Fluid Machines.
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Lecture-11.
Introduction and Analysis of Force on Francis Turbine (Radial Flow) Part I.

Good morning and welcome you all to this session of course on fluid machines. Last class we discussed the Pelton wheel, the limitations of Pelton wheel and its specific speed. Now, today we will start the reaction turbine and in continuation of the last class I would like to say that it has been appreciated that the Pelton wheel, Impulse turbine like Pelton wheel is not suitable for low head or high specific speed for its efficient operation for which we go to reaction turbine.

Now 1st of all we have to know what is the reaction turbine as we have already seen that in reaction turbine define the pressure head or static head of the fluid changes in the rotor along with the change of its kinetic head due to change in absolute velocity. Now if we see the difference between these with respect to the Pelton wheel, in a Pelton wheel, the head available at the inlet to the machine, that means at the nozzle which is mostly in the form of pressure is totally converted into kinetic energy. And the pressure at the exit of the nozzle is the atmospheric pressure.

In the jet and therefore the wheels of the Pelton turbine or the Pelton wheel is open to atmosphere and the jet engages at a time 1 or 2 little more blades, not all the blades, this is because number of Jets are limited. And at the same time, the Jets may not full totally covering the entire area of the spoon shaped bucket. But while in case of a reaction turbine if you compare, 1st thing in the stator, there is the nozzle, it is again a nozzle but in a different geometrical configuration, the inlet pressure head or static head is partly converted into velocity.

So therefore the fluid enters to the rotor blades with both at high pressure and high velocity and that pressure is above the atmospheric pressure. For this reason this runner or the rotor blades which are called as runners, I will tell afterwards, the rotor blades of a reaction turbine have to be made with the casing, because this cannot be made open. And at the same time the fluid fills the entire passage of the rotor and as it flows through the rotor, there is a change in the fluid pressure, means there is a change in the static or pressure head of the fluid along with the change in its kinetic energy based on the absolute velocity, that is the dynamic head which is known as Impulse action. That is the basic thing.

And to accomplish this change in pressure and in case of turbine the pressure has to be reduced, so the cross-sectional area of flow, that is the area normal to the velocity, flow velocity has to be reduced. That means the passage has to be a converging passage where the velocity relative to the runner will increase and the pressure will decrease. So these are the basic differences from the viewpoint of principle of operation of a reaction turbine from that of a Impulse turbine and mainly the differences have been made with respect to a Pelton wheel.

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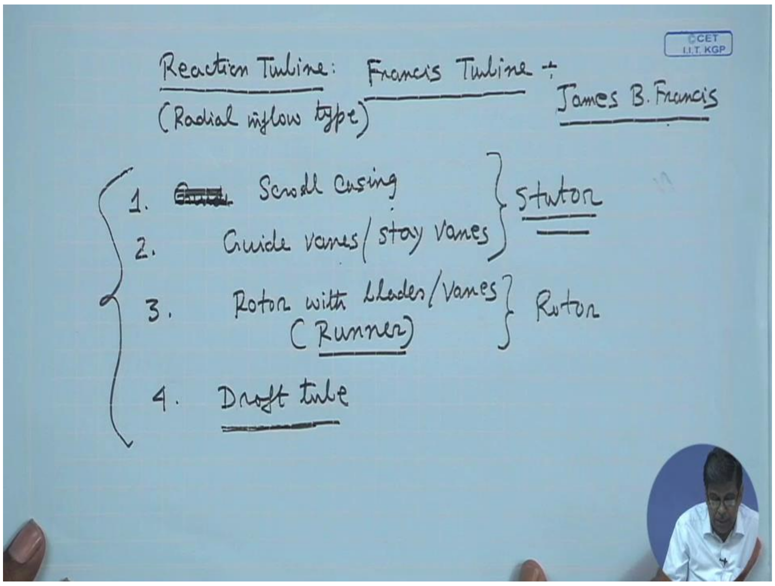

Now if we see that way, we can write a reaction turbine. 1st of all let us see that, we will discuss a reaction turbine which was, which is known as Francis turbine, a typical reaction turbine which is known as Francis turbine and it was contributed, the development was contributed by the scientist James American scientist or engineer, James B Francis and after his name it was known as, it is named as Francis. This is also in the middle of the 19th century. This is a radial flow turbine, the reaction turbine radial flow type.

And as you know the turbine always is radial in flow because the static head has to reduce, so this has to be in flow, which already I have discussed earlier, radial inflow type, radial inflow type. This is radial inflow type reaction turbine which is known as Francis turbine named after American engineer Francis who made much to the development of this turbine. Now the main components of the turbine if you see 1st is the guide vanes.

1st is not the guide vane, rather I will write. 1st is the scroll casing, scroll casing which is a spiral casing, number 2 is the guide vanes or stay vanes, number 3 is the rotor with blades or vanes, this is known as the runner mainly, this is known as runner. And number 4 is the draft tube. So a radial flow reaction turbine is a Francis turbine is a typical radial flow reaction turbine, Francis turbine consists of 4 main components, one is scroll casing. Now these components I have written in order of sequence of flow path.

The flow enters 1st in scroll casing which is spiral casing, then guide vanes or stay vanes, these are fixed vanes, rotor, then rotor with blades, now these 2 are fixed and actually this can be viewed as the stator of the machine. Then rotor which is mounted to the shaft rotates with the angular constant angular speed, the blades and vanes are there which are known as runner, this is the rotor of the machine. And finally at the discharge end of the runner, a fixed tube is added which is known as draft tube.

Before the water leaves or before the water is ejected or discharged at the level which is known as tail rest, that means the draft tube is the fixed tube which is attached to the outlet of the runner through which the water ultimately flows through the sump or to that level where the water is discharged, for example in the river which we call as the tail rest. So these 4 main parts constitute a reaction turbine, Francis type reaction turbine. So with this in the background, let us see how for a simple diagram how does it look like.

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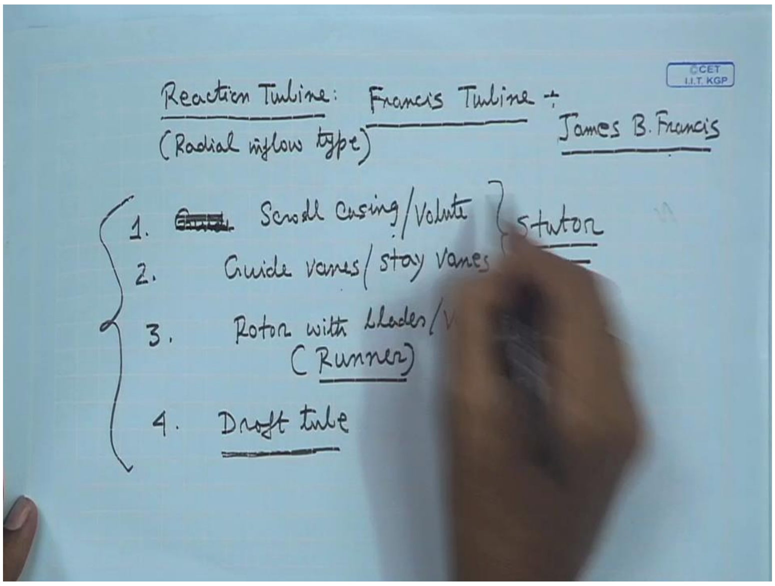

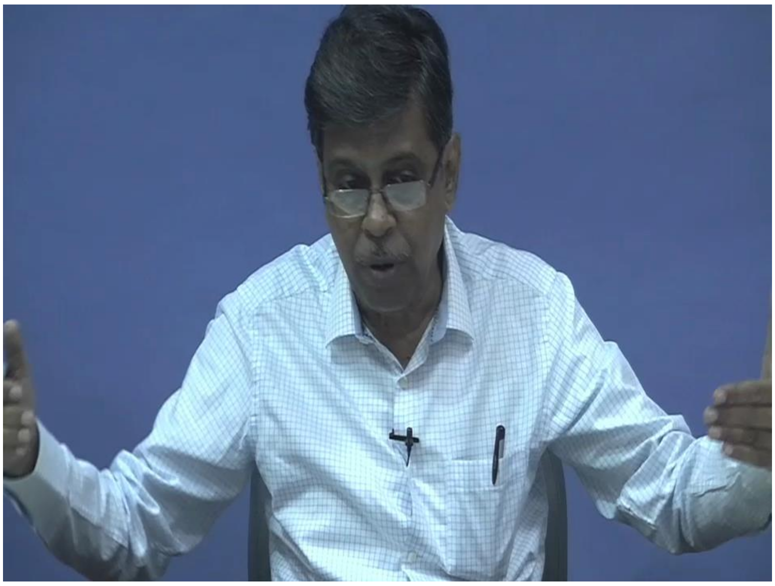
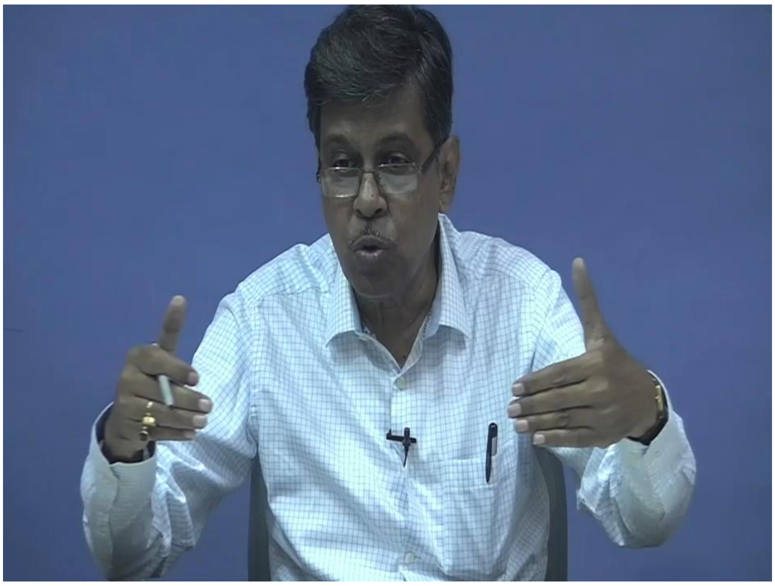
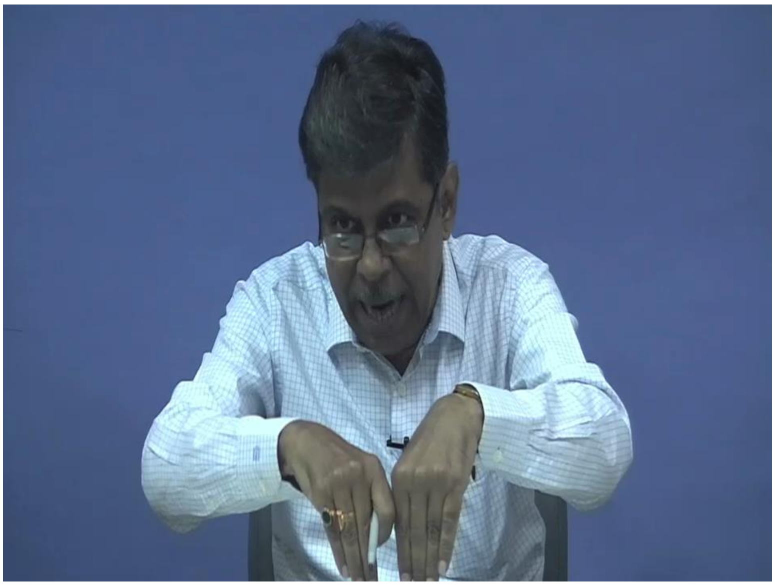

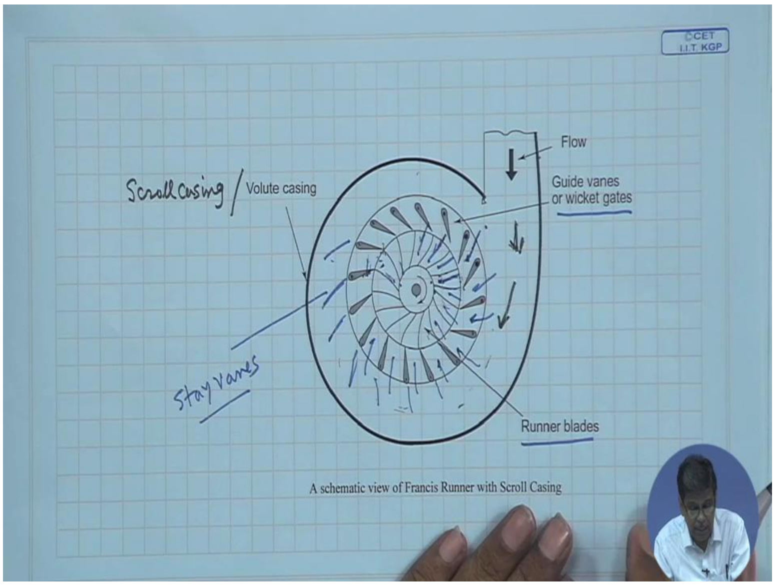

Now here, this is a spiral casing or the scroll casing or sometimes this is known as volute, volute, volute casing or here you can write scroll casing, both the name is there. Scrolling, scroll casing or volute casing, here also for correction we can write, this is another terminology, volute, scroll casing or volute or sometimes volute casing. Now the water enters at high pressure here and it flows in this direction. In the, this is the typical spiral casing is which provides an area which is reducing or it is reduced in the direction of the flow along this scroll casing.

The purpose of this reduction I will tell afterwards. Now here you see this is a number of fixed blades which is pivoted, which are pivoted at this point, these are the pivot points, these are pivoted at this point, these are pivoted at this point, so these are pivoted at this point. And for a given fixed position, this allows the flow through flow through this passage. So what happens as the flow comes and flows as the water comes and flows through the spiral casing, the flow enters like this, this is the flow enters in the passage of the, these blades. These are known as, these are known as guide vanes or wicket gates.

These are known as guide vanes or wicket gates, this these are stator part of the turbine. Now what happens, the flow is entering into this passage of guide vanes or wicket gates, so therefore the flow rate gets reduced in this direction. So the area is accordingly reduced, so that the velocity of flow in this spiral casing is made constant. So to maintain uniformity of the velocity along this direction this area is reduced since the flow is entering into this passage.

So this passage you see is a converging type which means here what happens, when this enters here, the pressure is reduced and velocity is increased, so therefore a part of the pressure is reduced here while it flows through this. So the part of the pressure head which is available here is reduced while it flows through this, this creates a convergent passage. And this is designed in such a way that it has 2 purposes, it reduces the pressure and increases the velocity and at the same time it deviates the fluid or water hear properly to this runner blades.

These are the runner blades, these are shown as, this is runner blades. That means this is mounted on the rotating this, this is the shaft. So these blades are runner blades. So therefore the fluid enters like this in the blade passages of the runner blades as it rotates. So therefore it is a radial inward flow, flow comes here, flows through the wicket gates or guide vanes whereas the purpose is that it provides a converging passage, pressure is reduced and velocity is increased, so at the same time it directs the fluid to the proper angle by which it can glide, that means it will match the angle of the runner blades so that it can glide through the runner blade and flow through the blade passages.

At the inlet it has high velocity and high-pressure also and it is an inward flow, and at the same time if you see, the flow passages of the runner blades made by the runner blade is also converging, that means when the fluid flows through the runner blades, by Impulse Action its velocity is reduced and also its pressure is reduced and finally at the outlet of the runner, it is suddenly it is turned to the axial direction, in this direction, it is not, it cannot be shown in this two-dimensional plane, that is a plane of the paper, it is shown.

That means this flow is coming like this which is basically radial and tangential direction. The flow is more, has mostly radial velocity and the tangential velocity, it is mostly in the radial and tangential direction, bulk flow is in the radial direction, it has both radial velocity and tangential velocity. But while coming through the runner at the outlet, it suddenly turns to the axial direction like this, that means this enters in the radial direction, let us consider a horizontal runner from the wicket gates or the guide vanes to the runner blades, it comes radially and then at the end of the runner, it takes a 90 degree turn and goes radially like this, which is the axial direction.

Goes, sorry, radially, both axially, the axial direction and goes through a tube known as draft tube. So draft tube is attached here which is not shown at the outlet of the runner. So this is the basic principle, sometimes the additional blades are also given here which are known as Stay vanes. Stay vanes are actually these guide vanes, here is some additional vanes are sometimes given to direct the, these are known as stay vanes to direct the fluid to the wicket gates.

Now wicket gates are stay vanes are pivoted at these points, the reason because, the reason of this is that the wicket gates can be rotated about this pivotal point so that this can increase or decrease the flow passage area between these 2 blades. This is required for changing the fluid flow to the runner for its governing, due to the change in load. That is why these guide vanes or wicket gates are pivoted, there may be additional guide vanes known as stay vanes.

So therefore we see the guide vanes or wicket gates or stay vanes, 1st it comes to the scroll casing and volute casing, then it flows through the guide vanes, stay vanes, the purpose of these vanes are to direct the fluid to the runner and at the same time the change in pressure, they reduce the static pressure by providing a converging area of flow, cross-sectional area of flow. And it properly directs the fluid to the runner blade passages and it flows runner blade passages and comes out of the draft tube finally to the tail rest level.

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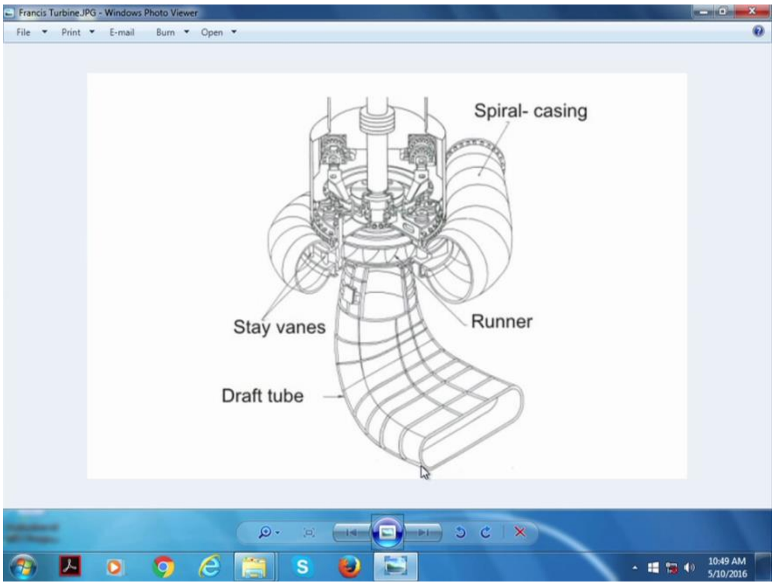

Let us have a look to this picture. Let us have a look to this picture, I do not know how much it will be… If you see this picture in clear, this is actually the turbines in practice, this is the vertical shaft. Just have a look, how does it look, the Francis turbine. This is the this is the practical diagram taken from some, I cannot exactly tell you the reference that this is a scroll casing or the spiral casing, it comes here, so it is difficult to understand, so this is the, there is the wicket gates, stay vanes are there, these are the stay vanes, these are the wicket gates and this is the runner ultimately it comes out.

So this flows in this direction from the spiral case, this direction, this is the radially inward flow direction but finally at the outlet of the runner, this is turned axially and this is the draft tube. Stay vanes, this is draft tube, these are the runner blades. So this is the overall picture of a Francis reaction turbine, so it is very difficult to understand in detail because it is not possible… But you can have a idea how does it look like and then the final water is discharged through this.

And the purpose of the draft tube I tell you here is to reduce the kinetic energy of water at the outlet. That means the water which is discharged from the machine at some velocity is carrying a kinetic energy and that is a wastage, wastage of energy, to reduce that waste energy, the kinetic energy of the water discharged from the machine, the tube is attached whose area of cross-section increases. This is basically a diverging tube, a diverging tube so that the flow velocity at the outlet of this tube is much smaller compared to that of the outlet of the runner.

So that the ultimate velocity, you have to discharge the water and to discharge the water you have to have some velocity or you cannot make this velocity is 0, so it should be kept as minimum as possible, then this draft tube is a part of the machine and finally the discharge or outlet of the draft tube is the discharged and outlets of the machine. And this comes with the relatively low velocity at the tail rest level so that the kinetic energy wasted or the kinetic energy lost which cannot be utilised for power generation is kept to minimum.

So after this we now, well, okay, this has already been explained, okay. Now, to understand the purpose of the draft tube and the principle of operation of a reaction machine, we should first know how the different energy quantities, the head energy per unit weight is being defined as the fluid flows through the different components of the Francis reaction turbine. Okay, basic purpose of the draft tube as I have have told to reduce the kinetic energy at the outlet of the machine and at the same time to keep the Francis runner at a much higher height than the tail rest level without sacrificing any energy, any head.

Because people apparently seem that if you place it much above, so you lose some potential energy because the tail dresses at a lower level and our turbine is a higher level but you can keep it, provided you attach a draft tube which is a part of the turbine itself. So understand that thing more clearly, we see this particular diagram.

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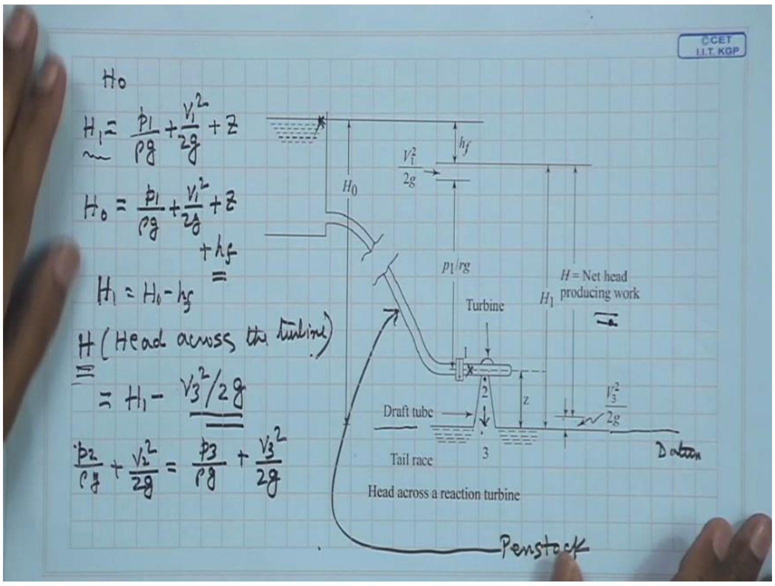

Here you will see that this is the height of water at a higher altitude, stored water and this is the pipeline which leaves from that reservoir at that high altitude to the turbine, this is the turbine and this is known as penstock, this is known as penstock, the terminology, this pipeline. This comes to the turbine and this is the draft tube as I have shown you, the turbine is a vertical shaft turbine, this comes like that flows inward, this is small diagram, schematic of turbine then it changes axially and then flows, this is the draft.

Now see the gross head is H0, let us consider this level, the tail rest level, this level as the datum, then the gross head is H0, the gross head is H0. Now if we write the head H1 at the inlet to the turbine, this point 1. This comprises a pressure head P1 by rho G, plus the velocity there of the fluid or the water V1 square by 2G plus this Z. And if we write the Bernoulli's equation between this point and a point at this inlet along a streamline, we can write H0 is equal to P1 by rho G plus V1 square by 2G plus Z1, that is modified Bernoulli's equation.

Which is written by considering a viscous force or the influence of the viscous dissipation through a loss term, that is the loss of head means the dissipation of mechanical energy into intermolecular energy which is manifested and is lost from the account of the mechanical energy. That is why in Bernoulli's equation, modified Bernoulli's equation, in consideration of the viscous effect, we use a term called loss of height, that is loss of energy per unit weight but this loss of energy is loss of mechanical energy which is being converted into intermolecular energy due to fluid friction and such energy cannot be lost, this has been told categorically in the fluid mechanics class.

So therefore we can write, this we consider as H1, that means the head, that will energy per unit weight, total head at inlet to the turbine, so H1 is therefore H0 minus HF. So here it is shown that dramatically that this is H0 and this is HF, HF is shown, this is the frictional loss, so therefore this H1 is the head at inlet to the machine. Now what will be the head that the machine or the turbine will utilise. This will be inlet head minus the head which is ejecting, so therefore if we define H as head across the turbine, that means the head across the turbine, the meaning is that the head which the turbine is enabled to utilised to develop mechanical energy.

That will be H1 minus the kinetic energy loss at the end or discharge of the machine, that means at the end of the draft tube, section is 3 and this is V3 square by 2G. So this is the kinetic energy loss, that means the velocity head, so this portion is shown as V3 square by 2G. So therefore this H is the net head producing work, this is known as head across the turbine or net head producing work. Both the terminology go, so this equals to H1 minus…

So therefore you see the purpose of this, providing this draft tube is that V3 square by 2G is very low to keep because this area is much higher, so that this is low, so that this net head across the turbine or the net head producing work is close to the head at inlet. But now one difficulty you see that if you write the Bernoulli's equation at inlet and outlet of the draft tube, we can write that P 2 by rho G plus V2 square by 2G is equal to P3 by rho G plus V3 square by 2G if we neglect the friction in the draft tube.

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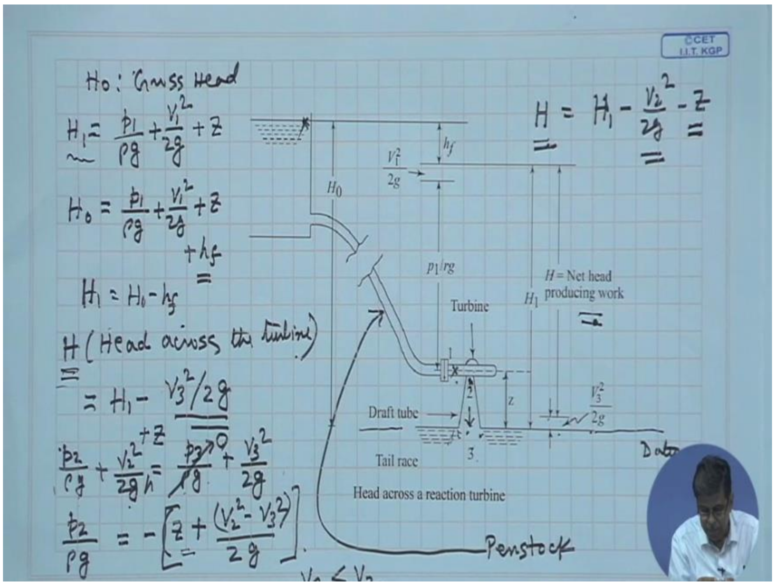

Draft tube is small, so if we neglect the friction in the draft tube, then we can write the Bernoulli's equation between a point at inlet and outlet along the streamline. So we can write that P 2 by rho G, now here, one thing, this pressure head, we are using, this pressure is above atmospheric pressure, that is one very important thing. Otherwise we could not write that this is the loss, total energy loss because this we consider the pressure is atmospheric pressure.

So if we consider here also, this P 2 is the pressure above atmospheric gauge pressure, P 3 is 0 because P3 is the atmospheric pressure, it discharges in the atmospheric pressure, so P2 by rho G therefore in consideration of all the pressure head is above the atmospheric head, that means the pressure is defined above the atmospheric pressure, then one can write P2 by rho G is equal to what, plus, sorry I have missed something, P2 by rho G plus V2 square by 2G, sorry, plus Z.

So P2 by rho G is minus Z comes here plus, Z minus Z plus V3 square minus V2 square, that can be written as V2 square minus V3 square by 2G. That may be given V 2 square, I am sorry that Z has to written, this elevation head. So at the point 2 pressure is P2 by rho G, V2 square by 2G plus Z, at this point Z is 0, pressure P3 at the point 3 is 0 because this pressure is defined above the atmospheric pressure, gauge pressure V3 square. Now here you see because of this divergence in area, this V3 is less than V2 and this is the purpose of the draft tube.

So this is positive, this is positive, so therefore we see, the inlet pressure of the draft tube is below the atmospheric pressure and it is obvious from the physical sense that if you decrease the velocity at the outlet and discharge it to the ambient pressure, that means here the pressure has to be less because decrease in velocity is associated with an increase in pressure. So if pressure is increased up to the atmospheric pressure, so pressure in the upstream has to be less than the atmospheric pressure.

From simple commonsense you can find it, by writing the Bernoulli's equation you can write it. But if you take care of the frictional losses, this will be little modified but it is true that the pressure at the inlet to this draft tube will be negative. So that is a danger and we have to see that this pressure should not go below the vapour pressure of the water at the working temperature. For example normal temperature, if we know the vapour pressure of the water, so this pressure should not fall below that, otherwise water will start boiling and the vapour bubbles will be generated, that is known as cavitation.

That we will discuss afterward, what to avoid that with pressure we have to be very careful. So therefore there is a limitation of the jet above which it has to be kept so that the cavitation does not occur. Another thing you have to appreciate that this Jet does not come into picture in the head across the turbine because this is a part of the turbine, so turbine can be kept at any height without sacrificing any head.

Because if the turbine, if there was no draft tube, the outlet, the loss of energy at the outlet, so this head across the turbine H could have been H1 minus, if this was the, V2 square by 2G minus Z. So in that case what happens, V2 square by 2G is high because V2 is higher than V3 and at the same time the Z coming into picture, so that net head producing work or the head across the turbine gets reduced. So therefore we can keep, make the draft tube to reduce this kinetic energy at the discharge of the machine by reducing it from V2 to V3 and at the same time we can place the turbine above this tail rest level at any Z without sacrificing the net head producing work or head across the turbine.

But there is a limitation, we cannot go to a very high Z, otherwise if P2 by rho G, the pressure at the inlet to the turbine which is the minimum pressure point should not go below the vapour pressure of the water at the working temperature, that initiates nucleation of vapour vapour in the liquid, vapour bubbles which causes cavitation.

This phenomena is known as cavitation, I will discuss it afterwards. So this gives you an overall picture how the gross head, this is the gross head, this is the gross head, how the gross head, head at the inlet to the turbine, head across the turbine or the net head producing work, the purpose of draft tube which is very important in terms of the head of the Francis turbine is also understood. Thank you and next class we will go for the analysis of force and the power in the Francis runner. Okay, thank you.