POWER PLANT SYSTEM ENGINEERING

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Module 4

Lec 1: Hydro-Power System: Part-I

Dear learners, greetings from IIT Guwahati. We are in the MOOCs course Power Plant System Engineering module 4 that is Hydro and Renewable Energy Power Generation Systems. So, in the first component of this module, we will focus on hydropower systems part 1. So, in this hydro power systems or in this lecture we will try to give some glimpses of hydroelectric power plants, its components, what are the different elements that are the part of this hydroelectric power plants. And most important features is the hydraulic turbine which is the main backbone for this hydropower system, in which power is developed from water.

And one such turbine is a Pelton wheel and we will discussed about the fluid mechanics and theoretical aspects of this Pelton wheel concepts and how it becomes useful for harnessing water power. So, let us try to see the feasibility of water power, what does this mean? The power which is available from water is normally called as hydraulic power. One can write a fundamental equation like power available from water is density multiplied by something like potential head or potential energy available in water.

Power available from water(hydraulic power), $P = \rho g Q H$

g:Acceleration due to gravity $\left(9.81\,\frac{\text{m}}{\text{s}^2}\right)$; H:Height of fall of water(Head)

Q:Volume flow rate of water;ρ:Density of water $\left(1000\,\frac{\text{kg}}{\text{m}^3}\right)$

That means, we are keeping some slug of or some quantity of water at a certain height and the density of water is 1000 kg/m^3. If you increase Q or H then we can have enormous amount of power which can be available from water. So, it means that if you try to use this water for electrical energy conversions, then one can write a fundamental equation stated below.

Electrical energy production, $W = 9.81 Q H \eta t$ kWh

η:Efficiency of turbine-generator assembly$(0.5\text{to}0.9)$; t:Operating time in hours $\left(8760\,\frac{\text{hr}}{\text{year}}\right)$

So, what it means that, by increasing Q and H and if the turbine can operate throughout the year that is 8760 hour per year, then we can see that this quantity is very huge. So, in other words, we can say there is certain feasibility of water power if it can be harnessed properly.

Then let us look into the possibilities, how we can harness. One way to look at it is when we have rain and it is falling on earth surface, then we have its potential energy availability. When it rains and rain water proceeds towards ocean in its path through the rivers. So, if we can see that river is available at certain height and if that slug of mass of water or the quantity of water is taken as the volume flow rate of water, then we can use that height of the reservoir or refer river to harness the water power. And since we do not require any kind of fuels, we call this as a natural available renewable energy source. So, the theme of this hydropower plant is that, the energy of water is being utilized to drive the turbine and in turn it produces the electricity. And apart from the thermal power, the water power is the next level power production unit and we call this as a hydroelectric power plant.

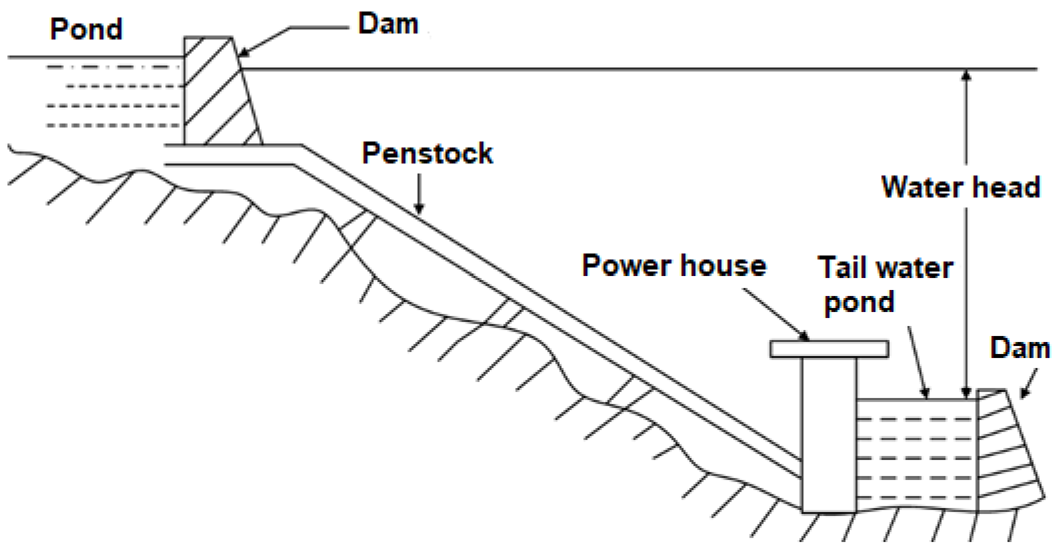
And till date 20% of the total power of the world is made by hydropower stations. Now, let's see the different advantages of hydroelectric power plants. So, basically water is perennially available in most of the rivers. Since there is no fuel is required, we can call it as white coal, it is a renewable form. The running cost of hydro power station is very low as compared to its competitive like thermal and nuclear power station. There is no concept of pollution.

Modern hydro generators have high efficiency over considerable range of load variations.

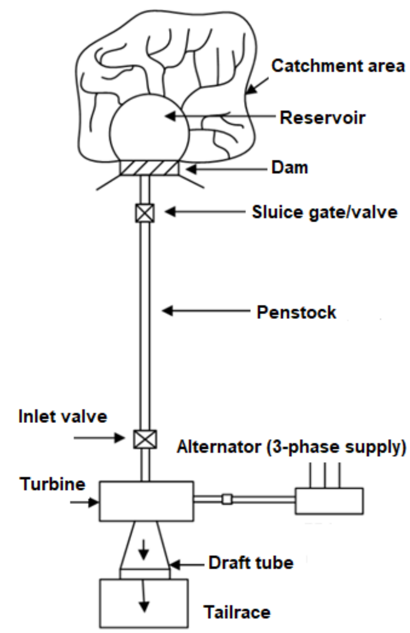
That means, hydroelectric turbines can be switched on or off in a very short time. Hydro power is emission free and it does not produce any greenhouse gases. The concept of hydro power plant is very simple and its system reliability is greater than any other power plants. Hydro power plants have a very greater life expectancy that means, if you install a hydro power station today and assuming that water will be available or the river will be existence for another 50 years, then as long as water is available, we can think of its life expectancy is about 50 years or more as compared to any other competitors like thermal or nuclear power plants. Hydro power plants are ideal spinning reserves and it can be integrated with other power plants. It provides the geographical ecosystems that means, with benefits of irrigation. As you need to store water through a dam, depending on the requirement of irrigations the water can be controlled. So, it helps in afforestation, navigation, aqua culture. And being simple in design and operations, hydro power plants do not also require any skilled manpower.

So, there are many advantages, but there are some loopholes or demerits. The hydro power generation incurs a very high capital cost with low rate of return that means, it is requires almost 15 to 20 years to get back the return on the entire infrastructure investment. And this power station is highly dependent on the quantity of the water which is available. And moreover hydro power plants are site specifics and because of these reasons they incur transmission losses. Somewhere there will be grid available, but the hydro power plant has to be located in restricted sites. Many a times the hydro power plants may disturb the ecology of the systems. So, emphasis is more given for small, mini or micro hydro power stations. Instead of thinking of a large power station, people nowadays think of mini or micro hydro power stations.

So, this is some of the schematic diagram. If you look at mini or micro hydro power stations, we can imagine to have water availability in a pond, construct a dam and allow the water through some pipes. Then it goes to the turbine and power house where we can harness this water power. So, available head for this is called as water head. So, such a simple concept can also be utilized through micro or mini hydel power stations.



Now, let us look into the complete features or elements of this hydroelectric power plants. This figure is the schematic diagram or layout of hydroelectric power plant. Here we can see the catchment area. So, it is the big area which is available or it is a river area across which the river spreads with a very steeper slope because we need to have a slope or free fall of water.



Layout of a hydroelectric power plant

So, we require some slope and in which a dam can be constructed. So, in a catchment area of river is a reservoir and this reservoir will be located across a dam. Then controlled water can come through this sluice gate or valve through pipelines, also called as a penstock. That means, in hydropower terminology this penstock is simply the water pipe. Then through this penstock, water goes to the turbine end. So, here at the turbine end we harness the power and then it can be integrated with alternator so that electric power generation can be possible.

Then the discharged water has to go through the tail rest. Tail rest is another kind of a catchment area where water is being discharged. One most important thing is that the water has to pass through a draft tube and this draft tube is a very significant component of this power plant unit because it creates a necessary control pressure difference upstream and downstream and water has to go in a smooth manner to the tail rest. So, with this objective so that it does not incur many hydraulic losses. So, these are the essential components.

So, I explained about the catchment area and dam. Then then we have the reservoir which is like natural water bodies, river or lake. Dam has to be constructed. This dam is required because we need to have a continuous operation of the turbine. So, we need to have a storing capacity. That means, we must have an estimates how much water should be available or volume flow rate of water is available while maintaining appropriate head. So, one can think of a dam to have a moderate head with large storage capacity or high head with small storage. So, these two possibilities we can think of, while constructing a dam.

Then next important component is spillway. Now, water flows through this penstock or dam, in some cases when the stability of the dam is in danger, then we should have provision for this reservoir basin to dispose of some of the water. That means, excess water should be relieved and this is relieved through a structure which is called as a spillway. So, in general it provides structural stability to the dam without raising the reservoir water to high flood level. Then the passage of water in a channel known as head race and it leads to the water in a conduit. Now for the water to come from the dam to the turbine, the possible ways that we can think of is a closed passage typically a penstock or pipe and we call this as a conduit. Since it is a closed conduit, a regulated pressure difference between the reservoir and turbine end is maintained. Other possible option is that we can open up this penstock that means, we can think of the penstock as an open channel flow from the reservoir end to turbine by assigning suitable slope for the passage of water. So this way we call this channel has two components, one is head race, other is the tail race. So, in that case what happens that entire flow through this open channel is almost atmospheric. So, this is another kind of possibility we can have while thinking for the passage of water from reservoir to turbine end.

Then we have other component like a surge tank. So, surge tank is nothing, but a small reservoir in which water level rises or falls to reduce the pressure swings when they are not transmitted in the closed conduit that means, when we have a penstock or closed conduit that means, we have a controlled pressure difference. Now, let us assume that the water is passing through an open channel or in a lake, in that case sometimes there is a reservoir basin that has a very high water then of course, the quantity of water in the lake will be also high. So, a surge tank is required so that it does not allow excess water. And most important component here the draft tube. So, draft tube is a divergent configuration which is made when the water is discharged from the turbine. So, this diffuser action of the draft tube regains major portion of the kinetic energy or velocity of the runner at the outlet which otherwise would go as a waste or exit loss. Then last component is called a power house. It is nothing, but a stable structure which has all types of plant equipment like hydraulic turbines, electric generators, governors, valves, storage batteries, switchboards etc.

Now, let us see how the hydro power plants can be classified. So, the classifications are normally done based on the availability of head. One can think of high head, medium head and low head. And this also can be linked to the quantity of water availability; high discharge, low discharge or medium discharge. So, accordingly we can say that we can think of mini or micro-hydel power plants, run-of-river without pondage, run-of-river with pondage, storage reservoir and all. The other way of classification is the nature of load that is base load or peak load. That means, whether the hydro power plant is designed for a simple base load operations or it is required to cater the peak load, that means, at the time of demand it can give the excess power. So, that way we call this as an electric load which is linked to this alternator and this alternator is further integrated to the turbine.

Then to give some estimates for example, if you think of a mini power plant, it operates with a height of 5- 20 m and it produces power in the range 1-5 MW. While micro power plants work under a head below 5 m, and produce the electricity range from 0.1-1 MW. But in any case we can go for maximum energy resources from the water up to 20,000MW. That means, it is a very high structure or it is a large scale hydroelectric power plant.

Now, let us move on to next segment which is hydraulic turbines. In fact, it is the backbone of a hydroelectric power plants because they convert potential energy of the water into the shaft work which in turn is coupled with the electric generator for producing the power. So, historically hydraulic turbines are derived from water wheels. So, initially there was no concept of hydraulic turbines rather people used to call this as water wheel. One such name comes up that is a Pelton wheel, but with more developments in recent days and based on that the hydraulic turbines are classifieds with difference in the elevation of water surface available between upstream and downstream of the turbine. And here if you look at this particular turbine, we have the reservoir and we have the tailrace, tailrace means where water is discharged. That means, the storage at this point and dispose of water at this point. So, we call this as a gross head. Now, coming back, water comes through certain pipelines. So, that is the reason we call this as a hydraulic grade lines which incurs a loss of h_f. So, ultimately the net head which is available to the water is H which is nothing, but the difference between gross head and hydraulic loss. And that head is varies in the range 2 to 2000 m. So, when it is low head we say 2-15 m, when you say medium head it is 16-70 m, when you say high head it is 71- 500 meters and very high head mean above 500 m. So, more or less we can say 2000 m is the topmost level in which the potential energy of water can be available. Now, depending on the availability of the flow the turbines are classified as low turbines and one such case is a Pelton wheel, medium availability of the flow and high discharge flow. So, we have Pelton wheel, Francis turbines and Kaplan turbines.

And apart from these the hydraulic turbines are classified based on the head and quantity of the water available to us. Second category is the working principle of the blade that is what I have mentioned earlier. When we say that passage of the water is through a penstock or controlled manner, then entire slug of water goes and heats the turbine and it is used for harnessing water power, this is one way. Other way to look at is that whatever potential energy available in this reservoir, first it is converted to kinetic energy by passing it through a nozzle and this kinetic energy is used to strike on blades or buckets on a wheel which rotates. So, that is another working principle. Another way is that direction of flow of water that means, initially it can be radial and final outlet from the turbine could be axial or it may be vice versa or it can be mixed flow. So, depending on the direction of the water flow it can also be specified. Classifications are also done depending on the axis of the shaft and also depending on the specific speed. Specific speed decides whether it is a very slow runner or a very fast runner.

So, whatever I have explained, this has been noted down here. Based on the mode of conversion of potential energy of water into shaft work the turbines are classified as impulse and reaction turbines. And in impulse mode the available head of water is converted to kinetic energy in a nozzle and then the water shoots out from the nozzle as a free jet at atmospheric pressure before and after striking the vanes of the turbine. Now another way of looking at is when the entire flow of head which is available in the reservoir is used to pass through a close conduit then it works in a reaction mode and in this reaction mode a control pressure difference is maintained and here the water is simply guided to strike on the blade. So, there is no conversion of the potential energy to kinetic energy in between. So, that is called as a reaction mode. We will try to explain subsequently about this impulse and reaction concepts.

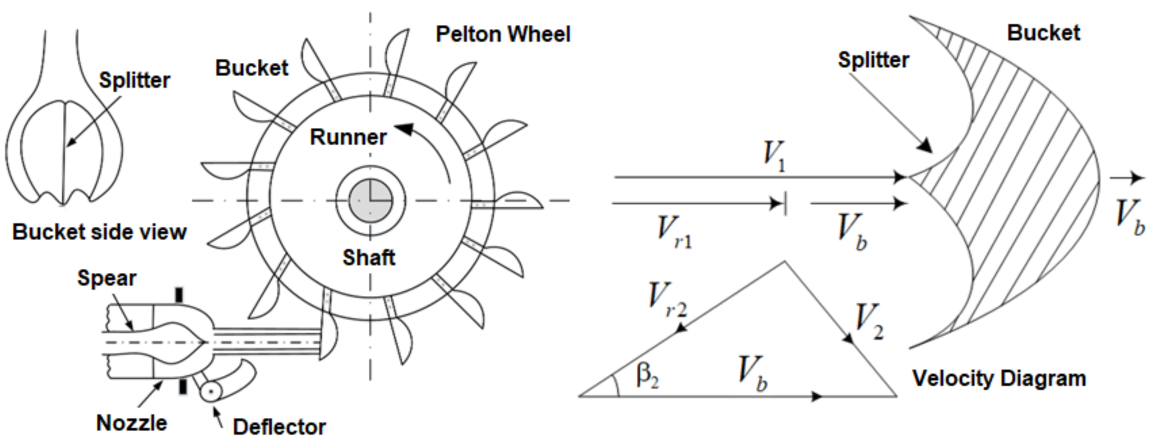
Then depending on the orthogonal directions of the turbine, it can be considered as a radial flow which is a Francis turbine, axial flow like Propeller and Kaplan turbine and tangential flow for Pelton turbine with respect to wheel and the shaft axis refers to the axial direction. Now, when the flow at the inlet is radial and axial at outlet then we call this a mixed flow. If the flow is neither parallel to axis nor perpendicular then it moves in an angular direction with respect to axis then, we call this a diagonal flow and such an example is Deriaz turbine.

Now, turbine shaft can be either vertical or horizontal. So, Pelton turbines have horizontal shaft while other turbines have vertical shafts. The last feature of classification is through specific speeds. More details about the definition of the specific speeds will be discussed in the subsequent class, but the bottom line or importance of this specific speed with respect to physical significance of the turbine is that low specific speed denotes slow runner and high specific speed denotes fast runner.

So, this is the overall complete classifications which is shown in the tables for the water turbines. We can say there are four categories of turbines, Pelton, Francis, Propeller & Kaplan and Dariaz turbine. Depending on the flow directions, they can have a tangential flow, radial, axial, diagonal flow. Based on the specific speeds, we can say slow, medium and high. So, in the slow range we have Pelton wheel, we have Francis turbine, we have

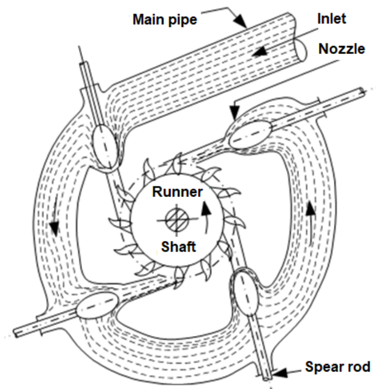
Kaplan turbine. Then classifications based on the size of the turbines, here we can have maximum head, maximum power, maximum diameter and also specific speed. So, we can say Pelton turbines have low specific speed whereas Kaplan turbines have very high specific speed. And if you link these two to head, normally Pelton wheels can operate at very high head. And when availability of head is less then we can go for a Kaplan turbine. So, that way the judgment is done, depending on locality, what type of turbine is best suited at that particular site.

Now, let us move on to the first class of turbine which is called as Pelton wheels. So, the summary is that these are impulse turbines, they are used for high head installations. The main working principle is that whatever water is available, that is first converted to the kinetic energy in nozzle and the nozzle discharges free jet of water that hits on the bucket which revolves around a shaft. So, this figure says that we have a shaft and across the shaft there is a runner. This runner uses the bucket. Now, wherever the water is available and it comes in a nozzle and this nozzle gives the free jets. There is a deflector whose position keeps on changing as the buckets are passed one by one.



So, when the first jet of water hits this bucket, it pushes the runner to rotate, so that next bucket again gets interacted with this water jets. So, through this process we can have a continuous rotation of this wheel and that is the reason we call it as a Pelton wheel. Pelton is the name of the scientist who proposed this concept of water wheel and since then it is called as a Pelton wheel.

Now, in order to make the estimates of how much energy that is being transmitted to the shaft, we need to explore this velocity diagram. So, when you see this water jet, we can say that velocity of the water is V_1. And it is goes as a jet and this velocity of the water is being utilized. Since the runner rotates at a rotational speed and this rotational speed based on the diameter can be considered as a linear speed of this bucket that is V_b which we can estimate based on the rotation. So, the total velocity of the jet is initially V_1 and it has two parts V_b & V_{r1}. And the water comes and hits a jet and it goes out through this bucket in this fashion and we have a splitter. So, when the water gets discharged from this bucket it is ensured that the discharged water does not interact with the inlet water jet, otherwise it will create an interference. So, based on that the velocity triangles can be constructed, one at inlet and one at outlet. So, through this process we can say that bucket is induced with a velocity V_b and also we can include this angle β_2. And in the next diagram I will show you how this velocity diagram is useful for harnessing the power.



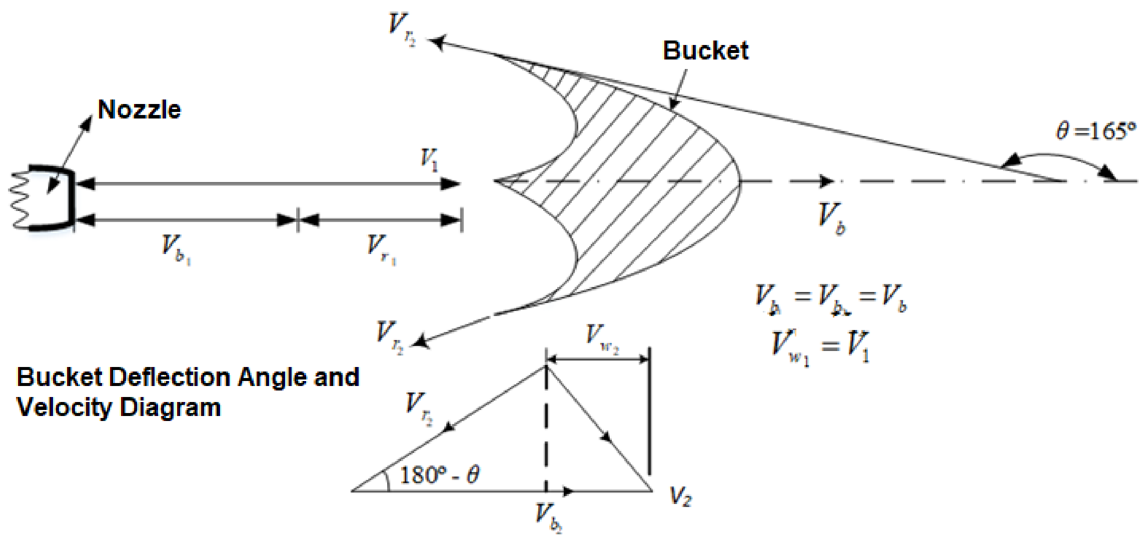
Multi-jet Pelton Wheel Arrangement

Now moving on to some deeper concept of this water jets, this is another kind of Pelton wheel arrangement which involves multi jets. So, in this previous figure we are showing that there is only one jet which is hitting water, but the concept can be extended to multiple jets. That means, you can see in the diagram water is coming from the inlet and it keeps on interacting with multiple nozzles, which are kept through these spear rods and this nozzles allow the water jets to hit these buckets at multiple locations. And this is what we call as a multiple Pelton wheels arrangement. So, in general we can go up to maximum 6 jets and through this we can achieve maximum specific speed of 30. There is an expression in which we can find out that depending on the number of jets, we can increase the specific speed for this particular Pelton wheel turbine. That means, initially when you had a single jet, we had relatively less specific speed but when we have more number of jets then we can increase the specific speed for the same turbine. So, that is called as a multi jet Pelton wheel arrangement.

Specific speed for multi-jet machine, $(N_s)_{mj} = \sqrt{n}(N_s)_{sj}$

n:number of jets ; $(N_s)_{sj}$:Specific speed of single-jet machine

Now this particular diagram gives you the concept of how to harness the water power or what is the energy transferred from the water to the turbine. So, for that we have to refer this velocity diagram. So, let us try to understand these velocity triangles at both inlet and outlet. We can see a nozzle and this nozzle gives you velocity V_1 which is the absolute velocity of the water jets. So, it has two components that is bucket component and relative velocity components and initially all are in the same line. And when the water goes out, it gets deflected in a certain manner and this deflection is normally kept as 165° and it is the most ideal way.



The main reason for keeping this deflection is that, when the water goes out or water exits from the bucket it should not interact with the main stream. That means V_{r2} & V_1 should not interact with each other. So, for that reason, this angle is designed and optimum angle has been fixed at 165°, so that it ensures maximum power subjected to no interaction of inlet and outlet water jets. Then we can introduce a parameter which is called as jet ratio. It is a sizing parameter which is the ratio of diameter of the bucket to the nozzle diameter and its value is in the range of 10 to 24.

Now, next thing is that how to quantify all parameters.

Velocity of the bucket, $V_b = \omega r = \frac{\pi D N}{60}; r = \frac{D}{2}$

(Bucket radius)Angular velocity,$\omega = \frac{2\pi N}{60}$; N:RPM of the wheel

Jet ratio,$J_r = \frac{D}{d}$; d&D:Nozzle and bucket diameter

Absolute velocity of water jet issuing from nozzle,$V_1 = C_v\sqrt{2gH}$

H:Net head for wheel; C_v:Coefficient of velocity(0.97 to 0.99)

So, here C_v is normally the coefficient of the velocity, as you can see that the relative velocity do exist between inlet and outlet so there is a loss coefficient and that loss coefficient is accounted in the range 0.97 to 0.99. So, this is the standard expressions in which V_1 is calculated.

Then next important segment is how to find the energy transfer and work output. The velocity of the jet issuing from the nozzle can be calculated based on the net head available at the nozzle and energy transferred to the wheel can be found out by using Euler equation.

Total energy transferred to the wheel(Euler equation): $E = \frac{(V_{w1}V_{b1} - V_{w2}V_{b2})}{g}$

Now, let us see what is V_{w1}, V_{b1}& V_{w2}, V_{b2}. So, if you look at this particular figure 1 stands for inlet 2 stands for outlet. So, at the inlet, if you look at bucket velocity, we can think that $V_{b1} = V_{b2} = V_b$. V_b is the linear velocity of the bucket. And coming back to V_{w1}& V_{w2}, it has two components. If you see the component of absolute velocity of water in horizontal direction we call as a whirl component and at the outlet, this horizontal component is V_{w2} and at the inlet, it is V_{w1}, which is nothing but V_1 itself because V_1 is purely in horizontal direction. There is a deflection angle 165° and water goes out at certain angle with relative velocity V_{r2}. Due to this relative velocity V_{r2} with same bucket velocity V_b, we will have absolute velocity V_2 and its horizontal component is V_{w2}.

So, through this diagram the Euler equation is been derived and finally for this Pelton wheel we write the equation as below.

$$E = \frac{(V_{w1}V_{b1} - V_{w2}V_{b2})}{g} = \frac{V_b}{g}(V_{w1} - V_{w2})$$

Now, from this velocity diagrams V_{w2} can be found out by considering V_{r2} & V_b. And this V_{r2} can be expressed in terms of blade friction coefficient. There is a difference in the velocity at the inlet and outlet in terms of absolute velocity and also relative velocity, which is expressed in as blade friction coefficient, k. So, that way V_{r2}can be linked to V_1& V_b through a factor k.

$$V_{w1} = V_1; V_{w2} = V_b - V_{r2}\cos(180 - \theta) = V_b + k(V_1 - V_b)\cos\theta$$

k:Blade friction coefficient $\left(= \frac{V_{r2}}{V_{r1}}\right) \Rightarrow V_{r2} = kV_{r1} = k(V_1 - V_b)$

So, putting these two expressions, we arrive at the energy transferred to the wheel as

$$E = \frac{(V_{w1}V_{b1} - V_{w2}V_{b2})}{g} = \frac{V_b}{g}(V_{w1} - V_{w2}) = \left(\frac{1 - k\cos\theta}{g}\right)(V_1V_b - V_b^2)$$

V_b:Velocity of bucket $\left(= \frac{\pi DN}{60}\right)$; V_r:Relative velocity of water

V_w:Velocity of whirl of water(tangential component)

V:Absolute velocity of water; θ:Bucket deflection angle$(= 165^0)$

Subscripts 1 & 2:Conditions of water at inlet and outlet of bucket

And moreover emphasis is given that bucket deflection angle is always kept as 165°.

Now through this expression for energy transferred to the wheel, one can find out the optimum velocity for the bucket because that is the need of the essential design feature. The optimum velocity at which bucket has to move also refers to the case for maximum energy. For harnessing maximum energy this expressions can be differentiated with respect to V_b so that we can find E_{max}, maximum energy that can be harnessed.

Total energy transferred to the wheel: $E = \left(\frac{1 - k\cos\theta}{g}\right)(V_1 V_b - V_b^2)$

For given value of V_1, k and θ,maximum energy $\Rightarrow \frac{dE}{dV_b} = 0; E\left(\frac{1 - k\cos\theta}{g}\right)\left(\frac{V_1^2}{4}\right)_{\max}$

Optimum bucket velocity for maximum work output $\Rightarrow V_b = \frac{V_1}{2}$

So, this means that bucket moves half of the jet velocity. Now another expressions we can find out for the efficiency level at which this wheel operates. One term or one efficiency that is defined as hydraulic efficiency. The other synonymous terms are blading efficiency or diagram efficiency because these efficiencies are calculated based on the velocity diagrams. So, hydraulic efficiency is defined as the ratio of energy transferred to the wheel to the kinetic energy of input jet. Now we can first find out what is the energy transferred to the wheel, then by introducing the kinetic energy in the denominator, we can define hydraulic efficiency. And we can also define a parameter which is called as velocity ratio.

Total energy transferred to the wheel: $E = \left(\frac{1 - k\cos\theta}{g}\right)(V_1 V_b - V_b^2)$

Hydraulic efficiency, $\eta_h = \frac{E}{\left(\frac{V_1^2}{2g}\right)} = 2(1 - k\cos\theta)(\rho - \rho^2)$

Kinetic energy of input water jet $= \frac{V_1^2}{2g}$; Velocity ratio,$\rho = \left(\frac{V_b}{V_1}\right)$

So, hydraulic efficiency is defined and subsequently for maximum hydraulic efficiency, one can also obtain that optimum velocity ratio is $1/2$. This means, either you take maximum efficiency or you take maximum work output the ratio of velocity of the bucket to the jet velocity is always $1/2$. So, this gives an indications that maximum bucket velocity is always half of the velocity with which jet strikes on the bucket. So, this is a very fundamental expressions for a Pelton wheel. Once we know the jet velocity, we can easily find out the bucket velocity. And with this design condition, the Pelton wheel is always allowed to operate. And for this optimum velocity, we can also find out hydraulic efficiency for maximum work and this also is same as what we have estimated earlier in the expression for E_{max}.

Hydraulic efficiency, $\eta_h = \dfrac{E}{\left(V_1^2/2g\right)} = 2\left(1-k\cos\theta\right)\left(\rho-\rho^2\right)$

For maximum hydraulic efficiency, $\dfrac{d\eta_h}{d\rho} = 0 \Rightarrow \rho_{opt} = \dfrac{V_b}{V_1} = \dfrac{1}{2}$ & $\left(\eta_h\right)_{\max} = \dfrac{1-k\cos\theta}{2}$

Hydraulic efficiency for maximum work, $\left(\eta_h\right)_{\max} = \dfrac{E_{\max}}{\left(V_1^2/2g\right)}$; $E_{\max} = \left(\dfrac{1-k\cos\theta}{g}\right)\left(\dfrac{V_1^2}{4}\right)$

$\Rightarrow \left(\eta_h\right)_{\max} = \dfrac{1-k\cos\theta}{2}$; For $k=1$ & $\theta = 180^0 \Rightarrow \left(\eta_h\right)_{\max} = 1$

Typical values, $k = 0.8$ to 0.85 & $\theta = 165^0 \Rightarrow \left(\eta_h\right)_{\max} = 0.88$ to 0.91

θ: Bucket deflection angle $\left(=165^0\right)$; k: Blade friction coeficient; Velocity ratio, $\rho = \left(V_b/V_1\right)$

V_b: Velocity of bucket $\left(=\dfrac{\pi DN}{60}\right)$; V_1: Absolute velocity of water

Now here by a close look we can say that when $\theta = 180°$, we can have maximum hydraulic efficiency that is 1. But in this case, we will have other problem that means, if θ becomes 180°, then the exit velocity will also oppose the inlet velocity, and this will have a detrimental effect on the power production. So, this particular option is always ruled out. So, the ideal number that is chosen for θ is 165°. And when θ is 165°, the corresponding blade coefficient falls in the range from 0.8-0.85 and this will give a hydraulic efficiency close to 0.88 - 0.91. So, that is the entire idea for a Pelton wheel to operate.

Then comes the last segment, Once we have velocity & energy, then we can also find out the discharge. With known condition of jet velocity and bucket velocity of the wheel, maximum energy output & volume flow rate can be calculated.

Of course, large size Pelton wheel always operates with a multi jet concept which can be used for very high head, to produce the power of maximum range up to 240MW. But there are some side effects of this Pelton wheel. The most common issue with Pelton wheel is the erosion that arises because this wheel operates throughout the year. So, there is an erosion of the blade that arises. And also there are issues with cavitation of the nozzles. For that reasons, to protect the buckets, typical choice of material is chrome alloy steel or stainless steel. So, these are some of the design features or characteristics for a Pelton wheel.

Absolute velocity of water jet issuing from nozzle, $V_1 = C_v\sqrt{2gH}$

Volume flow rate of water(discharge), $Q = AC_v\sqrt{2gH}$

Velocity of bucket(wheel), $V_b = \frac{V_1}{2} = \phi\sqrt{2gH};\ H$:Net head for wheel

C_v:Coefficient of velocity $(0.97\text{to}0.99);\ \phi$:Speed ratio $(0.43\text{to}0.48)$

Minimum number of buckets in the wheel, $z = \frac{J_r}{2} + 15;\ J_r$:Jet ratio $\left(= \frac{D}{d}\right)$

So, these are some realistic numbers that are normally used in the hydro power plants. So, this concludes, but before we leave from this lecture, let us try to understand a numerical problem based on this Pelton wheel.

Q1. A Pelton wheel with two similar jets operates at net head of 200 m. It transmits 5 MW power to the shaft running at 500 rpm. The power transmission efficiency through the pipelines and nozzles is 90%. The jets are tangential to a 1.5 m diameter circle with relative velocity decrement of 10% as it passes through the bucket. The blade deflection angle is 165°. Calculate the efficiency of the runner and diameter of the jet.

So, the problem statement says that a Pelton wheel has two jets. So, instead of multi jet, we say it is a two jet Pelton wheel that means, n = 2 and it works at a net head of 200 m. It transmits 5 MW power, while running a shaft at 500 rpm. The transmission efficiency through the pipeline and nozzle is 90%. The jets are tangential to a 1.5m diameter circle with relative decrement of 10% as it passes through the bucket. Blade deflection angle is 165°. We need to find out the efficiency of the runner and diameter of the jets.

To solve the problems we have to refer this particular velocity diagram in which we can say that initially water jets from the nozzle hits and it splits into two parts and water gets deflected by an angle 165°. So, to solve the problem first thing we have to recall is V_1, the absolute velocity of the water jet.

$V_1 = k\sqrt{2gH}$; Here data given, $H = 200\text{m}$

Now, there is a relative velocity decrement of 10%, so it is assumed that $k = 0.9$. So, putting this number we can say $V_1 = 0.9\sqrt{2 \times 9.81 \times 200} = 56.4\ \text{m/s}$.

So, once we know V_1 we can also estimate bucket velocity V_b.

$$V_b = \frac{\pi DN}{60}; N = 500\ \text{rpm}, \text{Diameter of the wheel}, D = 1.5\text{m}$$

$$\Rightarrow V_b = 39.3\ \text{m/s}$$

Now, we need to find out the efficiency of the runner.

$$\text{Hydraulic efficiency}, \eta_h = \frac{E}{\left(V_1^2/2g\right)}$$

$$\text{Now, Total energy transferred to the wheel: } E = \left(\frac{1 - k\cos\theta}{g}\right)(V_1 V_b - V_b^2)$$

So, putting this expression in the hydraulic efficiency,

$$\Rightarrow \eta_h = \frac{2\,(1 - k\cos\theta)\,(V_1 - V_b)V_b}{V_1^2}$$

$$\Rightarrow \eta_h = \frac{2\,(1 - 0.9\cos\theta)\,(56.4 - 39.3)39.3}{56.4^2} = 83\%$$

So, the first part of the question we got, that is hydraulic efficiency of the runner is 83%. Now, let us see, how to find out the diameter of the jet. Because we know there are two jets, so one can say how much power these can develop. As the turbine transmits 5 MW, so Power transmitted is 5000kW.

$$\text{So Power developed}, P = \frac{5000}{\eta_h} = 6024\ \text{kW}$$

Since there are two jets, Power developed per jet $= \frac{P}{2} = 3012$ kW

Power developed per jet $= \frac{1}{2} m V_1^2 = 3012 \times 10^3$

Now, $m = \rho A V_1$; $A = \frac{\pi}{4} d^2$; $d =$ diameter of the jet; density of water, $\rho = 1000\ \text{kg/m}^3$

So, we can rewrite the equation for power developed for jet as below.

$$\frac{1}{2} \rho A V_1 \times V_1^2 = 3012 \times 10^3 \Rightarrow d = 0.2 \text{ m}$$

So, the nozzle produces a water jet of diameter equal to 0.2 m. So, for this diameter, the hydraulic efficiency is 83% and it transmits power of 5MW, while running shaft at 500 rpm. So, with this I conclude. Thank you for your kind attention.