Basics of Mechanical Engineering-3

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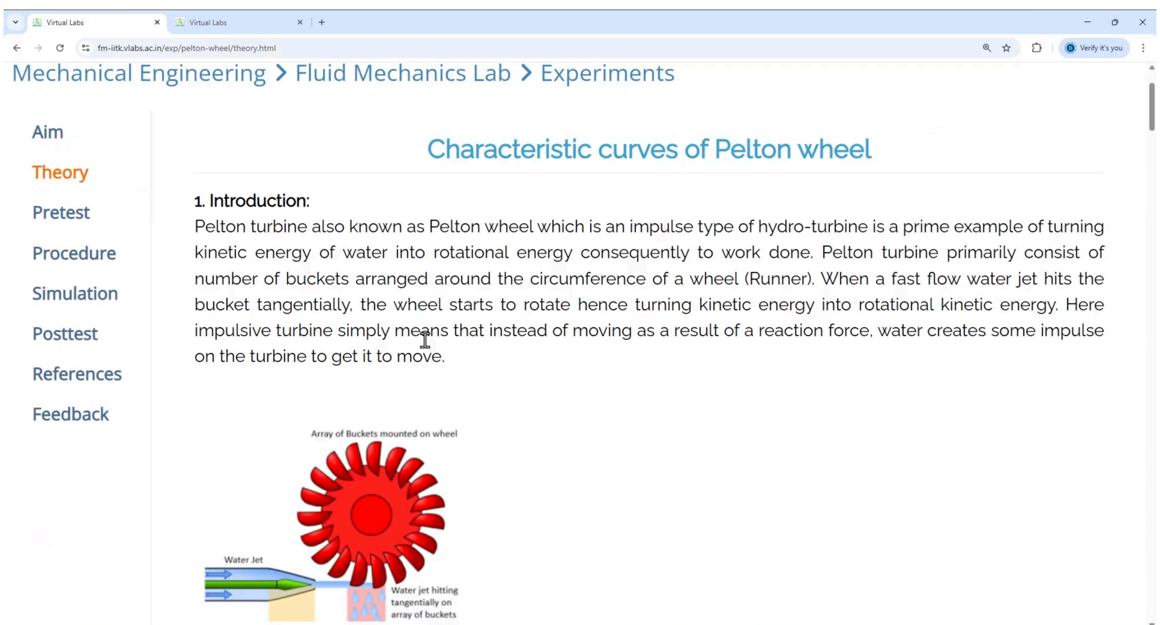
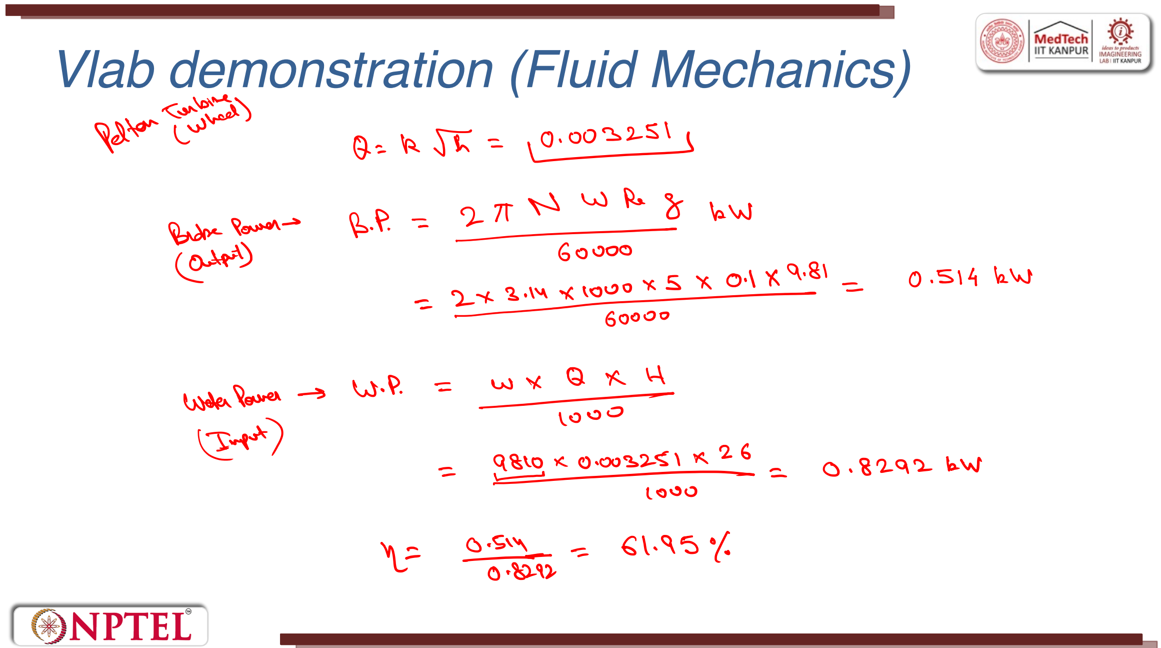
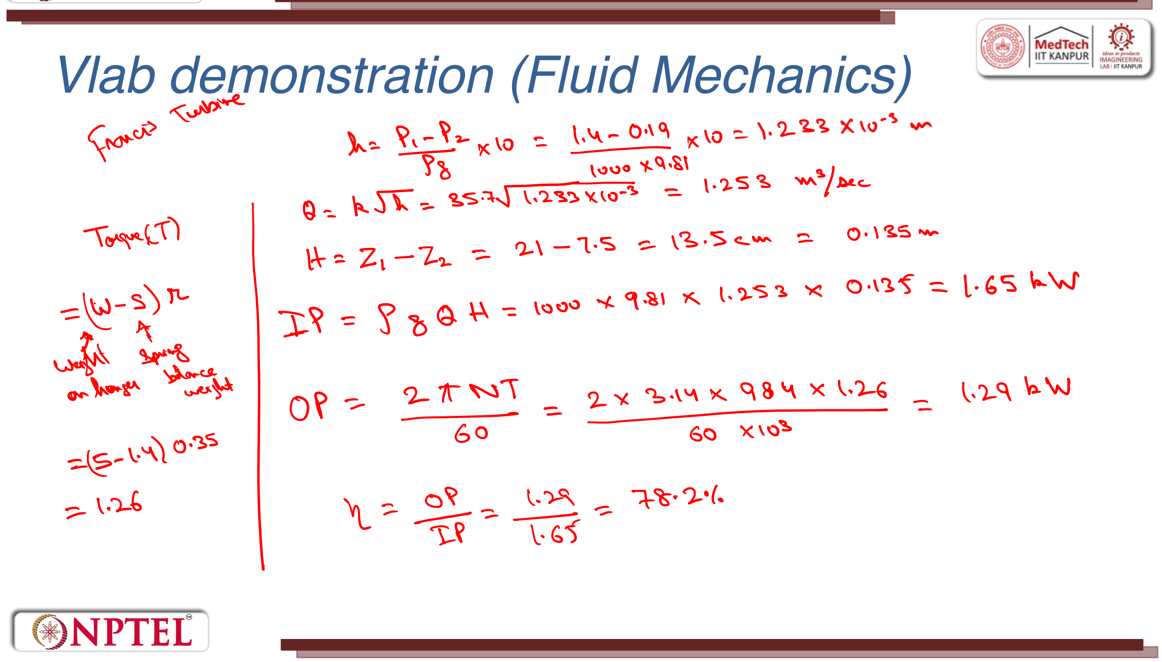
Week 11

Lecture 49: Virtual Lab. Demonstration (Fluid Mechanics, Part 3 of 3)

Welcome to the third part of the Virtual Laboratory Demonstration. I have talked about the basic theory of fluid mechanics and virtual demonstration. In the previous two parts, we discussed the flow conditions, Reynolds number, and Bernoulli's theorem. Then we talked about two kinds of pumps: the gear pump and the single-acting reciprocating pump. Now I will talk about the turbines.







Turbines are discussed this week only. I will talk about the Francis turbine, which is the most widely used. I will also talk about the Pelton wheel. The Kaplan turbine is also available in the list of experiments, which you can go through by yourself. For any queries, you can come by.

Now, I will return to the list of experiments and review the turbines discussed this week. In the previous lectures, we discussed various kinds of turbines: the Pelton turbine, Pelton wheel, Kaplan turbine, and Francis turbine. I will first cover the Pelton wheel here. The aim is to study the performance of a Pelton turbine and draw its operating characteristics. In theory, let us recall what a Pelton turbine is.

It is also known as the Pelton wheel, which is an impulsive type of hydro turbine, and it is a prime example of converting the kinetic energy of water into rotational energy, consequently producing work. The Pelton turbine consists of a number of buckets arranged around the circumference of a wheel. When a fast-flowing water jet hits the bucket tangentially, the wheel starts rotating, and this kinetic energy is generated through the stream of incoming water. Here, an impulsive turbine simply means that instead of moving as a result of reaction force, water creates an impulse on the turbine to make it move. That is, water comes in, the wheel starts rotating, and electricity is produced.

Now, the parts of the Pelton turbine include the penstock, the wheel, the nozzle, the spear, the jet of water, the casing to prevent leakage, the buckets or vanes, and the runner. Each of these parts is explained here. Now, the most important part explained here is the nozzle. In the nozzle, we have the spear, which increases the kinetic energy of the water that is going to strike the buckets or vanes. The quantity of water that strikes the bucket is controlled by the spear here.

The spear is installed inside the nozzle, and this regulates the flow that is going to strike the buckets. So, that is the primary purpose of the spear inside the nozzle. The runner with buckets. The buckets are generally shaped like this. You can see there is an undercut in the bucket so that when the water hits here, it can also discharge out.

So, there is always an undercut in the bucket. So, each bucket has a wall between two hemispherical bolts called a splitter. The splitter splits the jet of water in the buckets into two equal parts, and the jet of water comes out at the outer edge of the bucket. The buckets are designed in such a way that the jet of water striking the buckets is deflected through 160 to 170 degrees. So, this is one kind of Pelton turbine setup that is given here.

So, we have a penstock. A penstock is a pipe that conveys the flow from the storage to the turbine. From the water storage to the turbine, it comes through the penstock. When we talk about the heads, the head at which water is stored and the head at which it enters the turbine are two different heads, and there is a difference between them as well. That will also be taken into account when we try to find the actual efficiency of a Pelton wheel or Pelton turbine.

This is also given here. You see, this is the head race. This is the point at which the water is stored. This is the gross head. And also, the water falls here. So this is Hf. And net head is gross head minus Hf. The gross head is the head difference between the water level at the reservoir and the water level at the tailrace. Net effective head is the head available at the inlet of the turbine or is the net effective head. This is noted by H, that is H = Hg, that is gross head – Hf, where Hf is the loss of head.

The total loss of head due to friction during the transit of water from headrace to tailrace. And this is given by Hf = $4Lv^2/2gd$ where all the annotations are also given here. f is the coefficient of friction, L is the total length of the penstock, v is the mean flow velocity, d is the diameter of the penstock, g is the acceleration due to gravity. So, hydraulic efficiency would be calculated. Let us come to the procedure and try to see what relations are used and how this kind of characteristic curve could be plotted, where we are plotting discharge with respect to power or efficiency.

If we plot efficiency, it will go up and down like this, while the discharge is increasing. But the power increases when the discharge increases. Let me see some pre-test questions here. Undercut is provided to avoid interference of the water jet with incoming buckets. Splitter on the buckets—I just talked about the need for the splitter. The splitter on the bucket is used to split the water into two and change its direction. That is why it is called a splitter. The most widely used turbine for electricity generation is the Pelton, Kaplan, or Francis turbine. It is the Francis turbine.

The governor in Pelton turbines is provided to help maintain constant RPM. A Pelton wheel is to be designed with a wheel pitch diameter of 1 meter, jet diameter of 0.1 meter. The number of buckets would be calculated by the formula: Z = (15 + D)/2d. Here, D is 1 meter, and d is 0.1. So, this is calculated here, and the value is found to be 20 buckets, which are required.

Which component is not used in a Pelton wheel turbine? In the Pelton wheel turbine, a jet is used, a penstock is used, a draft tube is not used, and casing is used. The hydraulic efficiency of a Pelton turbine will be maximum when the blade velocity is equal to v/2. Hydraulic efficiency would be maximum. In a Pelton turbine, gas is defined as the ratio between the power delivered to the runner and the power supplied at the inlet of the turbine. So, this is hydraulic efficiency.

Among the following, which turbine has the least efficiency? The Pelton turbine has the least efficiency. The power supplied at the inlet of a turbine in SI units is known as at.

This we have discussed in the pumps as well. One is water power, one is brake power. At the inlet, the power that is supplied is water power. At the outlet, the discharge power is called brake power. So, the inlet power is asked about. It is water power. Let me submit.

Everything is correct here. Let me now come to the procedure. As mentioned here, the constant speed is maintained by varying the discharge by changing the spear position as the load changes. From the measured discharge Q, head (which is almost constant), and power developed P, the overall efficiency η_0 is calculated, and curves are plotted between η_0. And power with discharge—the curves which I showed you in the previous pages of this website.

Discharge is $k\sqrt{h}$, where k is a constant that depends upon the venturi meter dimensions. And h is the head. Shaft power or brake power—this is the output power. This is $2\pi NWRe \times 9.81$, which is $Re \times g \div 60{,}000$. Here, Re is not the Reynolds number; it is the effective radius of the brake drum.

When I say effective radius here, it is the radius of the drum—there is a drum, and there is a radius of that. A rope is running through this or is tied over this drum. The radius of the rope plus the radius of the drum is the effective radius. It is Re. 9.81 is g. Water power is wQH/1000, where w is the specific weight of water, taken as approximately 9810 newtons per cubic meter. Q is discharge in m^3/sec. H is the head of water.

Overall efficiency is brake power divided by water power. The procedure is: change the load on the hanger, adjust the delivery valve or centrifugal pump to keep the head the same, and adjust the spear position. With constant speed and almost constant head, note the still level reading, which is the hook gauge reading. By using the above-mentioned steps, change the load from low load to full load and tabulate the readings as given in Table 1. Plot the operating characteristic curve.

It is given here; the mean diameter of the drum is Dd + Df, where Dd is the diameter of the drum and Dr is the diameter of the rope. This is the table that we will construct here. Let me come to the simulation part, like the other experiments. It first asks us to switch on the power. You can see an arrow there. Switch on the power. Please wait until the water reaches; the water is coming here. But it will reach toward the full opening valve here.

Now, we will open the valve, and there comes the water flowing through it. You can see through the penstock; the water is entering the turbine. These runners or blades are there, through which the turbine is now running. Now, I will provide brake weight. Let me say a brake weight of 5 kg first and spear positioning at 1. So, at this value, we have seen the head is 26 meters. Weight 1 is 5 kg. Weight 2 is 0.5 kg. And RPM is 1000. And the flow meter reading is 3.251×10^{-3}.

That is Q. That means Q is directly given here. Q, though, could be calculated through Q is equal to k under root h, where k is given here for this specific turbine as 21.1, and under root h could also be put here. Now, Q is directly given as 3.251 into 10 to the power minus 3. Head is 26. Let me enter these values.

RPM is 1000. Net supply H value here is 26. Discharge is 3.251. I will put it as 0.003251 because into 10 to the power minus 3 is here. Brake weight is 5 kg. Spring weight is 0.5 kg. The difference between these two, 5 minus 0.5, is 4.5.

Input power and brake power have to be calculated here. Input power is to be calculated. That is the work power, and brake power is to be calculated using this formula. For this observation only, let me do the calculation. This is regarding the Pelton turbine, or we call it a Pelton wheel.

Q is given. Q could also be calculated as k under root h, but this is already given as 0.003251. Now, brake power. To calculate this, the relation given is $2\pi NW \times Re \times g \div 60{,}000$ kilowatts. So, this is equal to 2×3.14. N is RPM, which we have taken in the observation table as 1000. And W is brake weight.

Brake weight is 5 kg × Re. Effective radius you can see here. It has given the mean diameter of the brake drum M as 200 mm. Diameter is 200. That means the radius would be 100 mm.

We can take the effective radius as 100 mm. That is 0.1 meters. This radius is 0.1. And the value of g is 9.81. This divided by 60,000, which will be 60,000 here. This gives me the brake power as 0.514 kilowatts.

Now, when we talk about water power, water power is calculated using the relation that is given there. That is $\frac{WQH}{1000}$. Putting all the values here. W, that is the specific weight of water, is 9×10 N/m^3. The value of $Q = 0.003251 \times H$. For the first observation, the height is 26 meters divided by 1000. This value turns out to be 0.8292 kilowatts.

Because this is in watts, I am converting it to kilowatts by dividing it by 1000. Efficiency = output power/input power = 0.514/0.8292. This turns out to be 61.95%. So, we can put these values there.

Input power is calculated here as 0.8292. Output power is calculated as 0.514. Efficiency, which I have calculated, is 61.95%. Similarly, we can run it for the second position or second weight for 7 kg. I will make it at position two. Now it is running, and it is showing the head value as 32, the weight as 7 and 0.9 kg as W1 and W2, the RPM as 1000, and the flow meter reading as 4.597×10^{-3}.

These values could be put in there, and you can calculate all the values, check the result, and try to plot the characteristic curve between the efficiency and the discharge and between the power and the discharge. So, this is the Pelton wheel. I will take another turbine, the Francis turbine, because in the pre-test questions, we saw that the Francis turbine is the most commonly used turbine for electricity generation due to its high efficiency.

Let me try to come to the Francis turbine. I have come to the list of experiments once again. This is the last virtual demonstration that I am taking, which is on the Francis turbine, conducting experiments and drawing characteristic curves of the Francis turbine. Now, here the aim is—what the title of the experiment is—the performance of the Francis turbine and drawing operating characteristic curves. In theory, we talked about the Francis turbine.

It is the most widely used. It is a turbine that has a schematic arrangement like this. It has a turbine casing like this, a rotor, and a water reservoir. The Francis turbine is a type of mixed-flow reaction turbine. It became known as the Francis turbine around 1920 when a British engineer, James B. Francis, made many interventions into the development of this turbine and designed it as a new turbine.

It works with medium heads ranging from 40 meters to 600 meters. The main parts of a Francis turbine are the penstock, spiral scroll or casing that we have observed. The turbine blade is here. Water enters from one side, and this is how the water goes towards the blades or wicket gates. So, the blades or wicket gates are the only controlling part of the whole turbine, which opens and closes depending upon the demand of the power requirement.

In case of more power output requirements, it opens wider to allow more water to hit the blades and when low power output requirement is there, it opens less. So, the percentage of opening is also something we will observe when running the simulation. The governing mechanism that is used here is to change the position of the wicket gauge to affect the change in water flow depending upon the load conditions requirement and the positions which are here are 0 positions completely closed, 25% open, 50% open, 75% open, 100% that is completely open when very high power requirements are there. You can see here the guide vane; when it is opened more, there is a larger area for the water to hit. When it is opened less, there is a smaller area for the water to hit.

So, there is a pivot here that helps control the opening of the vanes. So, you see there is a water inlet there, the turbine blade is coming here, and this draft tube is conically going down so that the water flows out easily. The working of the reaction turbine involves water being brought to the runner through the wicket gate from the reservoir via the penstock. The water enters the runner at high pressure but low velocity, flows over the vanes, and the pressure head is gradually converted into velocity head. The kinetic energy generated causes the rotation of the turbine. In other words, the hydraulic energy is converted into mechanical energy.

The water leaving the runner enters the tailrace after passing through the draft tube, which gradually enlarges. That is, there is a conical enlargement in the draft tube, and the enlarged end is submerged deeply into the tailrace water. Due to this arrangement, a suction head is created at the exit of the runner. The advantages of the Francis turbine on wear and tear have a delayed effect on the efficiency of the Francis turbine compared to the Pelton turbine. Operating head variation can be easily controlled.

Even at low discharge of water, head failure does not occur. The runner and generator size is small. Only slight changes in efficiency over time are observed. Operating head can be utilized even when the variation in tailwater is relatively large compared to the total head. But there are certain disadvantages.

That is, dirty water can cause extremely rapid wear in high-head Francis turbines. Repair and inspection are reasonably much harder. Cavitation is an ever-present hazard. Cavitation can reduce efficiency and can even cause failure if not addressed. So, when the flow is not completely continuous or even laminar, cavitation occurs, forming water bubbles within the flow that also burst.

When they burst, the bursts also affect the surface of the pipe or the inner surface of the turbine that comes in contact with the cavitation bubbles. This cavitation is the effect present in Francis turbines. Let me come to the pre-test questions. The first question to test our knowledge before embarking on the simulation is: which one of the following statements is true? Both Pelton and Francis turbines are impulse turbines. Kaplan turbine is a radial-flow reaction turbine.

The Francis turbine is a mixed-flow reaction turbine. This is correct. The Kaplan turbine is an impulse turbine. The answer is C. The Francis turbine is a mixed-flow reaction turbine. Which of the following minimum values of available heads may the Francis turbine be used amongst 250, 150, 140?

Because we talked about the Francis turbine starting from 40 itself. I can put the answer as 40 meters. Which turbine has the maximum number of blades? The maximum number of blades are there in Francis turbines. In a Francis turbine, the pressure at the inlet is higher than the pressure at the outlet.

The inlet pressure is always greater in a Francis turbine. The available head in the case of a Francis turbine is converted completely into velocity, completely into pressure, partially into velocity head and pressure head, or partially into velocity head and completely into pressure head. It is partially into velocity and pressure heads. The cross-section of the blade of a Francis turbine is an airfoil. The Francis turbine is an inward-flow reaction turbine.

First is the correct answer. The major problem with the Francis turbine is not efficiency, not installation, not speed regulation. It is cavitation, as I discussed. The outlet of the Francis turbine is through the draft tube. That is an enlargement towards the downside.

The power output of the Francis turbine ranges from 5 to 800 megawatts. 1000 to 2000—these are very large numbers. I will put it as 5 to 800 megawatts. Let me submit. Everything is correct. Let me see the concept of cavitation, which is explained here.

Cavitation occurs when local pressure drops below the vapor pressure of the fluid, leading to the formation of vapor bubbles, which can cause significant damage to the turbine blades and reduce efficiency. That is when the local pressure drops below the vapor pressure, the bubbles are formed, and these burst and affect the health of the turbine equipment.

The procedure and experimental setup are just like this. This is a vacuum gauge, this is a centrifugal pump, and through the wall, we can control. The pressure gauge is there, and the water flows out of the draft tube. This we have already discussed. So, the Francis turbine setup is there. Note the inlet and outlet pipe diameters. That is, we will try to note the breakdown diameter, Z1, and Z2. That is, the distances of inlet and outlet pressure gauge settings.

This will be noted. Start the supply pump while keeping the guide vanes completely closed. Open the guide vanes partially. That is, half open, 1/4th open, 25%, 50%, 75%, measure the discharge Q, note the pressure gauge readings, note the readings of W (load on hanger), spring balance, and shaft speed. Vary the turbine speed by adjusting the load, W and S, on the brake drum and take 6 to 7 readings within the allowable speed range.

Change the guide vane opening to repeat steps 4 to 7. Here, V1 = $(Q/\pi/4) \times d1^2$. V2 = $(Q/\pi/4) \times d2^2$. Here, V1 and V2 are the absolute velocities of water entering and leaving. In Q, discharge, d1 and d2 are the diameters of the inlet and outlet pipes.

Respectively, here, H = P1/W - P2/w. That is pressure head, velocity head, and datum head. Here, for simplicity, we will just calculate H, the total head, as the difference between Z1 and Z2. Input power is wQH/75. The Output power = W – (SπDN/4500). These are the relations for input and output power.

There are also other relations given. In the simulation, this kind of observation table would be constructed and developed. Let us now come to the simulation. See, as I have told, 0, 1, 2, 3, 4 are 0%, 25%, 50%, 75%, and 100% opening of the valves. I will switch on the power.

When I switch on the power, you see water is coming from below. Here, the water is going through the motor. There is a flow opening. They say, 'Open the flow valve.' I will open the flow valve. The water will now enter the turbine. The turbine starts rotating. The RPM is 1200. Now they say, 'Apply weight.' As of now, the weight is 0 kg—weight 1 and weight 2. Let me apply a weight of 5 kg first. For a weight of 5 kg, I will open this to 25%. So here you see weight 1 is 5 kg, weight 2 is 1.4 kg, h2 is 0.19, and H1 is 1.4.

Let us note down all the readings on a paper, and then we can keep applying a load of 3 kg next at 50% opening. Here, the weight changes. The weight is 3 kg, and weight 2 is 0.3 kg. The RPM is 1024. For the first weight, what I did—let me do the calculations first, and I will keep on doing this.

The next load is 6 kg at 75% opening. Here also, the weight changes, and the RPM changes. The h1 and h2 values also change, even for zero weight. Let me try to see the observation and the given values here. Here, we have been given h, which is (P1 minus P2) divided by rho g—that is the difference between the pressures. The pressure values were given directly there: 1.4 and 0.19 mm mercury, divided by rho into g. Rho is 1000 for water, and g is 9.81.

And Q could be calculated using the venturi meter constant, which is 35.7, multiplied by the square root of h. h could be calculated from the given formula. Then we have capital H. Capital H is the total head. The total head would be the difference between the inlet pressure of the turbine and the outlet pressure of the turbine. That is 21 minus 7.5 centimeters. That is 13.5 centimeters, which is equal to 0.135 meters.

Then, input power is ρgQH. That is the formula given. And output power is $2\pi NT/60$. Let me try to calculate everything and put the values here. The value of the gate valve opening is 25% for the first observation. P1 value for the first observation of pressure 1 is 1.4. P2 is 0.19.

The RPM observed from the experiment was 984. The brake weight applied was 5 kg first, and the spring weight observed was 1.4 only. So, using these values, let me try to do a simple calculation for the Francis turbine. Let me first calculate $H = (P1 - P2) / (\rho g) \times 10 = (1.4 - 0.19) \times 10$.

That is $1000 \times g$, which is 9.81. This is 1.233×10^{-3} meters. Now, $Q = k \times \sqrt{h}$. k is given as 35.7, which is a constant value. This multiplied by $\sqrt{(1.233 \times 10^{-3})}$. The value of Q, the discharge, turns out to be 1.253 m^3/s. Now, the head, as I said, could be taken only between the potential head, which is $Z1 - Z2$, or $21 - 7.5 = 13.5$ cm, which is 0.135 m. Now comes the calculation of input power and output power. Input power is ρgQh. This is for the Francis turbine. $\rho = 1000$, we are talking about water. g is 9.81. Q is calculated there. That is 1.253. This is the head difference.

That is capital H. That is 0.135. This turns out to be 1.65 kilowatts. Output power is $2\pi NT/60$. Here, this new term T torque, that is torque T. Torque is the product of the difference between the hanger weight and the spring weight. Here, W is the weight on the hanger, and S is the spring balance weight. So, this difference times the radius because the diameter is given as 700.

We will take the radius as 350, that is 0.350 meters. So, this is equal to 5 - 1.4 x 0.35. This turns out to be 1.26. So, putting the values here. (2 x 3.14 x 984 x 1.26)/60. And it is RPM, and this multiplied by 10^{-3}, so that we have units in kilowatts. This is equal to 1.29 kilowatts. This gives me efficiency as output power/input power = 1.29/1.65 = 78.2%.

These are the calculations when you use pen and paper. But this is only for the first observation. For the 25% of the opening, we have seen that the RPM would vary. We have seen that the heads would vary. The weights would vary that we have selected.

It is always better to use an Excel sheet to do the calculations. And from the Excel sheet itself, the plot could also be made. Now, I will put these values here in the calculation table and try to find the final results. The head value that I have calculated here is 1.233 x 10^{-3} = 0.001233. Discharge, that is Q, turns out to be 1.25. Torque was calculated as 1.26.

Water head acting on the turbine, that was the difference between Z1 and Z2, that was in meters, if I say, that is 0.138 meters, which is 17.5 centimeters. Input power that I calculated is 1.65 kilowatts. Output power I calculated is 1.29. And the efficiency that I have gotten is 78.2 percent from all the efficiencies taken from the different observations. That is the four different observations at different levels of the opening of the load. The loads would vary. We have the final average efficiency.

So this could also be plotted, and we can have a characteristic curve based on the efficiency and discharge. So this is a simulation setup for a Francis turbine. Let me go through the post-test questions as well. The first question says: The reason for the gradual decrease in the cross-sectional area of the spiral casing of the Francis turbine from the entrance to the tip is that the gradual decrease is there to maintain a constant velocity. This is the correct answer.

To prevent loss of efficiency, to prevent leakage, to reduce material use. The best answer is to maintain constant velocity. That is the reason for the gradual decrease in the cross-sectional area of the spiral casing, so that the velocity is maintained. Dash is defined as the ratio between the power available at the shaft to the power supplied by water at the inlet. This we have discussed in the previous experiments.

This is the overall efficiency. Dash is defined as the ratio between the power produced by the runner to the power supplied by the water inlet. When we talk about the power produced by the runner and the power supplied by the water inlet, this is the hydraulic efficiency. This is defined as the ratio between the total quantity of water over the runner blades to the total quantity of water supplied to the turbine. This is the volumetric efficiency because we are talking about the total quantity of water here.

This is defined as the ratio between the power available at the shaft of the turbine to the power produced by the runner. When power is available at the shaft, power is produced by the runner. When these are compared, this is mechanical efficiency because we are comparing power. The dash converts dynamic pressure, which is kinetic energy, into static pressure. It is the draft tube.

A hydraulic turbine converts hydro energy into mechanical energy by using the dash of water, by using the potential energy of water, and by using the kinetic energy of water. Both of them are used. The answer should be both A and B. As we have seen during the explanation in the pre-test questions, cavitation occurs when there is low pressure. Because of the low pressure only, cavitation occurs. The pressure is lower than the vapor pressure.

That is, the pressure drops below the vapor pressure of the fluid, causing vapors to form bubbles that can implode. Imploding is inside. Exploding is outside. Imploding is inside. These bubbles burst and cause damage to the surface of the inner walls of the turbine. In cavitation, material fails due to erosion, that is, slow damage occurs.

In mixed flow turbines, water enters the runner—and comes out—. In mixed flow turbines, such as the Francis turbine, water enters radially and exits axially. Let me see. We have gotten 10 out of 10. Interestingly, there are questions about the kinds of efficiency.

When it is the power produced by the runner to the power supplied by water, it is hydraulic efficiency. When it refers to the quantity of total water over the runner base to the total quantity of water supplied to the turbine, it is the volume of the water—it is volumetric efficiency. When we talk about the power available at the shaft of the turbine to the power produced by the runner, it is mechanical efficiency. And the overall efficiency is when it refers to the power available at the shaft to the power supplied by water at the inlet. That is overall efficiency. With this, let us see the references upon which this is designed.

And there could always be feedback to share your experience. You can put your feedback in this. This feedback would come to us because these experiments—the fluid mechanics laboratory—is developed by Professor Ramkumar and me only. And anyway, you can give feedback on the forum questions, which is there for this course, Basics of Mechanical Engineering 3. We will try to cater to all your questions that were there. And we will try to meet next week. It is the last week. We will try to discuss something other than the regular mechanical things. We will try to talk about the role of statistics and the role of design of experiments in mechanical engineering.

Thank you.