Advanced Hydraulics
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Module - 6
Turbines
Lecture - 3
Turbines Part 3 (Pumps, Turbines)

Very good morning to everyone. So, we are continuing our lecture series on advanced hydraulics and we are in the last module called turbines. In the last lecture, we had described about pumps.

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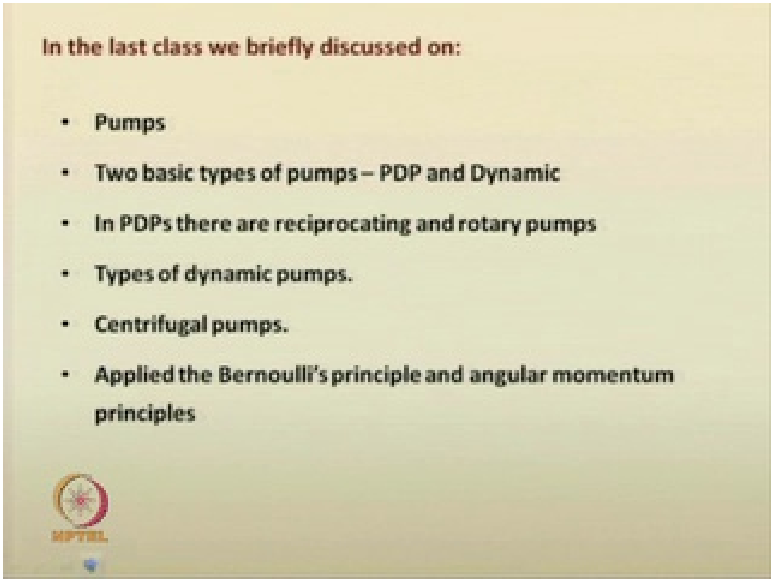

That is pumps how they are categorized? They are categorized as PDPs and dynamic. In PDPs, there are reciprocating and rotary pumps. We also suggested the types of dynamic pumps that are available. Centrifugal pump is one of the main dynamic pump. And we were trying to analyze the centrifugal pump. For that we use the Bernoulli's principle and angular momentum principles. So, we suggested about the angular momentum. Today, we will continue the same angular momentum and see how in the impeller blade of pump is said to be especially the centrifugal pump; how the pump theory works and all, how the quantities can be defined. Then subsequently, we will go for the go through the other aspects of pumps and all, and turbines if possible.

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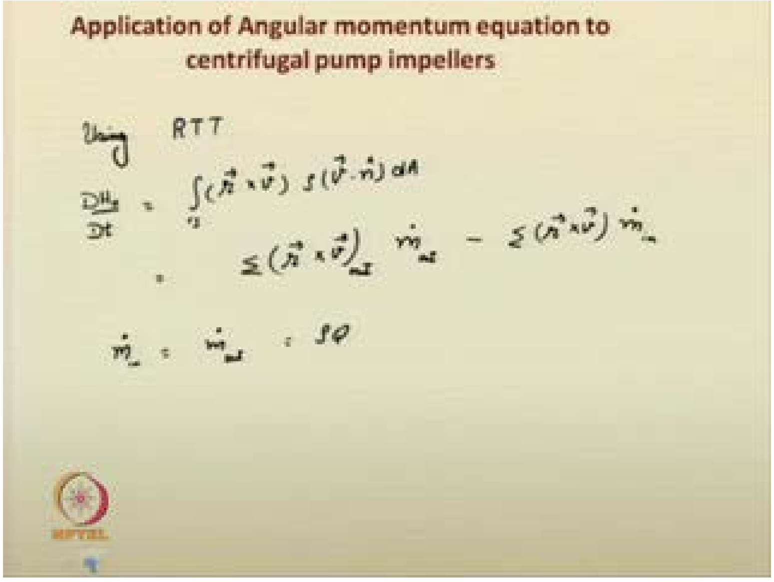

If you recall, the angular momentum equation that was described in the last class for the impeller blade and all. So, let me write the RTT form. So, if the angular momentum equation using Reynolds transport theorem, you had come up with the following relationship; that is DH by Dt, this is nothing but equal to r cross v rho v dot n... So, for any control volume, this was the angular momentum equation for steady state condition. And we also suggested for the for the case, which we are dealing right now, this can be given as r cross v at the outlet into the rate of mass that comes out through this particular surface minus r cross v m dot in; that is rate of mass there comes into the control volume through the inlet portion. Normally, as we are dealing with steady state condition m in, that is the mass that is coming out and mass that is going out, coming in and that is going out. They will be same, which can be given as rho Q.

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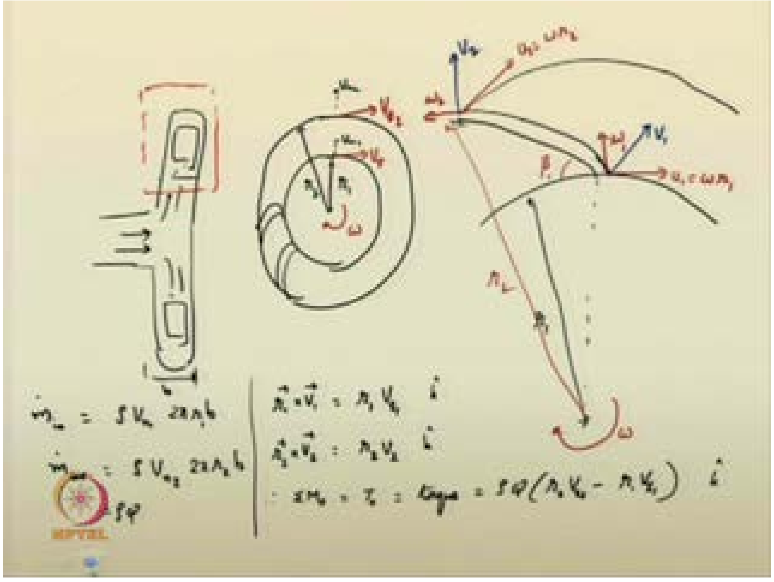

Let me ask you; say or just by this particular small figure; say we suggested flow comes axially into the impeller. And let us suggest this is the portion of the blade – impeller blade. So, we have… This can be given as one small circle of radius r 1; one big circle. So, this is an impeller disk. This is the small disk; this is the outer disk. And you will be having impellers of the following form like this – impeller blades. You have seen a snap shot of the impeller blade and all. Let us assume these particular quantities now. Say this is radius r 1 and this is radius r 2. So, in this case, if we suggest that, there is a tangential velocity at this location. You know that, water comes here; hits the blade. So, this is the starting portion of the impeller blade. I will just elaborately draw that particular portion again. That will be… Say if you consider this particular any blade and all. I can just again draw it. So, that way it will be much much better clear. This is the inner radius. So, this is an expanded view. So, please note that, this is not the actual (( )). So, this particular portion – it has been just expanded.

You have some radius somewhere here – r 1; this is r 2. The same thing; just in an expanded form we have drawn it. In this particular case, we can now just draw the quantity; say from this location, there is an impeller blade in the following form. Say I am just for our benefit; tangent… I am drawing an impeller blade like this now. This is how an impeller blade will come into the picture. Water – as it flows from like this and all; it will reach here; it will hit here; means it will reach here. This impeller blade – it is rotating at an angle omega. So, both… If the impeller wheel – it is rotating at an angle omega; definitely, the entire system – this both the inner disk and the outer disk – both are rotating; both the portions of that impeller disk (( )) is rotating. So, you can have say outer tangential velocity v 2. So, I will elaborate it now again in the next figure.

What we want to suggest is now; if this is the control volume that is you are going to consider; if this is the portion – the control volume. You can have now m dot in. This is nothing but equal to rho v n 1. Say if this is of thickness b; 2 pi r r 1 b 1. And m dot out is nothing but density into normal velocity from the exit. Say at this location, what is the v n 2; this is v n 1. We can see here water is coming and hitting like that. So, v n 2 2 pi r 2 b, so b is same for both the cases. In this particular case, this situation… So, we can now write r 1 cross v 1. This is nothing but equal to r 2 into v t 2 with a unit vector component perpendicular to both the vectors. So, r 2 cross v 2 – this is nothing but say please note that, we are making some simple mistakes. This is r 1 v t 1; r 1 v t 1 into sine theta – sin 90. That is the actual this thing. r 2 v 2 – the component; that vector will be perpendicular to both r 2 and v 2. Like this you can suggest now. Therefore, you will be writing sigma M 0. That is called the torque, is nothing but equal to rho Q; that is M in dot and M out dot – both are equal to rho Q. So, rho Q into r 2 v t 2 minus r 1 v t 1; that is having… That is perpendicular to this thing. So, this is the torque that has to be applied to the system – pump system.

Here axially if it is rotated in that direction perpendicular to both r and v; if it is rotated; that is a torque that is needed to be applied. These are called some Euler’s turbine machine equation. I can just again elaborate at this particular portion now. You can see here. Here water comes at a particular velocity. So, let us assume that the tangential velocity at the impeller inlet; that is, impeller is at a particular angle like this. So, this particular angle – let us assume it to be some angle called beta one. So, the tangential velocity – let us assume to the impeller direction be w 1. And let us assume at the exit point, at this location, the tangential velocity to the impeller blade is w 2. Like this you can assume certain quantity. So, water will be entering at the tangential velocity of the impeller blade direction like this. It will flow through this like this and it will come out like this. That should have been the theoretical situation. Or if the disk is not rotating, this is how the flow could have occurred.

Now, the disk is rotating at an angular velocity omega. If this is rotating at like this thing; we are suggesting that. So, this disk is rotating it. This disk will be having a velocity in this direction. That is called u 1. This is nothing but equal to omega r 1 – a tangential velocity. Similarly, at the exit point also, there will be a tangential velocity due to the rotation of the disk. u 2 – u 2 is equal to omega r 2. Like that you have now suggested components of velocity. So, there will be now a resultant velocity at the inlet portion of the impeller blade. There will be a resultant velocity, which I can just give it in a different color now. There will be a resultant velocity; say I am just writing it as v 1. This is the resultant velocity. A similar resultant velocity can be taken here also. So, this is how the exit occurs; that is, although water is going like this due to the rotation of blades and all, water will come and splash like that; it will come out like that. So, this is the resultant velocity of water at that outlet of the impeller blade and this is the resultant velocity at the inlet of the impeller blade. So, like that we have the directions now.

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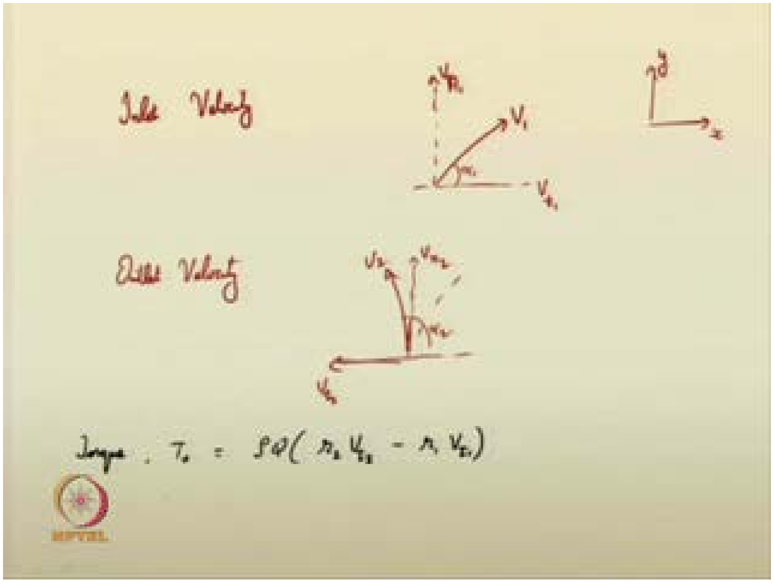

These components – this resultant velocity is v 1; that is, inlet… Inlet velocity as considered in the previous slide. Say v 1 – if it is like this; then that v 1 we can assume. Say if you have a two-dimensional co-ordinate system x y like this; if we are assuming such a co-ordinate system; then based on that co-ordinate system, let us assume that this is the tangential velocity v t 1 and this is the normal velocity v n 1. Similarly, outlet velocity can also be described in the same form. Say if it is like this – v 2; say we can write it; say this is v t 2 and this is v n 2. Like that one can easily write the components of velocity. And you can assume certain quantity say; this is alpha 1; this is alpha 2. So, the outlet means the resultant velocity need not be in this particular direction. It can also be like this also. That has to be calculated actually. So, one can infer it like that now. Using the same previous case, we have mentioned the net torque equation. Torque – I can now write it as t 0. This is nothing but rho Q into r 2 v t 2 minus r 1 v t 1. Like this I can write it. What is that property of this torque? Means why we want to describe this torque quantity? We have suggested that, we have to give external power supply to the pump system.

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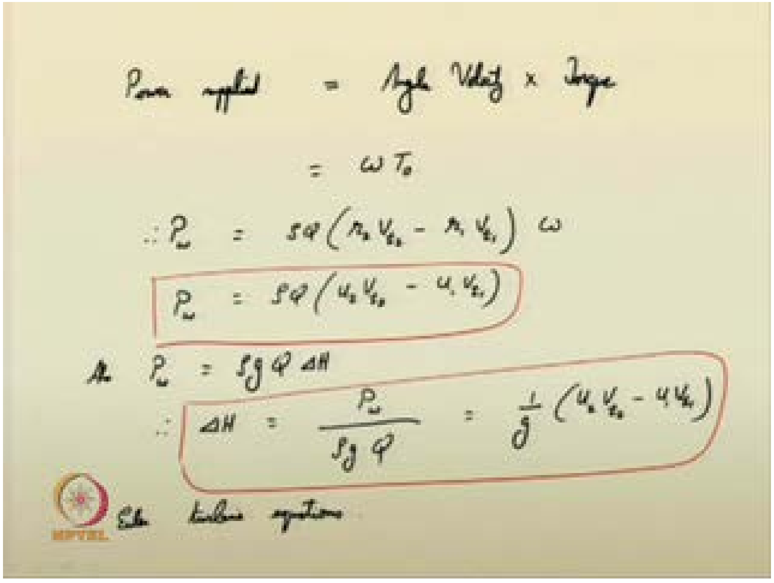

How much power should be supplied? Power supplied – it should be equal to the angular velocity into torque. This is omega into t 0. Therefore, we can write P w is equal to rho Q r 2 v t 2 minus r 1 v t 1 into omega. What is r 2 omega, and what is r 1 omega? Based on that, we can write this as u 2 v t 2 minus u 1 v t 1. So, this is the power supply. Also, P w is equal to rho g Q into difference in head. This we have studied earlier in the first lecture. Therefore, del H now can be computed based on the power supply P w by rho g Q. This is nothing but equal to 1 by g into u 2 v t 2 minus u 1 v t 1. So, these equations are combinedly called… Give it in a box, so this particular equation as well as this equation. Combinedly, we refer them as Euler's turbine or you can say Euler turbine equations. So, these quantities are referred in that way.

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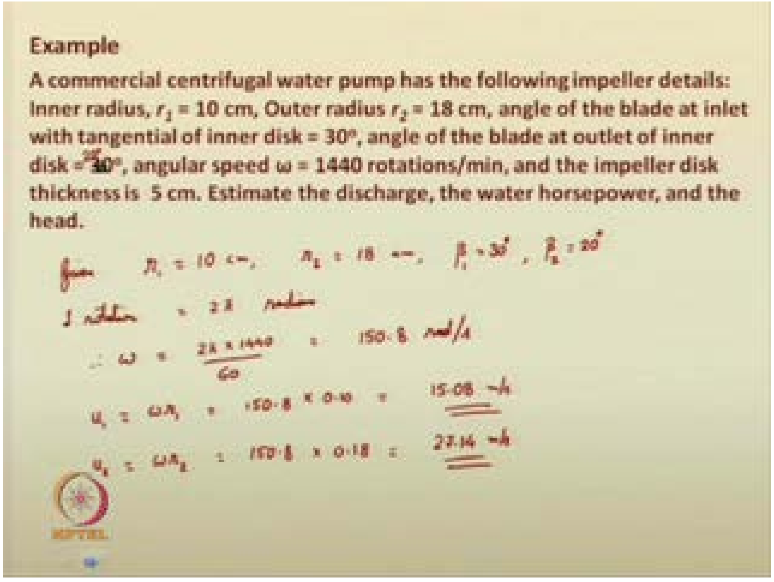

We will do one example problem related to these features of the impeller blades. Just carefully look into the question. Commercial centrifugal water pump has the following impeller details. The inner radius r 1 is equal to 10 centimeter; outer radius r 2 is equal to 18 centimeter; the angle of the blade at inlet with tangential of the inner disk – it is 30 degrees. If you recall that; you generally call it as beta 1; in the theory part, we have studied that. Then angle of the blade at outlet of inner disk – tangential; similarly think. It is 20 degrees. Please note that; this is not 30 degrees, it is 20 degrees. So, just we will correct it here. The angular speed omega is equal to 1440 rotations per minute and the impeller disk thickness is 5 centimeter. Now, estimate the discharge, the water horsepower, and the head that has been generated from the pump. Can you solve it?

It is a very… We have to go through the basics itself. Just recall the figure. You have this impeller – this thing; beta 1 is given as 30 degrees; beta 2 is given as 20 degrees; omega – this is also given. So, all the quantities are given to you. We will be suggesting now the following quantities. Given r 1 is equal to 10 centimeter; r 2 is equal to 18 centimeter; beta 1 is equal to 30 degrees; and beta 2 is equal to 20 degrees. Then what do you mean by… The angular speed is given as 1440 rotations per minute. So, one rotation, how do you express? One rotation is equal to 2 pi radians. Therefore, omega is equal to 2 pi into 1440. How much is this value? Or whatever be; if I want to give it… Say this is rotations per minute. So, I am just dividing it by 60 to give these many radians per second. So, I am getting this as 150.8 radians per second. So, I got omega as this quantity.

Now, recall the velocity at the tip of the inlet u 1. This is nothing but equal to angular velocity of the disk into r 1. This becomes 150.8 into r 1 – is 10 centimeter – that is, 0.1 meter. And at the inlet of the impeller blade, this is 15.08 meter per second. Similarly, at the outlet of the impeller blade, the tip velocity will be 150.8 into 0.18. This is 27.14 meter per second. So, we got the tip velocities. Let us now suggest that, for the design condition, usually when you design impeller blades and all; we design it in such a way that, the resultant velocity at the inlet is having only the normal component; that is, the tangential component for the resultant velocity is considered as 0 or you want to design it in such way that, the tangential velocity there – it is 0.

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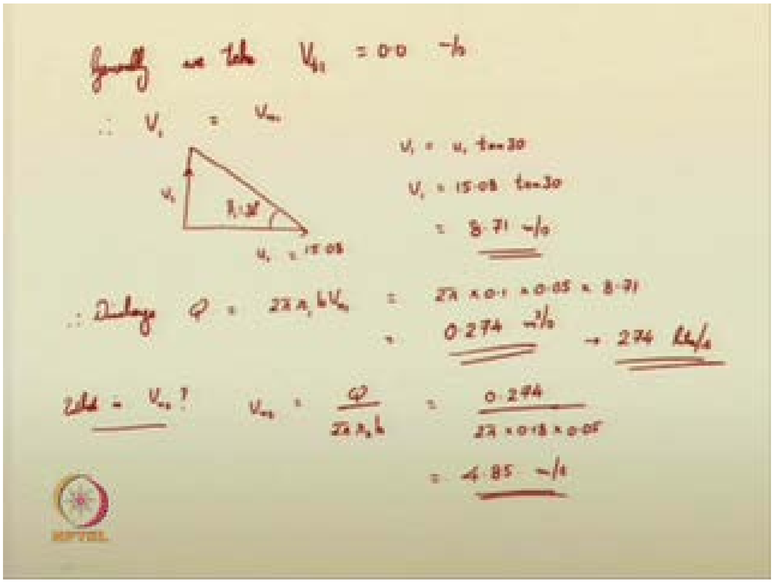

That is, generally, we take v t 1 is equal to 0. It is being the impeller blades are designed it in such a way. Therefore, whatever velocity is there – resultant velocity is there – v 1 at the inlet; this is same as the normal velocity v n 1. Now, we can suggest the following quantities. You have the tip velocity in this direction – 15.8 meter per second. This is u 1 at the inlet. And at the inlet, we have suggested the resultant velocity v 1. v 1 is like this. It is a normal component. And the angle of the blade we have given it as beta 1. We can now write the following quantity, v 1 is nothing but equal to u 1 tan 30 from this particular figure. So, v 1 is equal to 15.08 into tan 30; that you know that is equal to 8.71 meter per second. Therefore, discharge Q – this is given as – recall that discharge equation 2 pi r 1 into b into v n 1. So, this is 2 pi into 0.1 at the inlet; b is 5 centimeter. So, 0.5 then 8.71, this will give you 0.274 meter cube per second. So, this is the discharge in the particular pump; you have the discharge 0.274 meter cube per second. We are assuming steady state condition. So, this discharge will be maintained as it. If you want it in a practical form, this is nothing but the discharge from the pump is 274 liters per second. What is v n 2 now, normal velocity at outlet? What is v n 2? v n 2 is nothing but Q by 2 pi r 2 into b. So, 0.274 by 2 pi into 0.18 into 0.05. This is nothing but equal to 4.85 meter per second.

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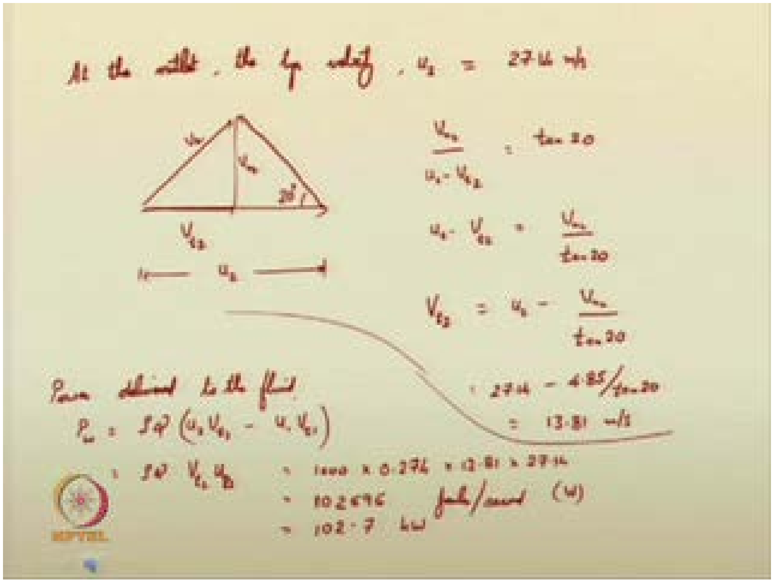

At the outlet, the tip velocity of the blade u 2 is equal to 27.14 meter per second. This we have already suggested now. Let us give it like this now. And v t 2 – there will be some quantity v t 2 also from something up to here. So, tangential velocity at the exit point – v t 2 – that is also available. You know that, the blade is having an angle 20 degrees with the outer surface of the disk and all. So, 20 degrees is the angle. Now, you know that, this is u 2. So, the resultant velocity v 2 will be something of this form. We can now easily compute what is v t 2. You can see from the quantities here – this is v n 2, v t 2. Like that one can easily compute it. So, v n 2 by u 2 minus v t 2 – this is equal to tan 20. So, just rearrange the terms here; you will get u 2 minus v t 2 is equal to v n 2 by tan 20. Again rearrange, substitute the quantities you have; 27.14 or let me we suggest like this. So, v t 2 – the tangential velocity at the exit point v t 2 is nothing but u 2 minus v n 2 by tan 20. Substitute the quantities. This is 27.14 minus 4.85 by tan 20. This will come to be about 13.81 meter per second. So, this is the tangential velocity at the exit point of the impeller blade.

Power delivered to the fluid – how will you calculate power delivered? You recall the Euler turbine equation. Power delivered to the fluid – I am just remarking this. This is nothing but P v is equal to rho Q u 2 v t 2 minus u 1 v t 1. Now, what is u 1 v t 1? You know the tangential velocity at inlet point – it is 0. So, this becomes rho Q v t 2 u 2. So, rho is – we are taking water – 1000 kilogram per meter cube. Discharge – you know it is 0.274. v t 2 – it is already computed now – 13.81. And u 2 – this is nothing but 27.14 meter per second. So, you have substituted all the quantities right now. Calculate this thing. This will come to be about 102696 joules per second; or, it is also called watt. You can also write this as approximately 102.7 kilowatt – the power.

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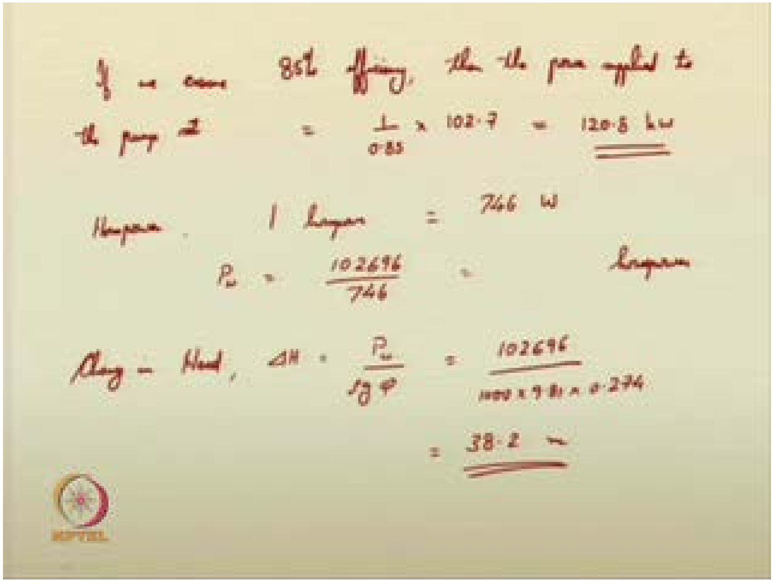

If we assume 85 percentage efficiency, then the power supplied to the pump set – this is equal to 1 by 0.85 into 102.7. It comes to be approximately 120.8 kilowatt. You need to provide a power of 120.8 kilo watt in that case. Now, how much is the horsepower? You can easily find horsepower. Horsepower – 1 horsepower is approximately equal to 746 watt. Therefore, you know that power in horsepower can be easily written as say 102696 by 746. How much? That I am giving it to you as homework. So, you can write it. This is the power in terms of horsepower. Change in head – it can be given as del H. So, del H is nothing but P w by rho g Q. So, this is 102696 by 1000 into 9.81 into 0.274. This is coming to be about roughly 38.2 meters. So, the change in head is coming to be roughly about 38 meters. So, this is the head. That is being changed when you provided that particular pump. What is the effect of blade angle on the pump head? In the last example, you already saw this is the change in head and all. In some cases, it depends on whether if you want more discharge or whether if you want more head displacement or change in head; whichever is the objective based on that you have to select the pump.

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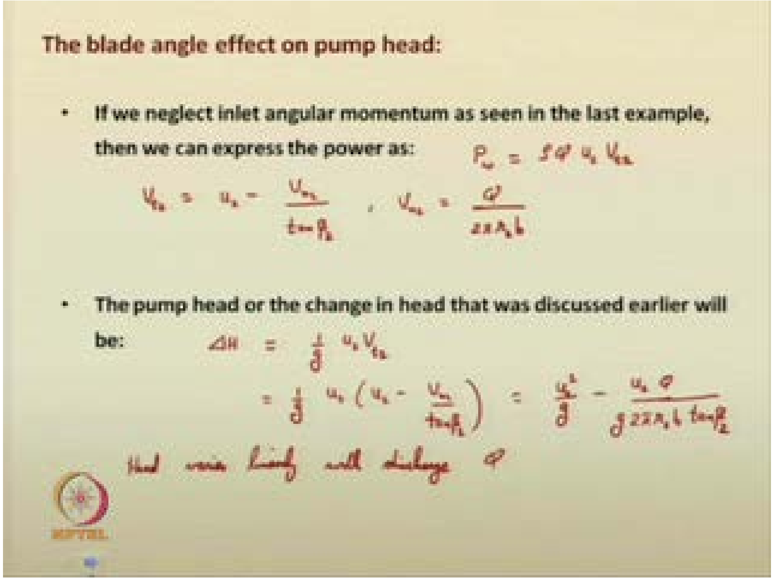

What is the effect of blade angle on the pump head? This del H term, whichever was quantified – it is called the pump head. If we neglect the inlet angular momentum as we have seen in the last example; then we can express the power; means we can usually express power as P w is equal to rho Q u 2 v t 2; where, v t 2 is nothing but equal to u 2 minus v n 2 by tan beta 2; then v n 2 is nothing but equal to the discharge by 2 pi r 2 b. We are assuming thickness b is constant. Then you can now easily write the pump head or change in head. It can be written as del H approximately equal to 1 by g u 2 into v 2. Recall the earlier portion. From that, you can easily write it now in this particular way. What is this quantity? You substitute 1 by g u 2; and v t 2 you know – it is nothing but u 2 minus v n 2 by tan beta 2.

So, this is nothing but u square by g minus u 2 cube g. And what is this? v n 2 is Q by 2 pi r 2 b. So, that quantity you are substituting it here – 2 pi r 2 b tan beta 2. Like this you are getting the relationship. What is the physical meaning of this quantity now? u 2 means we can see that del H – it is something related to discharge as well as the wind velocity. So, u 2 square at the… Wind velocity at the exit point of the blade – u 2 square by g. How will you quantify the thing? Head varies; I can just write it like this also. The head varies linearly with discharge Q.

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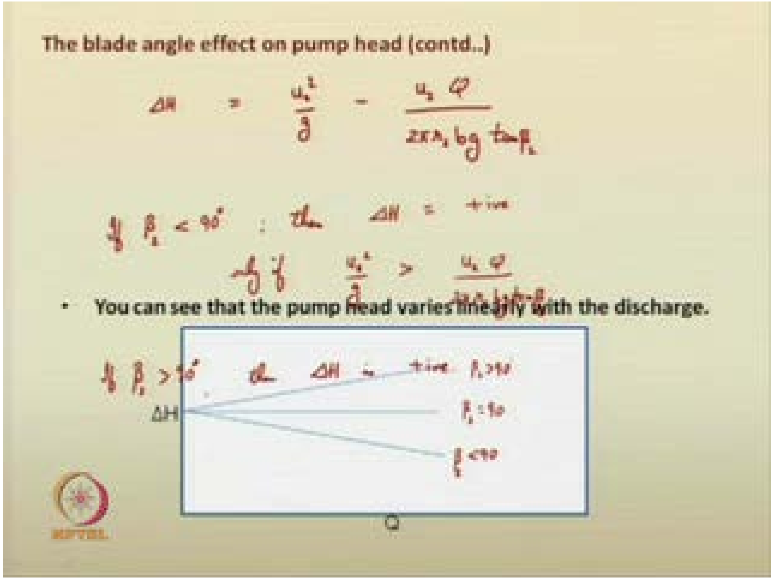

Del H equal to u 2 square by g minus u 2 Q by 2 pi r 2 b g tan beta 2. So, you can suggest now, if beta 2 here – if it is less than 90 degrees, what happens? Then del H is equal to – del H is positive. If beta 2 is less than 90 degrees, it will be always positive. Why? Because tan beta will… If it is beta 2 is less than 90 degree, then del H will be positive only if u 2 square by g is greater than u 2 Q by 2 pi r 2 bg tan beta 2 or u by g is greater than Q by 2 pi r 2 bg tan beta 2. Like that one can say. If beta 2 is greater than 90 degrees, then del H is positive, because you know, u 2 square by g – that is a positive quantity and here the minus and minus quantity is coming. So, it will become totally positive. So, I can now write the same quantities in the following form. We can represent it by the following picture; means whichever is being suggested; del H versus Q – if you plot it. So, this I can suggest that, in this particular diagram, this is for beta 2 less than 90; this is beta 2 equal to 90; and this is beta 2 greater than 90. Like this you can infer from this particular picture.

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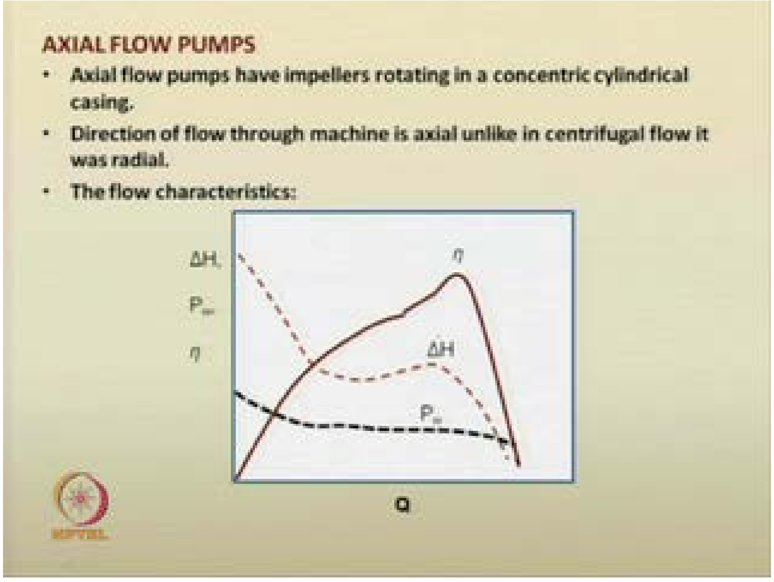

Next, what we would like to see is axial flow pumps. Till now, the centrifugal pumps, whichever we have studied – they are readily flowing pumps; means although they are dynamic pumps, flow into the impeller and all; they are in the radial direction; that is, from the impeller location base, it will just readily divert through the impeller blades to the diffuser section and subsequently to the outlet section and all. There are pumps, which allow flow in the axial direction as well. So, we have axial flow pumps, where the impellers are rotated in a concentric cylindrical casing. So, they will be rotated in the concentric cylindrical casing and they will be having some rupture points, where it is connected to inlet and outlet in the alternate… Alternatively, it will be connected. So, direction of flow through machine is axial unlike in centrifugal pumps.

The flow characteristics of axial flow pumps – it is being given by this following picture here. If you plot Q versus change in head or pump head or Q versus P w or Q versus efficiency, you will see that, there will be a maximum efficiency at certain particular discharge. Beyond that, if you increase the discharge even slightly, there will be a rapid decrease in the efficiency. Similarly, if you decrease; means if you have less discharge compared to that particular value, then also, the efficiency decreases. You can also see del H versus Q. If the pump head – if it is lower, you will get higher discharge; say efficiency… Similarly, power – it is more or less means we are not comparing that much. So, this particular feature of axial flow pumps plays a significant role.

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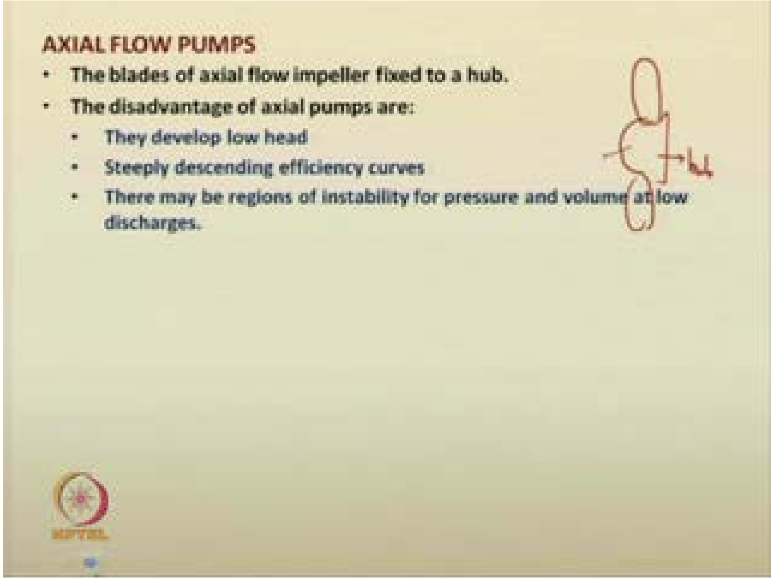

You will see that, the blades of the axial flow pumps – as they are fixed to a hub, the disadvantages of the axial flow pumps are… Hub means some particular this thing, where the blades are connected like this. Such quantities are called hub. So, the blades of the axial flow pumps, impeller fixed to a hub. Then the disadvantages are they develop low head; steeply descending efficiency curves; and there may be regions of instability for pressure and volume at low discharges.

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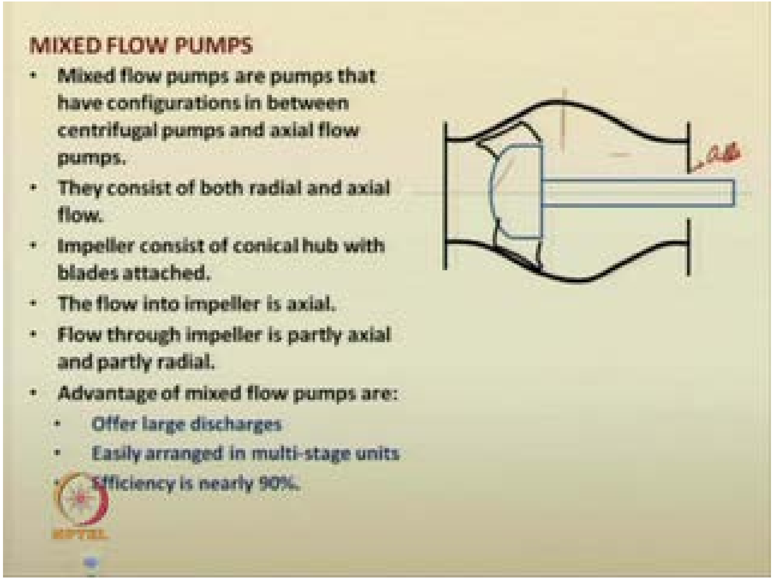

The next quantity, which we would like to study, is mixed flow pumps; where both radial and axial flow occurs in the pump that have configurations in between those things. So, you can suggest now – the impeller consists of a conical hub as it is suggested here. This is the conical hub with blades attached. These are the blades attached. The flow into the impeller is axial. You will have flow axially here. Then it will go readily (( )) then through the impeller, both readily and axial flows are occurring. As it has to flow like this, not only in the radial direction; it has to flow like this also; it has to cover (( )). This is the outlet portion. So, this much portion it has to cover. So, it has both axial and radial components. So, advantages of these pumps are – they offer large discharges; they can be easily arranged in multi-stage units; its efficiency is quite high; means they have nearly 90 percent efficiency; and you can use them.

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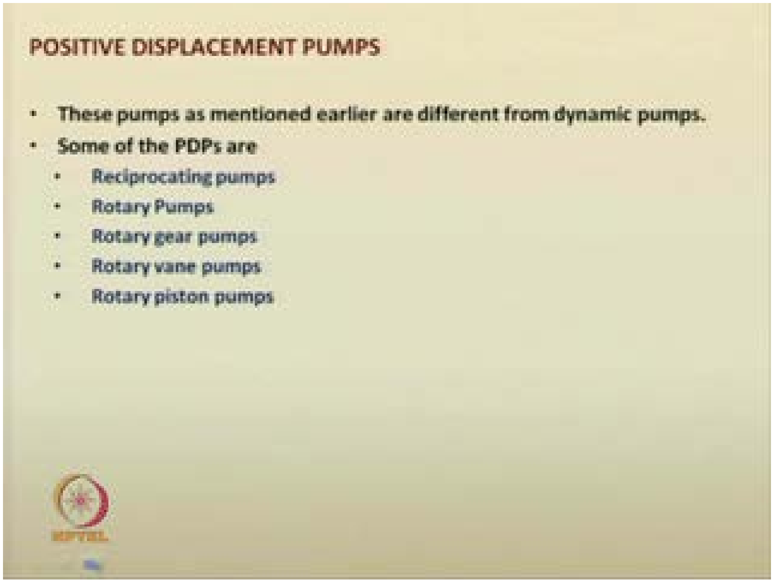

The next category of pumps, which we told; means we suggested that, there are two categories of pumps: dynamic pumps and positive-displacement pumps. In the positive-displacement pumps, as we have mentioned earlier, positive displacement pumps – they are different from the dynamics pumps; some of the pumps we have studied – reciprocating pumps, rotary pumps, rotary gear pumps, rotary vane pumps, rotary piston pumps. We will just briefly give a quick or we just quickly look into these aspects.

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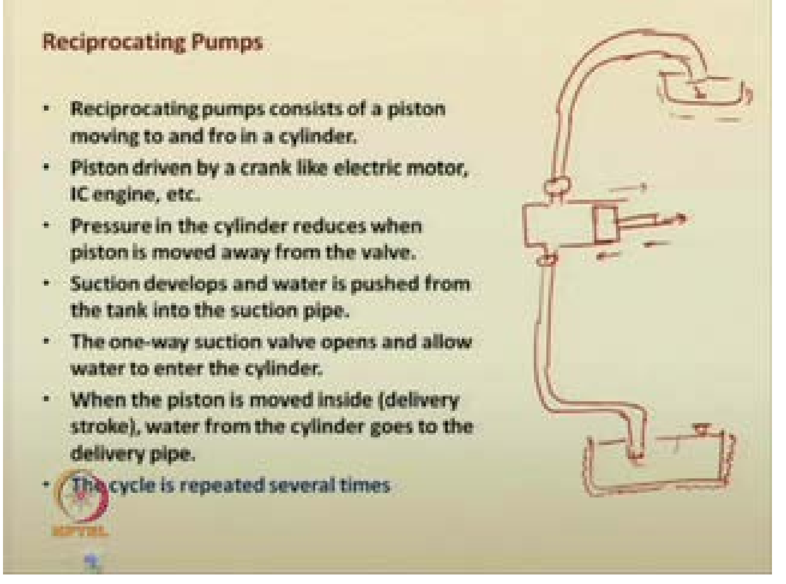

What is meant by reciprocating pumps? So, reciprocating pumps, it consists of a piston moving to and fro in a cylinder. You have a piston moving to and fro in a cylinder. So, the piston is driven by a crank like electric motor or IC engine, etcetera. In that the piston is driven by a crank or electric motor, IC engine, I will just give a diagrammatic representation of the thing. The pressure in the cylinder reduces when piston is moved away from the valve; that is during the suction portion, that is, it is getting the suction… Suction this is suction develops in that cylinder and water is pushed from the suction pipe. When the water is pushed from the suction pipe, it opens a suction valve and it allows water to enter into the chamber or the cylinder.

So, when the piston subsequently as it reaches the limit, then the piston moves in the opposite direction and it tries to close the cylinder. In that case, what happens? The piston is moved inside. So, it is called the delivery stroke. This is suction stroke and delivery stroke. So, water from the cylinder now goes into the delivery pipe. This is how the reciprocating pump works. So, this cycle is repeated several times, and based on that efficiency, things are noted there. Say if I just draw cylinder like this. I am just connecting it to a small valve here, so this a closed cylinder. A piston can give it in a different color also. A piston is suggested here, so which the piston moves in this direction as well as in this direction. So, when the piston moves in this direction, the chamber gets expanded; that is the volume in the… It is getting expanded.

I forgot to draw the subsequent portions. So, there is a (( )) or hose connected to the tank or lake or river, whichever be water body from which you need to extract water. So, the open… Let us assume the water body, whichever you are taking into account; it is open to the atmosphere. So, atmospheric pressure exists at the surface of that water body. When the piston is moved away like this in this portion, suction develops here. It is called a suction stroke of the (( )) this thing. Suction develops here. So, this portion will be in suction low pressure… Atmospheric pressure will be now greater than the pressure in this quantity. So, it will push water like this and water is pushed into the hose and it reaches here. The valve opens and it enters in this chamber.

Now, what happens? This reaches the limit here and it now goes into the delivery stroke. So, it goes in the opposite direction like this – this piston. So, the chamber is getting closed, pressure is getting increased; this valve is opened; water is now pushed through this hose like this to the delivery region. So, it may be a water tank or a… Whether if it is irrigation; whichever be, water will be pushed into it. So, this is the simple mechanism of reciprocating pumps.

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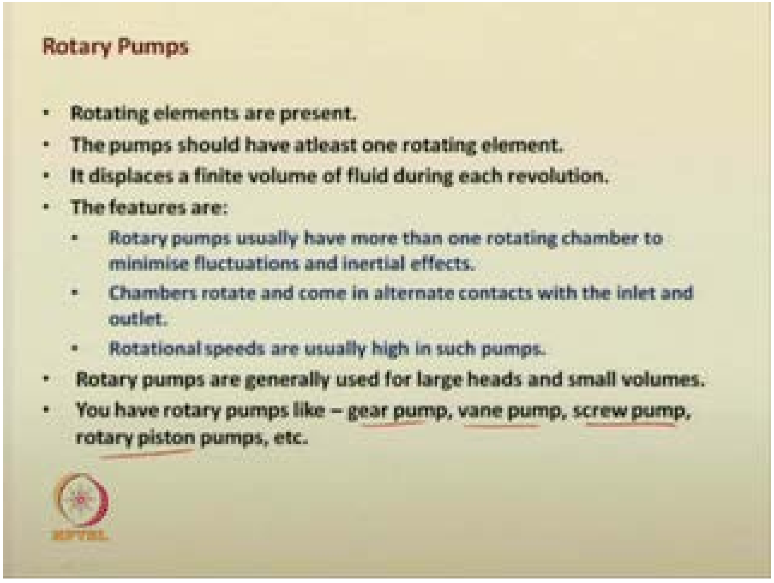

Rotary pumps – they consist of rotating elements. It has rotating elements. At least one rotating element should be there. It displaces a finite volume of fluid during each revolution. The features are – rotary pumps usually have more than one rotating chamber to minimize fluctuations and inertial effects; the chambers rotate and come in alternate contacts with the inlet and outlet; the rotational speeds are usually high in such rotary pumps. Rotary pumps are generally used for very large heads and small volumes, if you want to displace only small volume; but very large head is there. For those cases, rotary pumps are used. You have rotary pumps like gear pump, vane pump, screw pump, rotary piston pumps, etcetera. As we do not want to go further into the details of these types of pumps, we just want to stop those quantities here. Just as a brief passing by statement – we would like to make those.