Physics of Renewable Energy Systems
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Lecture 16
Hydroelectric Power Station and Turbines

Hello welcome back to the course on Physics of Renewable Energy Systems. Let us continue with this module on hydroelectric power.

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So, in today's lecture, we will talk to you about the Hydroelectric Power Stations. You will find that in these power stations there are various types of turbines which are installed and depending upon the turbines, you will have varying orders of efficiency in extracting the wave power. So, all these three terms are related and I hope that you will understand these concepts by the time we finish this lecture.

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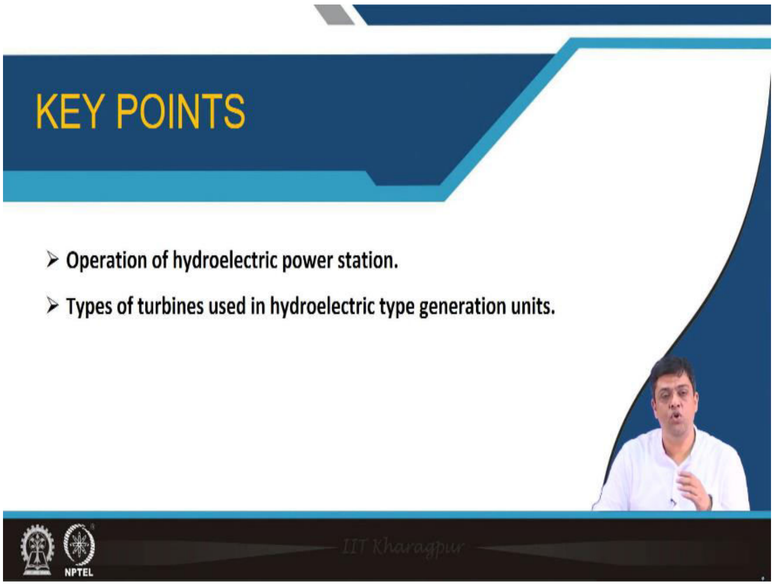

And you will be able to explain the operation of a typical hydroelectric power station to your friends or somebody who comes and asks you about the operation of a dam and when you go and visit a dam sometime later, you will understand various components more thoroughly and you will enjoy that visit.

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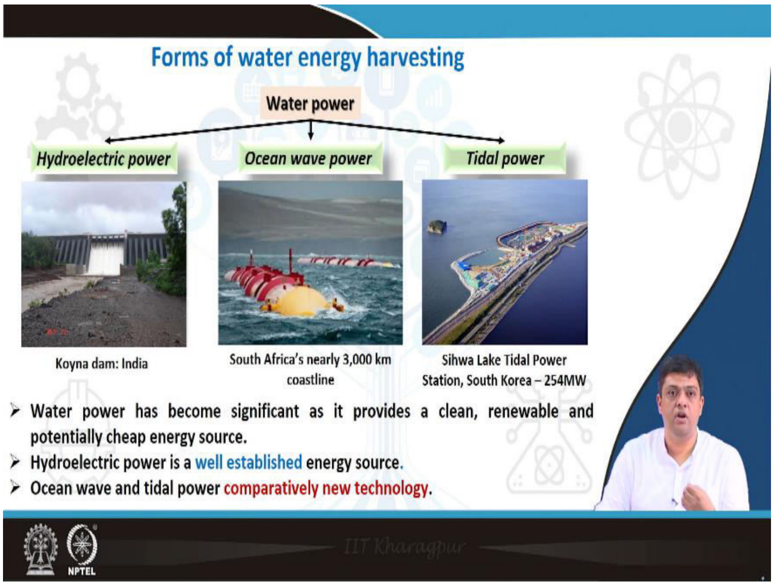

As we discussed in the previous class, we have various forms of water energy harvesting. We can harvest energy of water using the construction of dams. You can extract wave power or you can also extract tidal power. Water based systems are typically considered as renewable source which are continuously available and because of that they are economically viable and society accepts it. For us, hydroelectric power is a well-established technology but sooner or later you will also see the advent of technologies based on extraction of power using ocean waves or tidal.

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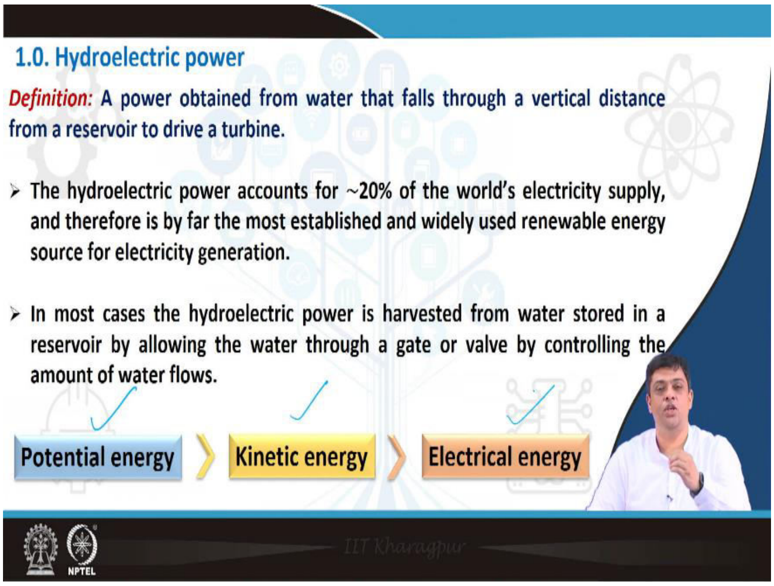

In today's lecture, let us start with hydroelectric power. We have discussed about the definition about the hydroelectric power and what are we going to discuss? You have a reservoir where you are storing water at a height. What is the energy associated? Potential energy. This water flows down the vertical distance.

Now flowing water, which type of energy are you talking about? You are talking about kinetic energy. This flowing water comes and hits the turbine which rotate. If you are hitting the turbines directly which are connected to the converters then what do you get, you get electrical energy. This is a very simple way of explaining the operation in a water dam. So, let us first discuss about the construction and then we will also give you detail protocols which are followed while these dams are operated.

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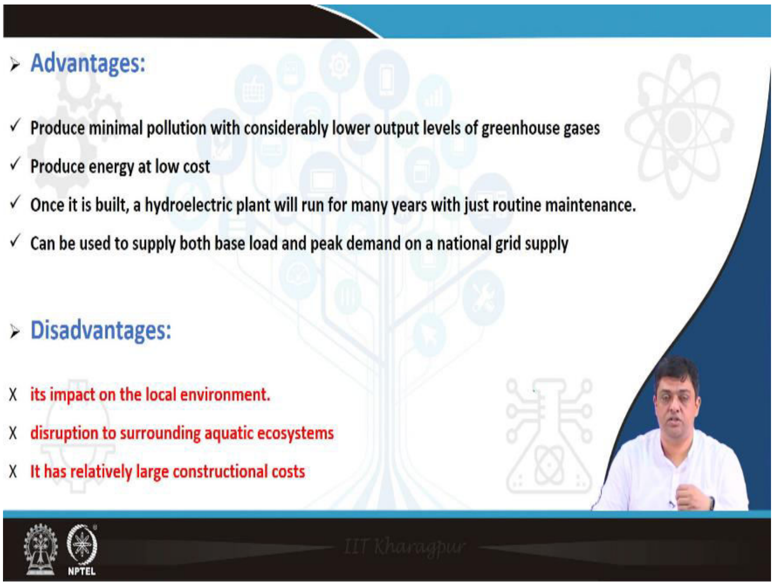

We have also discussed in the previous class regarding the advantages and disadvantages. What are the major advantages of these hydroelectric based power stations? Very quick revision, the greenhouse emission is limited. It is cost efficient, once built easy maintenance and it can be directly integrated to the national grid.

Disadvantages? Serious, very serious impact on local environment and the ecosystems and the initial capital cost is very high. How do we want to counter these disadvantages? Build the dams which have new and novel designs, along with that, bring in the knowledge and bring in the technology which are able to counter these limiting factors.

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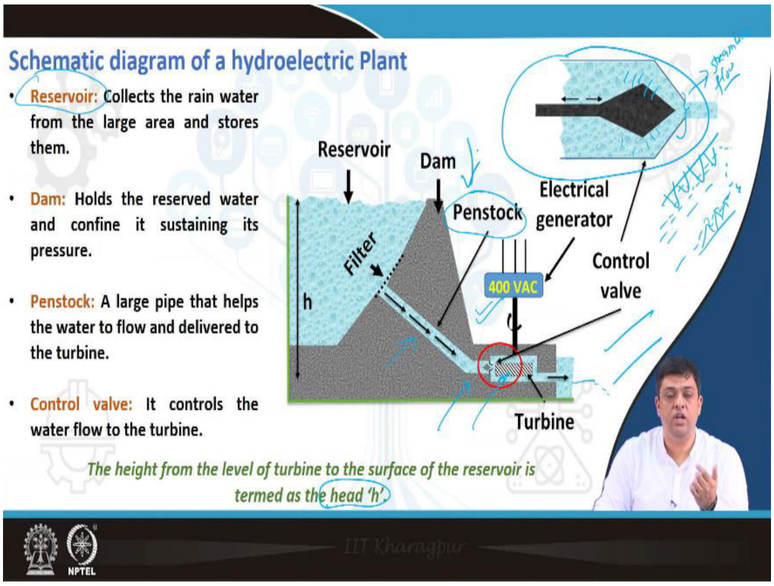

So, this is a typical construction of a dam. The first thing which you know about the dams is that they are constructed in the path of the rivers which are flowing from height towards the plane, that is the way you construct most of the dams.

Why? Because this flowing water can be made to cover the area and get accumulated in an area which is called as the reservoir. This reservoir then supplies water down the channel, down the channel which hits the turbine and the operation of this turbine leads to the generation of electricity and after the transfer of energy to the turbines, the water continues in its path and flows down the stream. This is what you have understood.

The reservoirs can also be so constructed that along with the water which is coming downstream, it also actually collects the rain water from a large area and stores it. So, you can also construct reservoirs in the catchment area. I hope you understand the term catchment area. That means it is the area from which you where you find that water comes in from different areas and gets accumulated if it has rained in other places.

So, reservoirs can also be constructed in the catchment areas. What is the dam? So, you have these cement big blocks or the these walls which are constructed, these are so constructed they are strong concrete constructed structures because they hold the reserved water and confine them while sustaining the pressure.

So, two things are now there you have the source of water and the boundary which is confining this water in that region and not allowing to flow in nearby areas. What was the concept of the hydroelectric power? You have to send the water from a height to lower height. So, what I should give them a path and that path is called the penstock.

It is basically a tunnel or a large pipe that helps the water to flow downwards and deliver this water for interaction with the turbine plates. Is the construction of penstock very simple? Actually, it involves slightly more detailed information. The construction of the penstock must be such that the internal wall of the penstock does not have the capacity to induce large frictional forces towards the flowing water.

Otherwise, you will change the nature of flowing fluid and if you remember, for extracting maximum power you require a flow of fluid which has a stream line flow, but if you have a wall which has let us say a wall which has abrasions, then the flowing water will have a turbulent flow. So, then when this turbulent flowing or the fluid which has a turbulent nature interacts with the turbine, then the maximum power cannot be extracted.

So, what should be the point that should be kept in mind? That the internal walls should be such that do not induce frictional forces or induce viscous drags and therefore the internal wall must be smooth. That is one thing which should be remembered very clearly. Now, as the water is flowing downwards then also because of this height difference you will have certain appearance of turbulence in the flow of the fluid.

To eliminate or minimize this turbulence, you use this control wall which is shown here and the zoom picture is shown on the top. This control wall reduces or minimizes the turbulence in the flowing fluid and when the fluid after being compressed because of this typical nature of the control wall, when they come out you anticipate that you will have a stream line flow and this fluid which is having a streamline nature will then interact with the turbine.

So, that is the importance of the control wall. It controls the water flow to the turbine while it also ensures that the fluid has a streamline nature and the height h defines the level at which the turbine is from the surface of the reservoir and is termed as not as height but as head. You will understand slightly more details about this term head and how does this effect on the loss because of frictional forces actually reduces this value of h and that loss is called the head loss and that will become clear in subsequent slide.

But please remember, that even the best of designs you will have certain frictional losses coming in the penstock and that results in the appearance of the concept of head loss and that reduces your height of the dam and if you see the Bernoulli's equation you will understand what is the consequence of this head loss.

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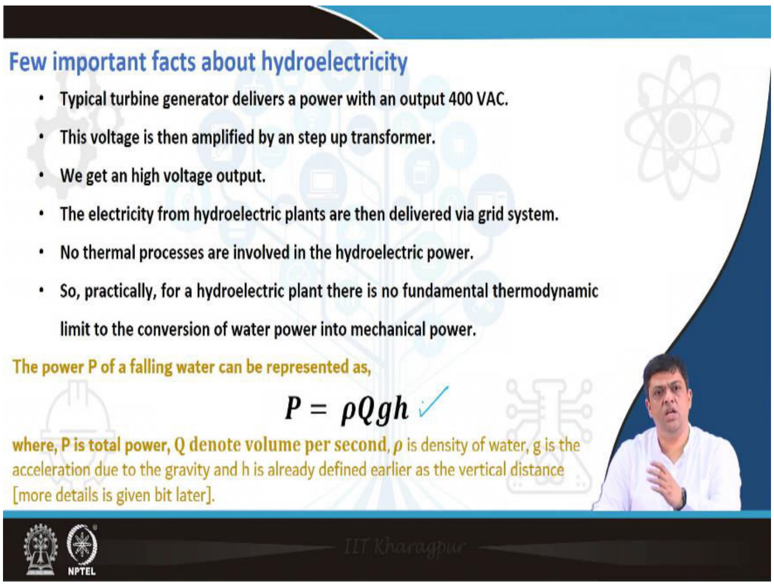

So, very quick important facts about hydroelectricity. The typical turbine generators deliver a power with an input of around 400 volts. The voltage is then amplified by a step-up transformer and then made to travel to the power stations using high voltage lines. You can have the electricity from hydroelectric plants that can be sent to various power stations which are connected in the grid system.

Mostly, you do not relate any thermal processes and practically, for a hydroelectric plant there is no fundamental thermodynamic limit to the conversion of water power into mechanical power and knowing the density, the flow rate or volume per second which is flowing down the gravity or acceleration due to gravity and the head you can find the power which is extracted from the falling water is given by rho Qgh. This is the amount of power which can be extracted.

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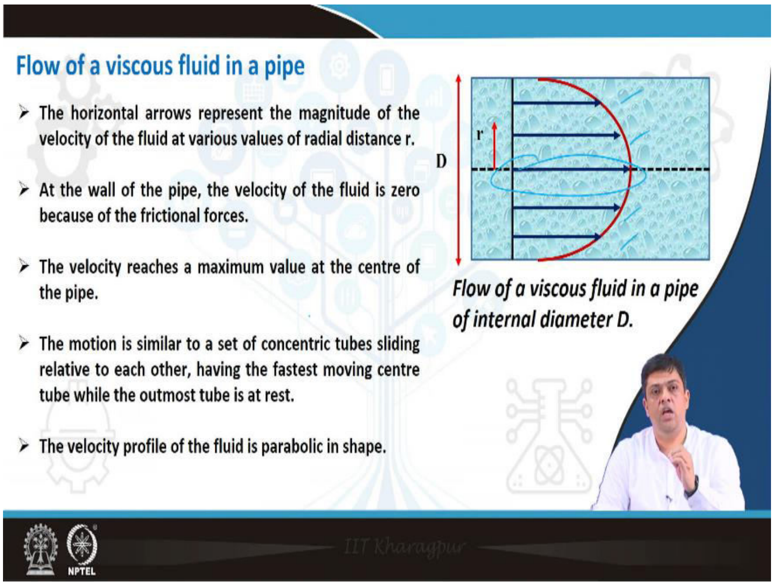

As we discussed in the previous module, you have a fluid and that fluid is flowing down a pipe which can be with reducing diameter and then you have the interaction with the wall and then you were extracting power. That was the topic discussed in detail in the wind energy module. Let us quickly revise that and see how this concept is taken further when we talk in terms of hydroelectric power.

Here the motion is similar to a set of concentric tubes slightly relative to each other and having the fastest moving centre tube while the outmost tube is at rest and the velocity profile of this fluid is a parabolic shape and this is typically the shape which you get in the flow of viscous fluids.

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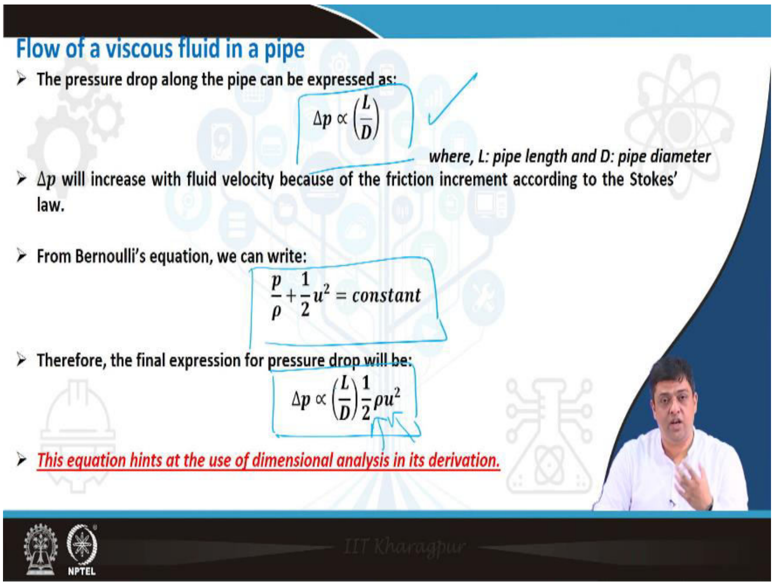

The pressure drop along the pipe can then be expressed as delta p is equal to L by D, where L is the length of the pipe, D is the diameter. This will increase with fluid velocity because the frictional forces are such that they have an increment according to Stokes' law and along with the information coming in from Bernoulli's equation, we can write the form p by rho is plus half u square is a constant.

Using this relation in the equation written on the top, we can find that the change in the pressure or the pressure drop is proportional to length, diameter and the density or the velocity. So, these are the terms which you will have when you calculate the pressure drop when the fluid flows from one point to the other. Immediately one thing should become clear to you.

Can you have an infinite length of pen stock? If you have pressure drop would be large. Can you have a very large diameter? If you have very large diameter, imagine what will be the height of the concrete walls which you are using to construct the protect the reservoirs. If you have fluids with different densities then you will have the power output which will be different.

Because the pressure by which the fluid is coming down would be different and if you have the height which is very similar, then the velocity of the fluid which is coming from let us say height which is very of the height of the turbine and the height of the reserve at the height at which the reservoir surface is are very similar, then the velocity of the fluid would be quite small.

So, you have to have a difference, so that the velocity is slightly higher and then if you have again you need velocity to be very high that means the length becomes bit larger. Otherwise, you will have a very steep dam. If you have a very steep dam it has its construction issues.

So, all these factors have to be optimized before this very simple term of change in pressure can even be calculated in times and because this is going to be constructed in an area and if you change these terms primarily length and D, the size of the water dam will also change. So, all these factors are critical while we design the dam.

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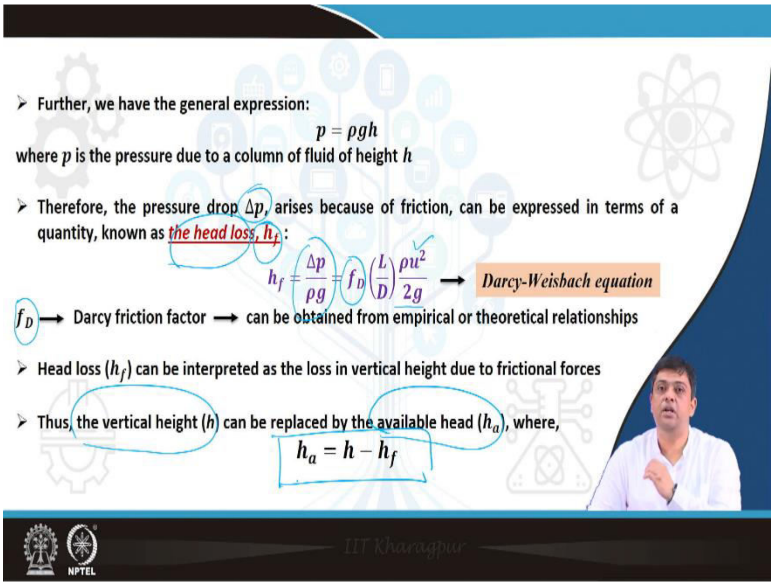

As we have discussed that the general equation of pressure is rho g h and what did we talk about the pressure drop delta p that arises because of what, the friction. Friction between what? Friction between this inner wall of the surfaces of the penstock and the flowing fluids and this is actually expressed in terms of the quantity defined as hf or the head loss and hf is given as delta p by rho g that is equal to f_D into L by D rho u square by 2g.

This is the Darcy-Weisbach equation, where f_D is the Darcy friction factor and can be obtained from empirical or theoretical relationships. So, how do we actually define head loss? It is the loss which is associated with the vertical height and this loss is actually originating because of the frictional forces. So, you would have thought that the pressure which you will get at the turbine blade would actually be rho gh but because of the flowing fluid.

But because there are frictional forces which act on these flowing fluids, that results in what? It results in certain loss of energy and that is called as the loss. So, the quantity vertical height can be replaced by the term available head which is written as h_a, where h_a is equal to h minus h_f. So, if you have the inner walls which are inducing very high frictional forces, what will be the available h_a? The value will reduce. Ideally you want ha to be equal to h but that is not possible.

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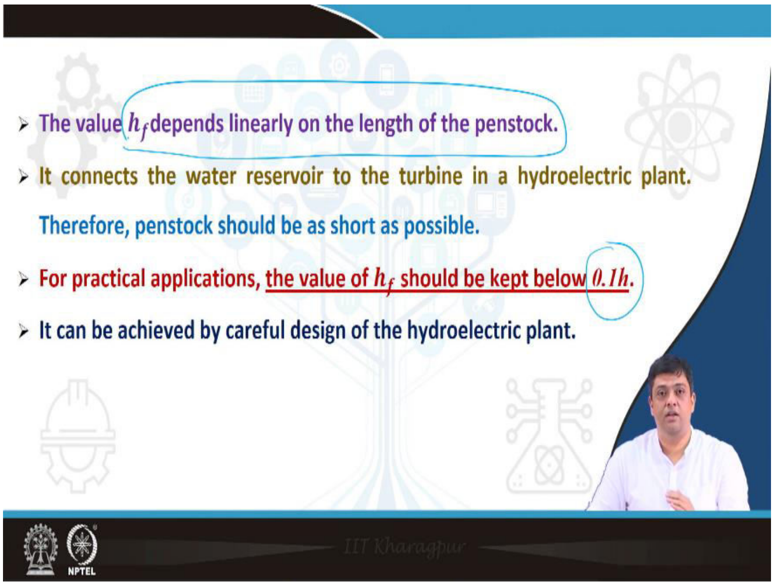

And for practical applications, the value of hf should be kept below 0.1h and this can be obtained by careful design of hydroelectric plants. Please remember, we have already discussed that hf depends linearly on the length of the penstock as I explained in the slides earlier. If you go back to this slide where I was discussing about the construction of the dam, there was one more thing which I did not mention at that point but I hope you had seen it.

Can you remember what that was? That was the installation of a filter at the entry point of the penstock you had a filter which was placed and why do we place the filter? Because the filter ensures that no unwarranted impurities flow down the penstock otherwise, if those impurities or objects which can be very hard, if they go and interact with the turbine, the turbine blades may get damaged and your whole system will come to a standstill. So, the role of filter must also be understood very clearly.

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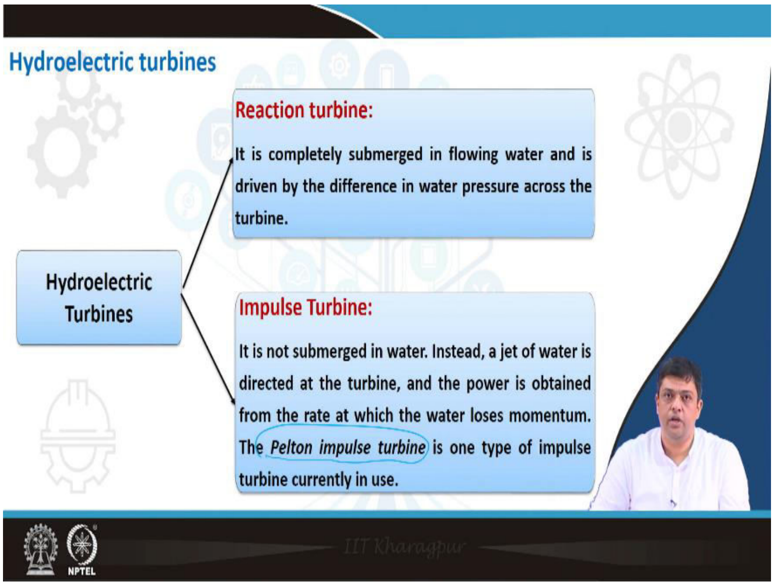

If you see I am continuously talking to you about the turbines, because they will play a critical role in extracting the power and the kinds of turbines which are used are classified under two major headings, hydroelectric turbines which are reaction type or hydroelectric turbines which are impulse type.

The reaction turbines are the ones which are completely submerged in the flowing water and they are mostly driven by the difference in the water pressure across the turbines. Whereas, the impulse turbines are not submerged in the water. So, you had a water column coming down. So, in case of the reaction turbines, the turbines are submerged fully, but if you have the impulse turbines, they may not be fully submerged, they may be half submerged.

So, you can have these two types of turbines and a typical impulse type turbine which are becoming very popular are the Pelton type impulse turbine and we will discuss about these two turbines quickly in following slides.

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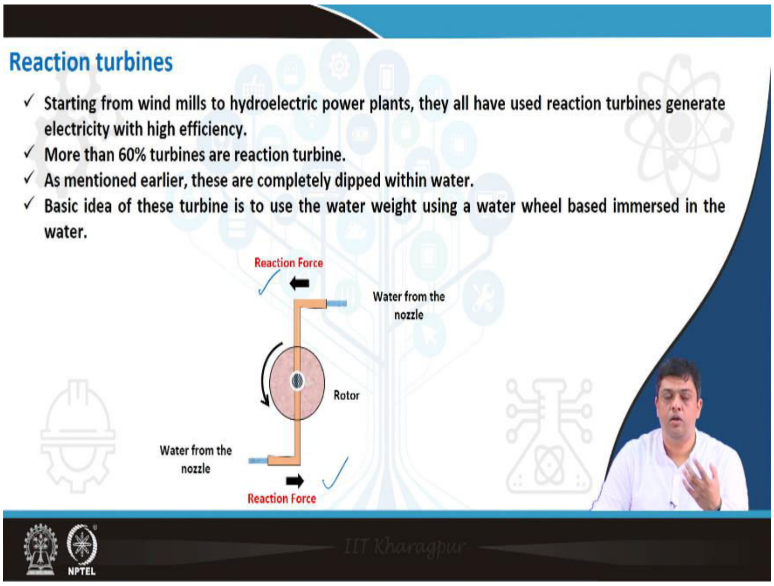

Reaction turbines as stated earlier are fully submerged in the water and 60 percent of the turbines which are associated or installed in these hydroelectric plants are of this type. What you have? You have water entering from the nozzles and then are having the reaction force acting in the opposite direction and resulting in the rotation of this rotor. So, this is the typical way you ensure the rotation of this rotor.

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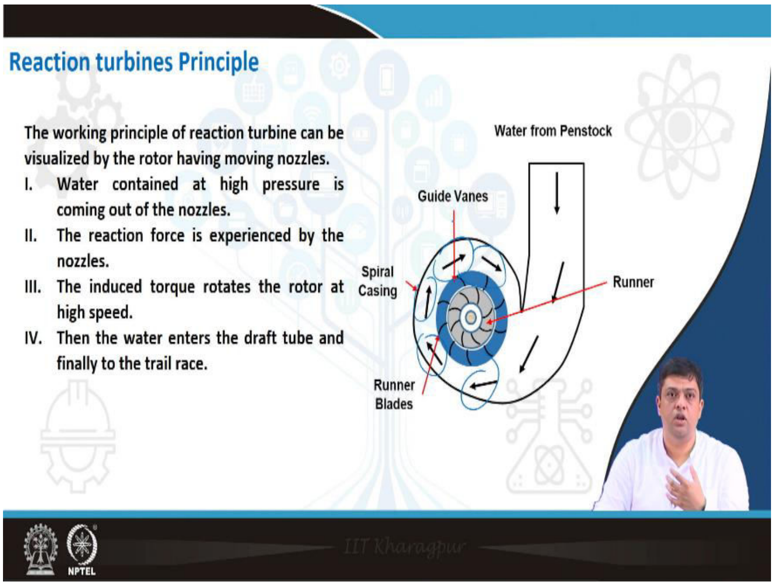

To explain this in slightly more details, you will see that the water is contained at high pressure and is coming out of the nozzle. The reaction force is experienced by the nozzles, the induced torques when this water is interacting with the turbine plates or the rotor, the torque is induced and then finally the water enters the draft tube and then goes through the trail race. That is what the typical operation of these reaction turbines are.

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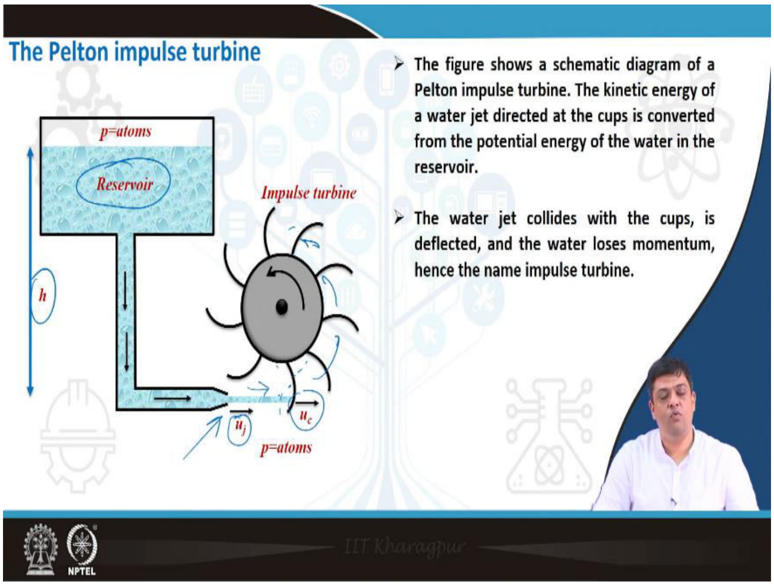

In comparison, so in the earlier case you had the turbine which was surrounded by water continuously and you had two nozzles which were inducing the motion of these rotor. Then came a new design where you said okay let us not submerge the turbines continuously inside the water, depending upon the requirement we will have the water hitting the turbine blades or will extract the turbine blades out of the water if you want to reduce the capacity of the generator.

Then came the concept of Pelton impulse design. So, what you have? You have the reservoir you have the head and down at the bottom you have the nozzle. At the nozzle you have the velocity of this fluid coming out as u_j and if you see this flowing water hits the turbine blade and that results in the motion of the plate.

Then when this blade moves forward, the next one comes in its place an again the jet of water hits the turbine blade and it rotates. So, this is the typical Pelton impulse turbine, where the water jet collides with the cups, the water is deflected while that is happening this loss in momentum is basically transferred to the blades and that results in the rotation of these turbine blades and you have the output and this is why it is called an impulse turbine.

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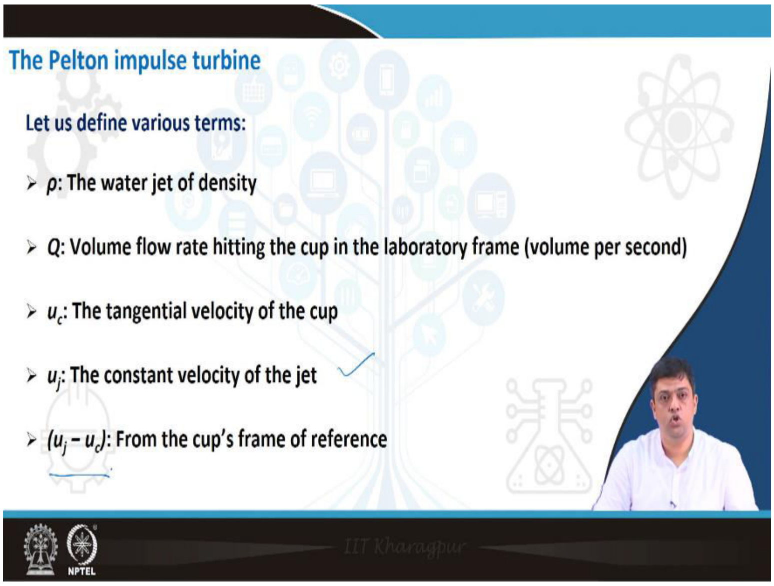

So, let us define various terms in impulse turbines which are related to the mathematics which we will perform in next few slides. Rho, the density of the water or the fluid coming down. Q, volume flow rate hitting the cup. u_c, the tangential velocity of the cup, uj, the constant velocity of the jet and u_j minus u_c, that is from the cups frame of reference. So, the difference in the two velocities but from the cups frame of reference.

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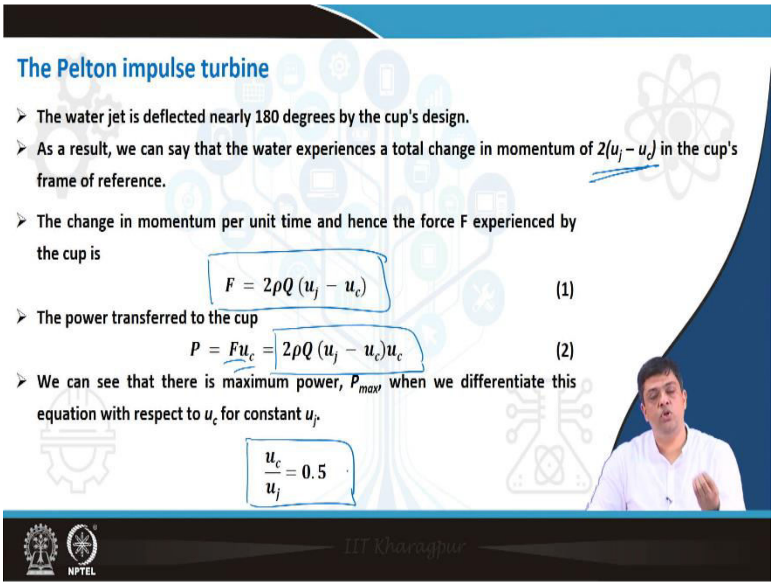

As you saw, the design of the cup was such that the water which was hitting was deflected nearly 180 degrees. Therefore, the water experiences a total change in momentum which is given by twice of u_j minus u_c while you are seeing from the cups frame of reference. Now, if you write change in momentum per unit time.

What are we talking about? We are talking about force. Force experienced by the cup that becomes equal to 2 rho Q into u_j minus u_c. The power transferred to the cup would therefore be equal to F into u_c and using the above equation we get power transferred to the cup is equal to 2 rho Q u_j minus u_c into u_c.

And if you want to calculate the maximum power which can be obtained, you will find that this will be obtained when we differentiate the above equation that is equation number two with respect to u_c for a constant u_f or u_j and then you will get the maximum power only when u_c by u_j is equal to 0.5. So, now we also know what should be the value of the flowing fluid which should come out of the nozzle and also the fluid which should hit the turbine plates.

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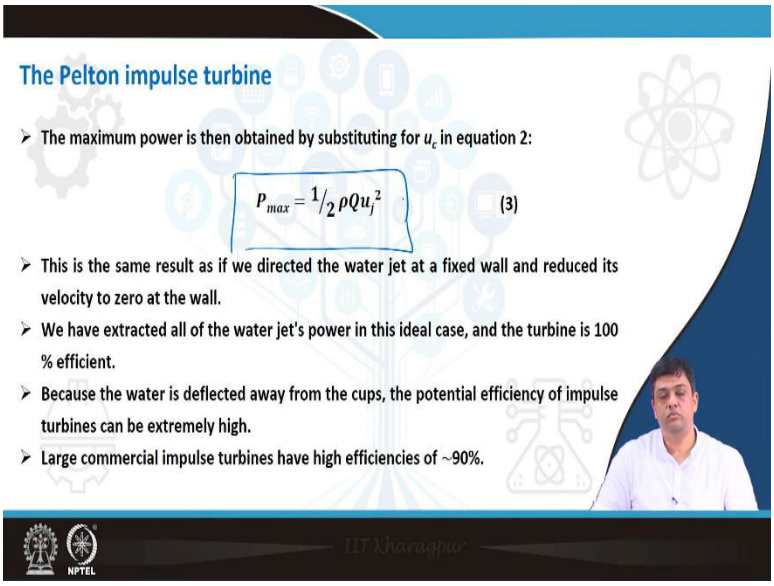

Once I have obtained the values of u_c, we can get the maximum power and that is equal to P max equals to half rho Qu_j square and if you remember from the previous module, this is the same result what we obtained when we were discussing about the flow of water jet hitting a fixed wall and when the velocity of this water jet actually was reducing to 0.

So, the concept which we discussed during the analysis of a wind turbine or a fluid mechanics still holds good because here also we are talking about the flow of a fluid and trying to extract power from there. In case of the discussion till now, we have extracted all of the water jets power and believing that there is no loss.

And in this discussion that means the efficiency would be 100 percent, but reality is slightly different because there would be losses associated at different steps and large commercial impulse turbines have an efficiency in the range of 90 percent plus minus but that is a very high value.

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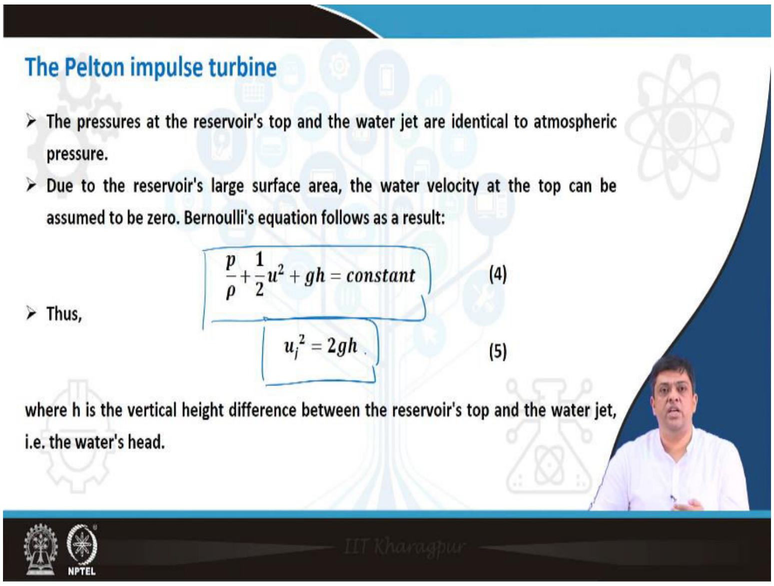

Now, if you talk about in terms of what we had discussed in the dams, the pressure at the reservoir top and the water jet are identical to atmospheric pressure. Now due to the large surface area of the reservoir, the water velocity at the top can be assumed to be 0. So, if you have a very large reservoir, you see that the ripples are quite minimal and the velocity at the top of this reservoir surface is assumed to be 0.

Using Bernoulli's equation what you can write? You can immediately write p by rho plus half u square plus g_h is constant. Thus, u_j square becomes equals to 2gh, where h is the vertical height difference between the reservoirs top and water jet that is water head. So, you may sometimes write u_j square is actually equal to $2gh_a$, where h_a is the available height.

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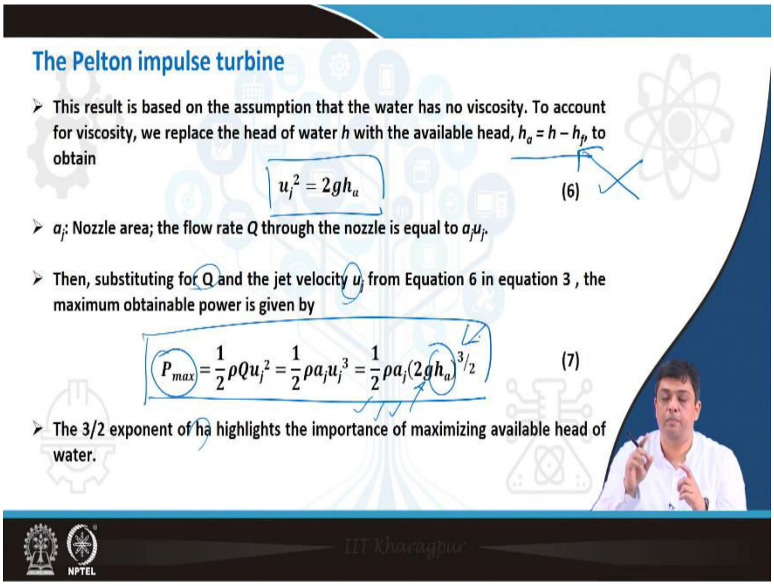

We have assumed till now that water has no viscosity but that is not true. Therefore, to account for viscosity what have we done, we actually take the available head that is ha that is defined by h minus hf where hf was what, the head loss. So, what do you obtain? You obtain ug square is equal to $2gh_a$.

Now let us consider that a_j is the nozzle area while the flow rate Q through the nozzle is equal to a_j U_j. Then you can substitute for Q and the jet velocity u_j followed by the use of equation 6 in the earlier equation 3, you will get the maximum power is actually equal to half of rho a_j $2gh_a$ 3 by 2. The exponent 3 by 2 of h_a highlights the importance of maximizing the available head of water.

So, why it indicates that it is important to maximize ha value? How can you make maximize h_a value? You have to ensure that head loss is minimal and that is why we had written in the earlier case that head loss is generally kept as 0.1 of h. Otherwise, g is a constant here in this equation. If h_a becomes small, the maximum power will also reduce significantly because of this exponent 3 by 2.

So, you must ensure that the losses coming in because of the frictional forces that may appear between the inner wall of the penstock and the flowing fluid in terms of motion in dams are reduced and if you are just taking a case of a turbine, then the flow of the water from the reservoir through the nozzle and then hitting the cups of these impulse turbines must be such that the flow down this pipe is not resulting in loss because of frictional forces between the inner wall of the pipe and the flowing fluid.

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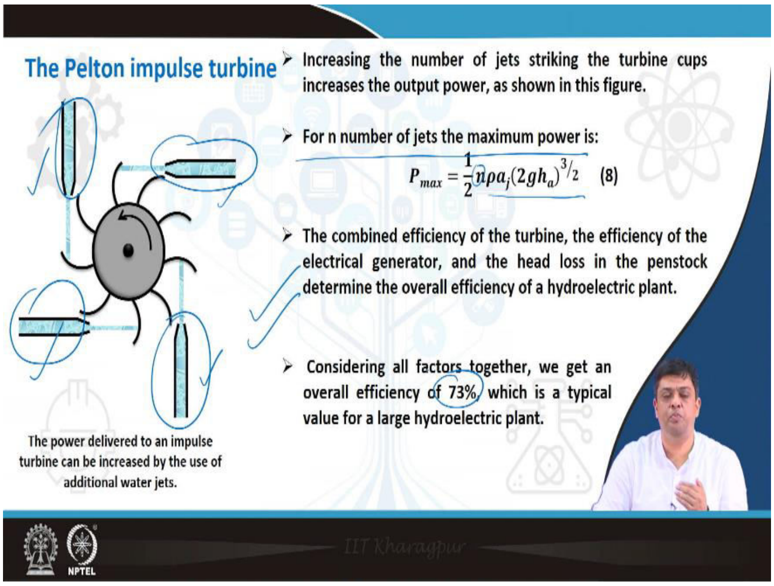

What were we seeing in the previous example? We were seeing that the Pelton impulse turbine was such that there was one nozzle hitting the cups of these turbines. Immediately somebody may come in that if you want to improve the rotation speed or the rotation of these turbines, what you do?

Do not hit this cup using only one nozzle but use large number of nozzles, so that you can ensure that there is no reduction in the speed while the blades are rotating and also high speed can be obtained and this concept has been tried where the number of nozzles which are going to throw out the jet of water which will hit the cup of the turbine blade is increased.

So, if you have n number of jets hitting the cups, so if in this case let us say 4, then the maximum power which can be extracted is given as half into n and rest of the terms remain same that is rho a_j twice gh_a 3 by 2. The combined efficiency of the turbine, the efficiency of the electrical generator and the head loss of the penstock determines the overall efficiency of this hydroelectric plant and this concept has been discussed earlier.

And although when we were talking about the efficiencies, you said that you can actually work at 100 percent efficiency but then there are various losses as we have indicated here and generally the value which you get is around 73 percent efficient system. So, considering all the factors which have been mentioned till now, we can get an overall efficiency of 73 percent and this is the typical value associated with a large hydroelectric plant.

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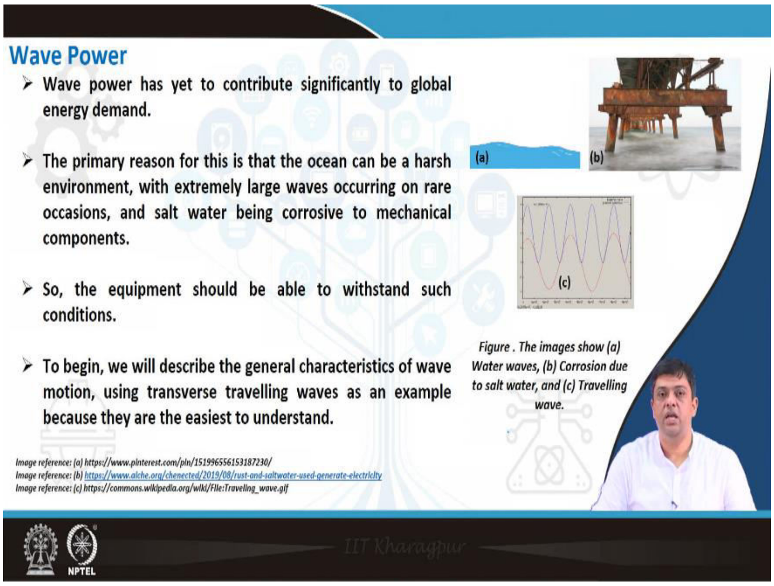

So, we have discussed the first way of harvesting energy from flowing water. There are other topics which I mentioned earlier, you can have extraction of energy from ocean waves or tides and now we will move towards those topics in the subsequent lectures.

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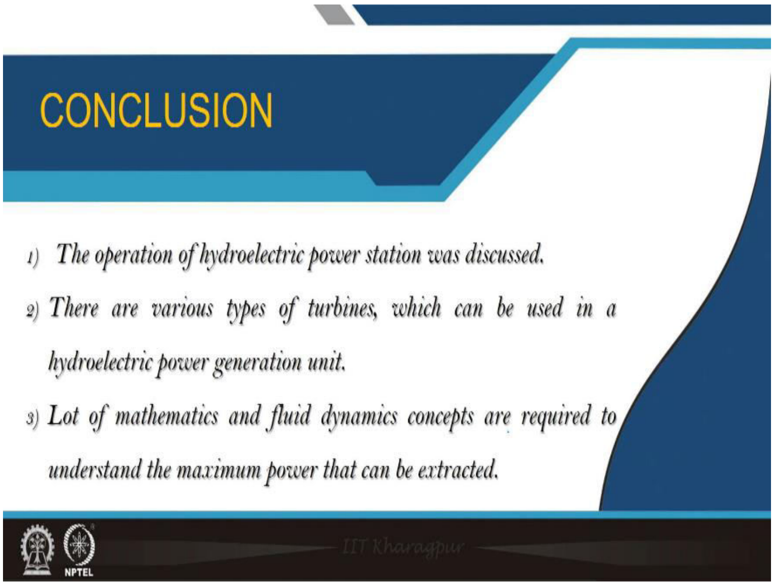

And I really hope that the points and the topics which were covered in today's lecture have given you the confidence to explain the operation of hydroelectric power station to your friend or somebody who wants to know about it. There are various types of turbines which can be used in hydroelectric power generation units and we have discussed two types, the reaction type or the impulse type.

You should also be very clear that lot of mathematics and fluid dynamic concepts are required to understand the maximum power that can be extracted in such systems and I recommend that you practice the derivation of these formulas on your own, before solving the numericals.

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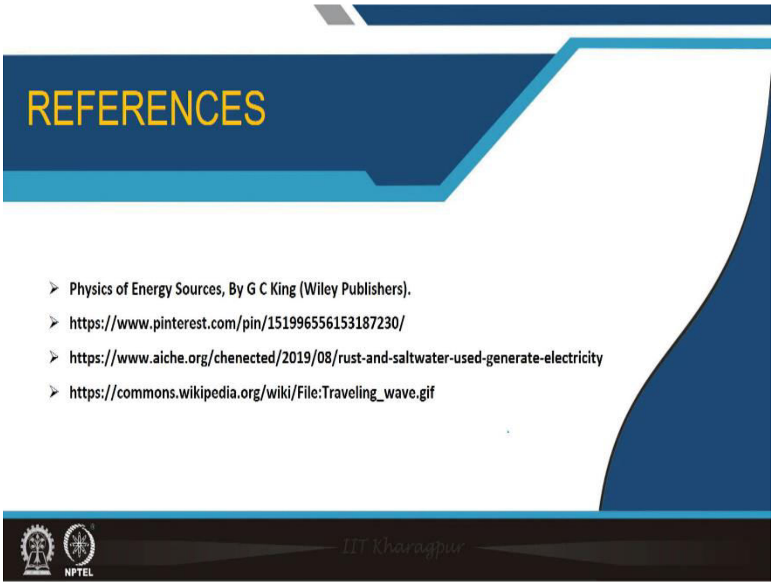

These are the references which we followed in today's lecture. So, I thank you for attending today's lecture on hydroelectric plant and in the next lecture, we will move to the next topic of this module. Thank you very much