Principle of Hydraulic Machines and System Design
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Lecture – 26
Impulse Turbine: Pelton wheel – II

So, we have discussed about the Pelton wheel; which is an impulse turbine. And we have discussed about the net head available on the wheel. So, the net head available on the wheel is $H_{gross} – Z - H_l$. So, if I go back to my previous slide where it is clearly seen that the net head available is of course, the total gross head is basically the you know head available between the HRL and TRL that is head race level and tail race level.

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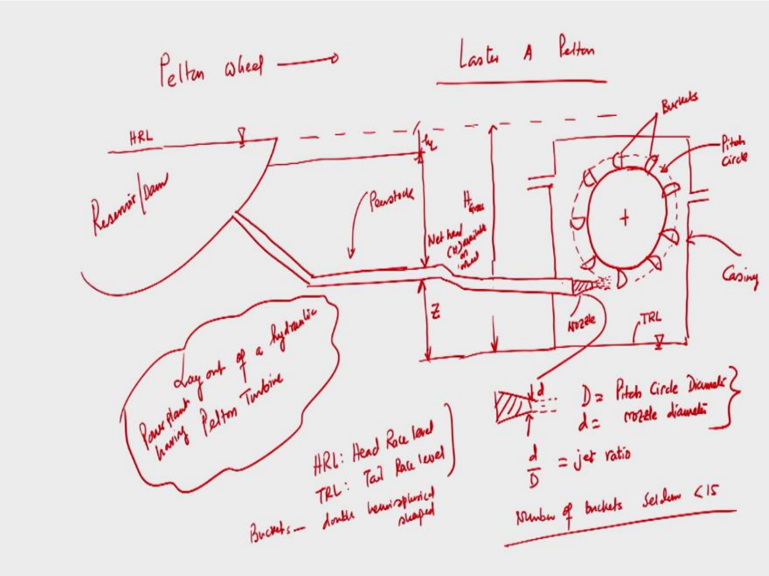

But the net head available on the wheel is H gross minus this height z and the frictional losses that is there when liquid fluid is flowing though the penstock.

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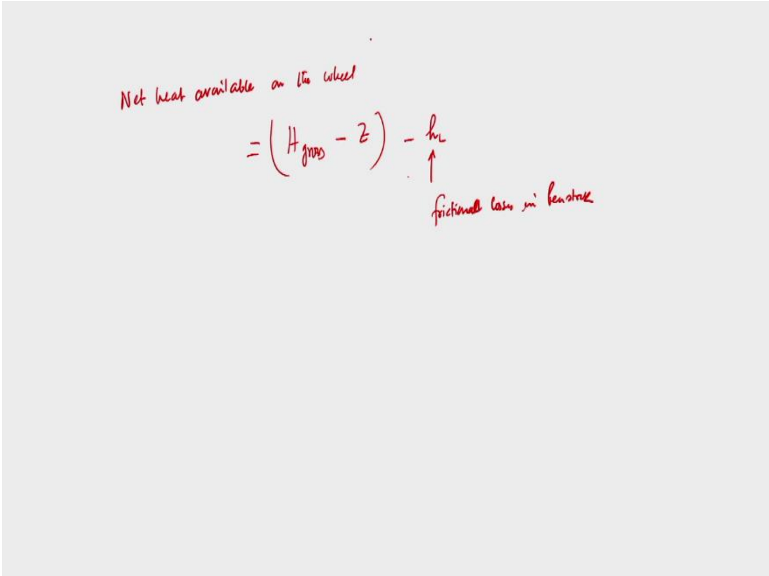

So, this is the net head available. Now we need to quantify fine that is what we have discussed that maybe power whenever; now fluid is flowing to the nozzle I mean then the head is we are getting some kinetic energy of we are getting velocity so kinetic energy. So, the power output from the nozzle may not be the power transferred by the fluid to the wheel. So, there will be a certain amount of losses and we need to know what the losses are. And before we going to discuss about the losses, let us first try to analyse what would be the efficiency and to do that we need to draw the velocity triangles at the inlet and outlet. So, today we will now draw the velocity angles at the inlet and outlet whenever fluid is flowing you know fluid is flowing though the penstock and it is going to the nozzle and ultimately the jet is striking the buckets of a Pelton wheel.

So, if I draw the velocity triangles and probably, we have discussed about the bucket safe. We have discussed about the function of different parts of the bucket that is splitter edge and notch. And bucket is so designed that we also have discussed that if the you know deflection of the jet is exactly opposite to the incoming jet, then we may have probably higher efficiency, but this is not the case because in that case the incoming outcoming jet from the bucket might strike might create resistance to the jet which is going to come. And in that case, it will create a resistance for the whole rotation. So, we will now draw the velocity triangles at the inlet and outlet. And to do that suppose we will now quantify the wheel efficiency or efficiency of the Pelton wheel.

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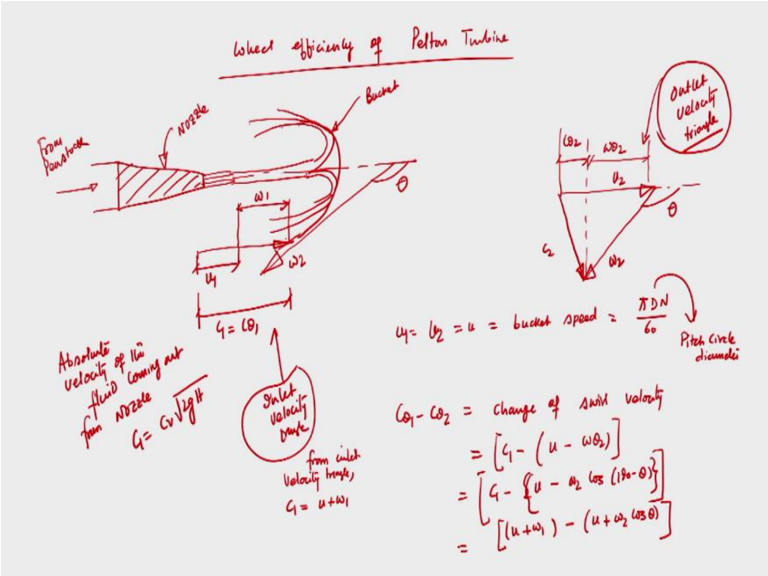

So, today we will discuss about wheel efficiency of a Pelton wheel Pelton of Pelton turbine. So, we need to draw the velocity triangles at the inlet and outlet so you know the bucket shape. So, suppose liquid is coming from the nozzle liquid from reservoir it is coming through the penstock, then it is taken to the nozzle. So, this is penstock, so this is from penstock, then this is nozzle and then the z is striking the buckets.

So, whenever jet is striking the bucket as I said you there is a splitter edge. So, which divides equally the incoming jet into 2 parts and then the jet follows the round shape of the rather inners round inner surface of the bucket and coming out from the bucket. So, the jet which will going and ultimately it will come out so suppose is the bucket. So, this is the bucket and jet is after striking the bucket it follows the round inner surface of the bucket and coming out from the bucket that is what we have discussed last day.

So, now we need to draw the velocity triangles so the fluid which is coming out from the nozzle. So, maybe if I extended this portion, then this angle let us say this is theta this angle is θ and this is the velocity of this is the relative velocity I mean this is the relative velocity at the outlet. So, if I draw the velocity of the jet which is coming out from the nozzle that is C v that equal to sorry. So, absolute velocity of the fluid coming out from nozzle

$$C_1 = C_v\sqrt{2gH}$$

Now, the inlet velocity triangle that is very important inlet velocity triangle that we need to know; so inlet velocity triangle is like this. So, this is will be w 1 and this is u 1 and this is w 1 and C1 total. So, this is the C1 = $C_{\theta 1}$ so this is the inlet velocity triangle. So, this is inlet velocity triangle and we can have outlet velocity triangles that we know that, this angle is theta. So, and this will be our absolute velocity this is w2 this is C2 and this component will be $C_{\theta 2}$ and this will be equal to U2. Here U2 is equal to U1.

U1 = U2 = bucket speed = $\frac{\pi DN}{60}$ where D is the pitch circle diameter pitch circle diameter right.

We have drawn the inlet velocity triangle, and this is the outlet velocity triangle sorry, this is outlet velocity triangle. So, now, from the inlet and outlet velocity triangle we have we can now quantify what should be the change of momentum. So, from there we can estimate about the wheel efficiency. So, note that we can write that from the inlet velocity triangle that now $C_\theta = $ U that is basically flow velocity. Now so what is the, you know change in absolute you know $C_{\theta 2}$ and $C_{\theta 1}$.

So, $C_{\theta 1} - C_{\theta 2} =$ swirl velocity between inlet and outlet of the bucket

$$C_{\theta 1} - C_{\theta 2} = C_1 - (u - W_{\theta 2})$$

$$= C_1 - (u - W_2 \cos(180 - \theta))$$

$$= u + W_1 - (u + W_2 \cos\theta)$$

$$= W_1 \, [1 - \frac{W_2}{W_1} \cos\theta]$$

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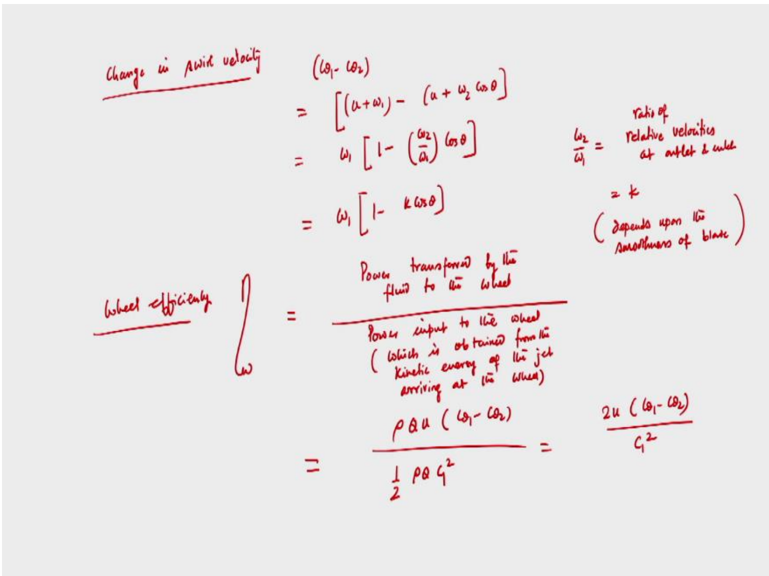

This w2/w1 that is the relative speed ratio, ratio of relative velocities at outlet and inlet if I write in terms of K, which depends upon the roughness of the blade so this K which depends upon the smoothness of the blade surface of the blade. So, it depends upon the smoothness of the blade.

So, if I write that $W_1\ [1 - K\cos\theta]$. So, K is the ratio of relative velocities at the outlet and inlet which depends upon the blade smoothness or roughness of the blade.

Wheel efficiency $\eta = \frac{power\ transferred\ by\ the\ fluid\ to\ the\ wheel}{power\ input\ to\ the\ wheel}$

So, now, we can define blade efficiency or wheel efficiency, wheel efficiency eta efficiency, that is can be defined as the ratio of power transferred by the fluid to the wheel, to the what power input to the wheel which is obtained from the nozzle output; from the kinetic energy of the jet arriving at the wheel, which is obtained from the kinetic energy of the jet that is power input to the wheel that is power output from the nozzle. So, kinetic energy of the jet arriving at the wheel.

So this two ratios so it wheel efficiency which is defined as the ratio of power transferred by the fluid to the wheel of course, very important to the power input to the wheel that is that is why I said that power input to the wheel that is the kinetic energy which is coming or the kinetic energy leaving the nozzle may not be transferred you know to the wheel shaft so there will be some amount of losses. So, the ratio between these two powers I mean we can call it wheel efficiency. So, wheel efficiency is defined as the power transferred by the fluid to the wheel to the ratio to the power input to the wheel; that is which is obtained from the kinetic energy of the jet arriving at the wheel.

Wheel efficiency $\eta_w = \frac{\rho Q\, u\, (C_{\theta 1} - C_{\theta 2})}{\frac{1}{2}\rho Q\, {C_1}^2} = \frac{2\, u\, (C_{\theta 1} - C_{\theta 2})}{{C_1}^2} = 2\ \frac{u}{C_1}\ \frac{C_{\theta 1} - C_{\theta 2}}{C_1} = 2\ \frac{u}{C_1}\ \frac{W_1\, [1 - K\cos\theta]}{C_1}$

$$W_1 = C_1 - u$$

$$\eta_w = 2\ \frac{u}{C_1}\left(1 - \frac{u}{C_1}\right)[1 - K\cos\theta]$$

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$$\eta_w = \frac{2u(\omega_1 - \omega_2)}{c_1^2} = 2\left(\frac{u}{c_1}\right)\frac{(\omega_1 - \omega_2)}{c_1}$$

$$(\omega_1 - \omega_2) = \omega_1[1 - k\cos\theta]$$

$$= 2\left(\frac{u}{c_1}\right)\left(\frac{\omega_1}{c_1}\right)(1 - k\cos\theta)$$

$$= 2\left(\frac{u}{c_1}\right)\left(1 - \frac{u}{c_1}\right)(1 - k\cos\theta)$$

Note that $\omega_1 = (c_1 - u_1) = (c_1 - u)$

$$\boxed{\eta_w = 2\left(\frac{u}{c_1}\right)\left(1 - \frac{u}{c_1}\right)(1 - k\cos\theta)}$$

$\left(\frac{u}{c_1}\right)$ = Speed ratio

For maximum wheel efficiency

$$\frac{d(\eta_w)}{d(u/c_1)} = 0 \Rightarrow (c_1 = 2u) \Rightarrow \frac{u}{c_1} = \frac{1}{2}$$

$\boxed{\text{Speed ratio} = 1/2}$

$$\boxed{\eta_{w,max} = \frac{1}{2}(1 - k\cos\theta)}$$

Ah there I mean this is expression mathematical expression of for the wheel efficiency now for maximizing. So, our target will be to obtain maximum wheel efficiency that is what I discussed that; if the out you know jet deflection, deflection of the jet by suitable designing the bucket can be done that it should deflect exactly in opposite direction. It is coming out almost in the opposite direction not exactly the opposite direction but if it comes exactly in the opposite direction of the incoming jet probably there, we may get higher wheel speed.

But that will have that will create another problem that may strikes to you know the preceding get which is going to come is continuously rotating. And instead of having higher wheel speed it may create resistance to the wheel you know wheel rotation.

So, we may have you know a drop in the efficiency so that is why you know theta that is deflection angle is 165 there is the maximum deflection that can be done to obtain the maximum wheel efficiency, that can be obtained from this expression also. Now what we can write that for maximum wheel efficiency what we can do. So, that d U/C1 this is very important is known as speed ratio, this is known as speed ratio. So, velocity of the blade to the you know, absolute velocity of the jet right or fluid striking the blade that is speed ratio.

Now, what we can obtain for maximizing for maximum for maximum wheel efficiency for maximum wheel efficiency, what we can obtain?

$$\frac{d\eta_w}{d\frac{u}{c_1}} = 0$$

Speed ratio= $\frac{u}{C_1} = \frac{1}{2}$

$$\eta_{wmax} = \frac{1}{2}[1 - K\cos\theta]$$

So, this is the maximum you know wheel efficiency that we obtain. So, and that is obtained for a speed ration is equal to half. So, this is what is the important so we need to know that speed ratio is equal to half, we can have obtain higher wheel efficiency, but it is seen that it is very important that it is seen that we have seen that the energy transferred from the fluid to the bucket is not energy transferred from the fluid to the bucket is not completely transferred to the output shaft very important.

Now my question is the now my point is the energy transferred from the fluid to the bucket is not wholly the totally transferred you know to the output shaft of the machine.

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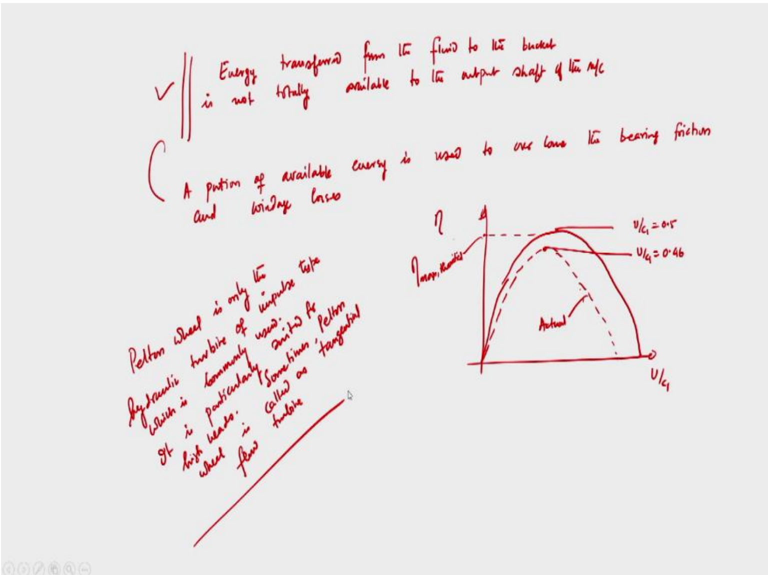

So, I am writing the energy transferred from the fluid to the bucket is not totally available to the output shaft of the machine to the you know to the output shaft of the machine this is very important. So, energy transferred from the fluid to the bucket is not totally available to the output shaft of the machine because there are losses some energy is converted to because this is very important because a portion or of some energies or portion of the energy a portion of available energy is used to overcome the bearing friction and windage loss.

So, this very important; that means, a portion of available energy is used to overcome the bearing friction because all the you know machines are you know connected in a common shaft. So, there will be a I mean we have to overcome the friction frictional losses will be there not only that windage loss. What is windage loss? The that resistance created by the air because when wheel is rotating along with the buckets so there will be some amount of frictional resistance offered by the air and that is windage loss.

So, and also nozzle is also an integral part of the you know this Pelton turbine. So, losses in the nozzle also contributes that you know the reduction of the wheel efficiency of the machine. So, what I am telling nozzle is nozzle is also integral part of the Pelton wheel so there will be a losses in the nozzle as well. So, losses in the nozzle also reduces the overall efficiency of the machine. So, what we have seen that, if I now try to draw the you know efficiency versus speed ratio U/C1 and this is efficiency. And it is seen that eta you know when maximum speed ratio maximum efficiency is obtained when U/C1 = 0.5. So, this is known as eta max; eta max I am writing theoretical so this is eta max theoretical.

So, these are theoretical one; so what I am said that energy transferred from the fluid to the bucket is not totally available to output shaft of the machine because a portion of the available energy is used to overcome the bearing friction losses as well as the windage losses because when Pelton wheel is running, then of course, because it is not totally covered by the fluid like a reaction turbine.

So, the air will create resistance to the rotation of the Pelton wheel that is why there will be some amount of losses that is known as windage loss. Not only that since nozzle is also integral part of the Pelton wheel. So, we need to take into account the losses in the nozzle itself and the losses in the nozzle itself also will try to reduce the efficiency of the Pelton wheel.

So, accounting all these losses even if although we have derived that the maximum theoretical efficiency is obtained for a speed ratio is equal to 0.5, but if we take into account all this losses it is seen that the actual efficiency actual maximum efficiency which is obtained slightly less than the speed ratio and which is 0.46. So, you know actual curve actual efficiency actual maximum actual case is always less than you know so this is U/C1 = 0.46.

So, this is actual this is actual curve. So, the theoretical value 0.5 that is we have obtained from maximum wheel efficiency that is a theoretical value, but because of the losses that that is what we have discussed and that that bearing friction losses windage losses and losses in the nozzle itself will reduce the value of speed ratio 0.46, I mean at which the maximum wheel efficiency is obtained.

So, this is what is all about the wheel speed and wheel efficiency. And we will discuss about the pump specific, you know turbine specific speed also the similarity law. And we have discussed about the you know Buckingham pi theorem when we have discussed about pump and from and from that theorem, we have driven the few coefficients that is head coefficient flow coefficient also the power coefficient. So, all these three coefficients are also remaining also true for the hydraulic turbine as well. Only the difference is in a pump the direction of energy conversion is different then what is happening in the turbine. So, now we will proceed to solve a numerical problem.

So, this is all about the Pelton wheel that we have seen. The Pelton wheel a very important that Pelton wheel is only the hydraulic turbine of impulse impulse type which is commonly used. So, I am writing that Pelton wheel is only the hydraulic turbine of impulse type which is in which is commonly used commonly used. And it is particularly suited particularly suited for high head for high heads and sometimes Pelton wheel sometimes Pelton wheel is called as tangential flow turbine tangential flow turbine.

Why tangential flow turbine? Because we have seen that the jet is striking almost in the tangential direction of the pitch circle diameter. So, just like a reaction turbine we have classified a radial flow axial flow. Sometimes it is known as tangential flow turbine and it is Pelton is only the hydraulic turbine of impulse type, which is commonly used, and it is in general suited for high heads. I will also would like to discuss in this context that we have seen this turbine is I mean will produce power suppose I would like to generate a certain amount of power using hydraulic power plant or maybe in one case we have impulse turbine let us say Pelton wheel in another case we have a Francis turbine that is reaction turbine.

Since Pelton wheel is normally suited for high heads so to obtain higher output, we need always we require high heads. But sometimes it is not possible to have high head, then what we have to do only we can increase the diameter you know if we would like to get suppose more amount of power from the same Pelton wheel then we need to increase the wheel diameter. So, that will increase, or we have to have you know more than of nozzles. So, for that we have to have higher you know bigger size of the turbine. And that is not and that is why to obtain the same power it is always recommended that reaction turbine will be it is also it is always recommended to have a reaction turbine.

Anyway, so with this now we will proceed to solve up numerical problem from where it will be clear that how we can obtain efficiency from the given values of you know head and other I mean nozzle diameter and all those things. So, we have discussed that Pelton wheel is no way suited for high heads. So, if we would like to obtain same power from the Pelton wheel then of course, and reaction turbine for the given power output Pelton wheel requires a high head or if we do not have high head, then we have to have a few more nozzles and also the wheel diameter has to increase and that is not you know recommended because in that case it will increase of size bigger size.

So, in that case I mean reaction turbine is very important because reaction turbine can be avoided even at a moderate head to obtain the same power output. So, now, we will solve one numerical problem related to this impulse turbine. So, let me write the problem first then we will proceed to solve. So, problem is in a hydraulic electric scheme a number of Pelton wheels are.

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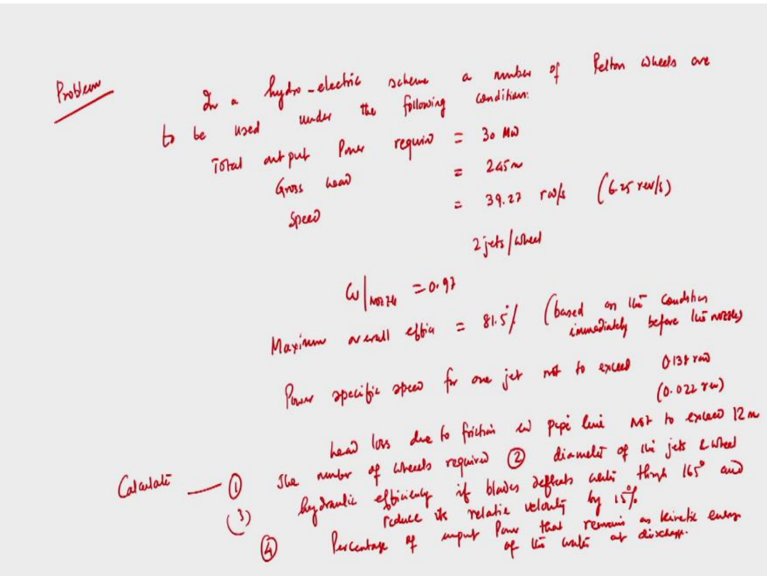

So, a problem in a hydroelectric scheme a number of Pelton wheels are to be used are to be used under the following condition right. Total output power required is equal to 30-megawatt gross head is equal to 245 metre, speed is equal to 39.27 radian per second, that is 6.25

revolution per second. It is given 2 jets per wheel Cv of the nozzle is equal to 0.97, that is coefficient of velocity.

Maximum overall efficiency based on the condition immediately before the nozzle's maximum, maximum overall efficiency is equal to 81.5 percent, that is given. That is based on the condition immediately before the nozzle and power specific speed for 1 jet not to exceed 1 power specific speed this is important. Power specific speed for 1 jet not to exceed 0.138 radian that is 0.02 revolution.

Head loss to friction in pipeline does not exceed 12 metre, head loss you know head loss due to friction due to friction in pipeline not to exceed 12 metre. So, what we have to calculate? First we have to calculate number 1 is the number of wheels required the number of wheels required; 2, diameter of the jets and wheels diameter of the jets and wheel. 3, hydraulic efficiency if blades deflect water through 165. If blades deflect water through 165 degree this is important and reduce a relative velocity by 15 percent and reduce its relative velocity by 15 percent and 4 percentage of the input power, that remains as kinetic energy water as discharge. Percentage of input power that remains as kinetic energy of the water at discharge.

So, we have to solve this problem, so it is given that in a hydraulic power plant scheme Pelton wheels are to be used for the following condition. So, we need to develop a jet 30-megawatt power, gross head is available 245 metre, speed is given 625 revolution per second and there are 2 jets per wheel. Nozzle Cv is given 0.97 0.97 coefficient of velocity maximum wheel efficiency 1.5 percent based on the condition immediately before nozzle immediately before the nozzle.

Power specific speed for 1 jet not to exceed point 0, 0.22 revolution so we have to calculate head loss due to friction in the pipeline. If head loss due to friction in the pipeline does not exceed 12 metre then the number of wheels requires diameter of the jet and wheel hydraulic efficiency blades deflects water though 165 degree and reduce a relative velocity 15 percent. And percentage of input power that remains kinetic energy of the water at the discharge so we will we have to solve this problem.

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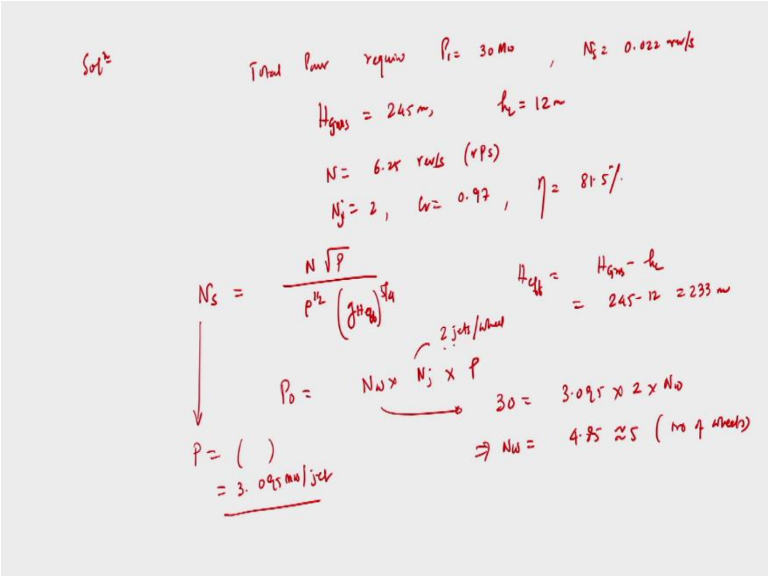

So, the solution this is very important we have to solve the problem that, so what is given? So, total power it is given total power required total power total power required P naught is equal to 30 megawatt that is given. And Ns is equal to given 0.022 revolution per second that is given because it is given. You know specific power specific for specific speed for 1 nozzle not to exceed this. And H gross is equal to 245 metre, frictional losses will not exceed 12 metre that is given. Speed is given 6.25 revelations per second or rps revolution per second.

$$N_s = \frac{N\sqrt{P}}{\rho^{\frac{1}{2}}\,(gH_{eff})^{\frac{5}{4}}}$$

Po = $N_w N_j\ P$

$N_w = 4.95$

Because H effective is H gross minus frictional loss that should not exceed 12 metre, from there we calculate P that is the power that power into number of jets per wheel multiplied by the number of wheels will be the total overall power. That is total power required from there we have calculated the number of wheels will be 5 it should not exceed 5. So, there since there are 2 jets per wheel; so there are this N j is equal to twice jets per wheel fine. So, next we have to calculate other you know other solution that is what is other we need to calculate that is diameter of the jets and wheels that you have to calculate ok.

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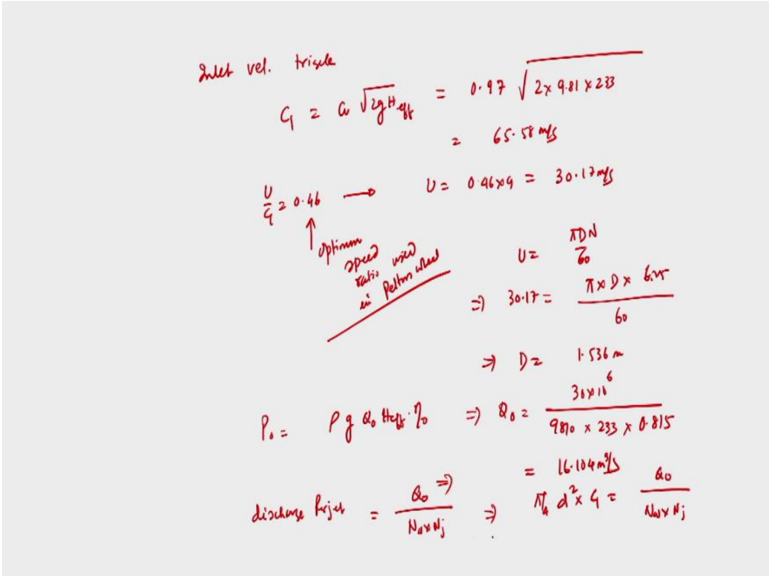

Then we have to calculate so from inlet velocity triangle from inlet velocity triangle we know

$C_1 = C_v\sqrt{2gH}$ = 65.58 m/s

$\frac{u}{C_1} = 0.6$

U=30.17 m/s

D = 1.536 m

$P_o = \rho Q g\, H_{eff}\, \eta_o$

Qo = 16.104 m^3/sec

Discharge per jet = $\frac{Qo}{Nw\,Nj} = \frac{\pi}{4}\, d^2 C1$

d = 0.177 m

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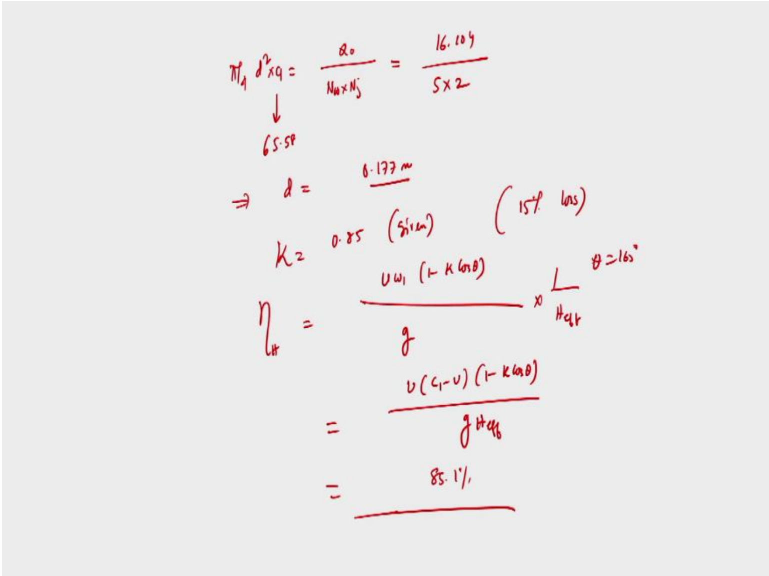

K = 0.85

$$\eta_H = \frac{u\,w_1(1-k\cos\theta)}{gH_{eff}} = \frac{u\,(C_1-u)(1-k\cos\theta)}{gH_{eff}} = 85.1\%$$

So, this is the hydraulic efficiency of the turbine. So, this is the way we have to solve the you know if we know the power output that is what we need from the Pelton turbine. And then we have to calculate what should be the hydraulic pitch cycle diameter of the wheels, what should be the diameter of the jet, and number of wheels is required.

One important thing is that because that gross head is not equal to the net head available at the wheel. So, we need to calculate net head available at the wheel and based on that we can calculate what should be the, you know other parameter.

So, although we are having H effective is something else, but that head is not be converted equivalent amount of kinetic energy or the energy of the rotation of the wheel so, and since from there we can calculate what will be the hydraulic efficiency. So, with this I stop here today and we will continue our next discussion in the next lecture.

Thank you.