$

$\theta = 20°;\ \gamma = 30°;\ \eta_n = 85\%$

$$k_v = \frac{v_{r1}}{v_{r2}} = 0.8$$

a) We need to find out work done per kg of steam and blade velocity.

Work done, $\dot{W} = \dot{m} V_B (V_{s1} \cos\theta - V_{s2} \cos\delta)$

Work done per kg, $\dfrac{\dot{W}}{\dot{m}} = V_B (V_{s1} \cos\theta - V_{s2} \cos\delta)$

Of course, we do not know these numbers. So, this data and this velocity triangle will help us in estimating this angle.

So, let us try to concentrate inlet triangle.

$$AD = V_{r1} \sin\emptyset = V_{s1} \sin\theta$$

$$CD = V_{r1} \sin\emptyset = BD - BC$$

$$\Rightarrow V_{r1} \cos\emptyset = V_{s1} \cos\theta - V_B$$

Then both the two equations will give you

$$\tan\emptyset = \frac{V_{s1} \sin\theta}{V_{s1} \cos\theta - V_B} = \frac{330\ \sin 20°}{330\ \cos 20° - 130} = 0.62\ \Rightarrow\ \emptyset = 32°$$

Now

$V_{r1} \sin \emptyset = V_{s1} \sin \theta$

$\Rightarrow V_{r1} = \frac{V_{s1} \sin \theta}{\sin \emptyset} = \frac{330 \ \sin 20°}{\sin 32°} = 213 \ m/s$

We know,

$k_v = \frac{v_{r1}}{v_{r2}} = \ 0.8 \Rightarrow V_{r2} = 0.8(213) = 170.4 \ m/s$

Now we will move on to the outlet triangle.

$PR = V_{r2} \sin \gamma = V_{r2} \sin(180 - \delta) \Rightarrow \ V_{r2} \sin \gamma = V_{s2} \sin \delta$ - - - - - - - - (1)

Other expression that we can get from this

$CR = CB + BR \Rightarrow V_{r2} \cos \gamma = V_B + V_{r2} \cos(180 - \delta) = V_B - V_{r2} \cos \delta$ - - - - - - - - - (2)

From equation

$\tan \delta = \frac{V_{r2} \sin \gamma}{V_B - V_{r2} \cos \delta} = \frac{85.2}{-17.6}$ = -4.84 $\Rightarrow \ \delta = 102°$

So, $\delta > 90°$; we will see that how this helps us in calculating the power.

Now

$V_{s2} = \frac{V_{r2} \ \sin \gamma}{\sin \delta} = \frac{170.4 \sin 30°}{\sin 102°} = 87 \ m/s$

Work done per kg,

$\frac{\dot{W}}{\dot{m}} = V_B(V_{s1} \cos \theta - V_{s2} \cos \delta)$

$= \ 130(330 \cos 20° - 87 \cos 102°)$= 130(310+18) = 42.64 kJ/kg

Blade efficiency, $\eta_b = \frac{\dot{W}/\dot{m}}{V_{s2}^2/2} = \frac{2 \times 42.64 \times 1000}{330 \times 330} = \ 78.3\%$

b) We have to find out what is the enthalpy drop.

So, for that reasons we have to draw this either enthalpy Mollier diagram or temperature entropy diagram.


So, we can see that steam which is available and the drop takes place that is 2s-1 or 1-2.

So, with reference to steam table at 20 bar & 250 °C $\Rightarrow h_1 = 2902.3\ kJ/kg$

In this process had it been isentropic, we would have

$s_1 = s_{2s} = 6.6546 = s_f + x\, s_{fg}$

$s_f$ & $s_{fg}$ has to be calculated at 0.07 bar.

$s_f = 0.5582$ kJ/kg.K; $s_{fg} = 7.7198$ kJ/kg.K

$h_f = 163.16$ kJ/kg; $h_{fg} = 2409.54$ kJ/kg

With all these values we can get, $x = 0.7757$

Now

$h_2 = h_f + x\, h_{fg} = 2032.9$ kJ/kg

Turbine efficiency, $\eta_t = \frac{h_1 - h_2}{h_1 - h_{2s}} = 0.7$ (data given)

$\Rightarrow h_1 - h_2 = 612.6\ kJ/kg$

So, basically the steam which is available at 20 bar and 250 °Chas to drop this much enthalpy to arrive at the condenser pressure. But our work done per kg of the steam is about 42.64 kJ/kg which means that per stage we are able to recover only 42.64 kJ/kg.

So, this means number of stages $=\frac{(\Delta h)_{tot}}{(\Delta h)_{stage}} = \frac{612.6}{42.64} \approx 15$

Hence, we require 15 number of stage to drop about 612.6 kJ/ kg enthalpy of the steam by equally dividing in them with work output as 42.64 kJ/kg.. That means, 15 number of stage is being used and it is nothing, but a pressure compounded impulse turbine. So, with these discussions, thank you for your attention.