Fluid Dynamics And Turbo Machines.
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Part C.
Module-2.
Lecture-9.
Hydraulic Turbines: Reaction Turbines.

I welcome you all for our continued discussion on hydraulic turbines. In the last lecture we have talked about the Pelton turbine which is an impulse type of turbine. We have talked about the components of Pelton turbine and how to regulate the flow. Today we will talk about the reaction turbines or to be more specific as I told you that in this course we are keeping only Pelton, Francis and Kaplan, so we will only consider Francis and Kaplan turbines as examples of reaction turbines.

Most of the discussions on reaction turbines are actually covered when, in my opinion, when we discuss the in the 2^{nd} week the general discussion on Turbo machines and its performance. What we have not done is the component of the reaction turbines, Francis and Kaplan, so I will spend some time to discuss the components, the velocity triangles which is **esse** essential for this understanding and analysing problems of turbines was discussed in connection with the generalised treatment of Turbo machines and we will revisit the velocity triangles when we talk about the tutorial problems.

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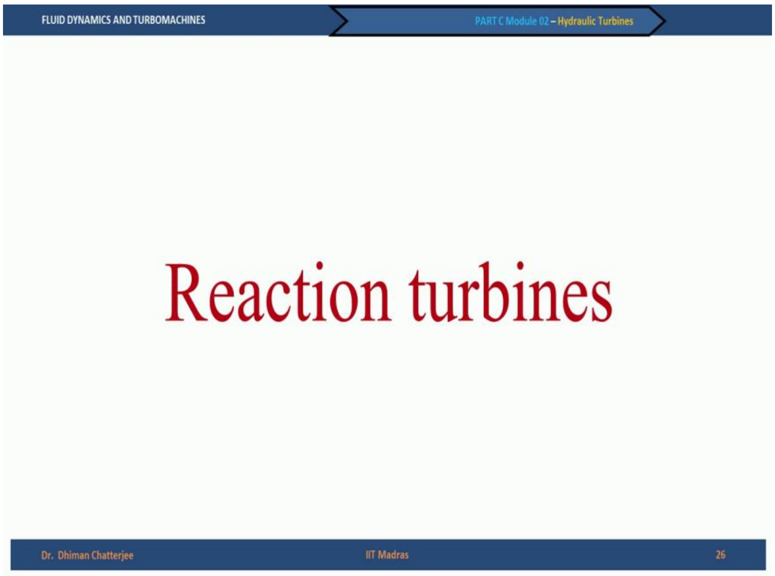

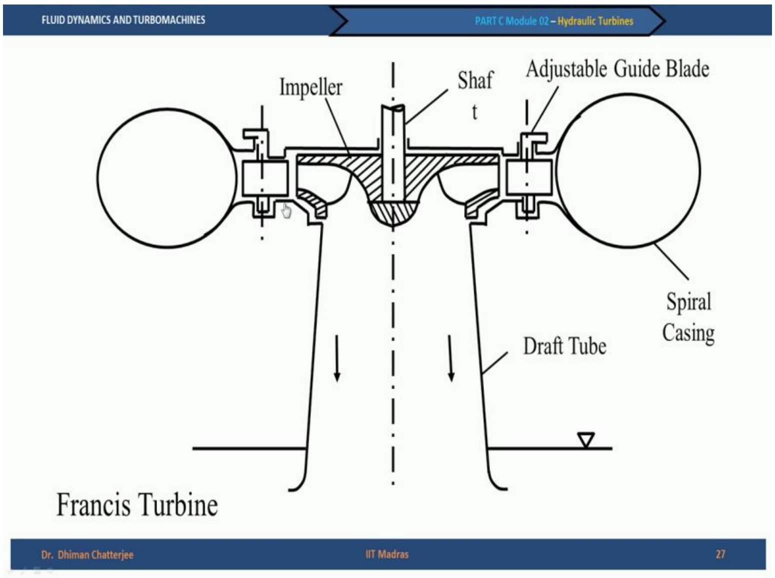

Today we will talk mainly about the components. So let us look at it. We are talking about reaction turbines, we are talking about Francis turbine to begin with. And this is what I had shown earlier about a Francis turbine. And you can see that it has a casing here, I will show more about it, the flow enters from this side, it is actually annular space around it, I will show you that is called the spiral casing, it is the same like you have seen in case of the volute casing in case of pumps and flows to the turbine blades which is an impeller which is connected to the shaft which is rotating.

And flows out in the structure called draft tube. In case of Pelton turbine, you have not come across the structure of draft tube and hence we will talk more about draft tube in this portion but the first component that will the flow sees when it enters the Francis turbine is the casing.

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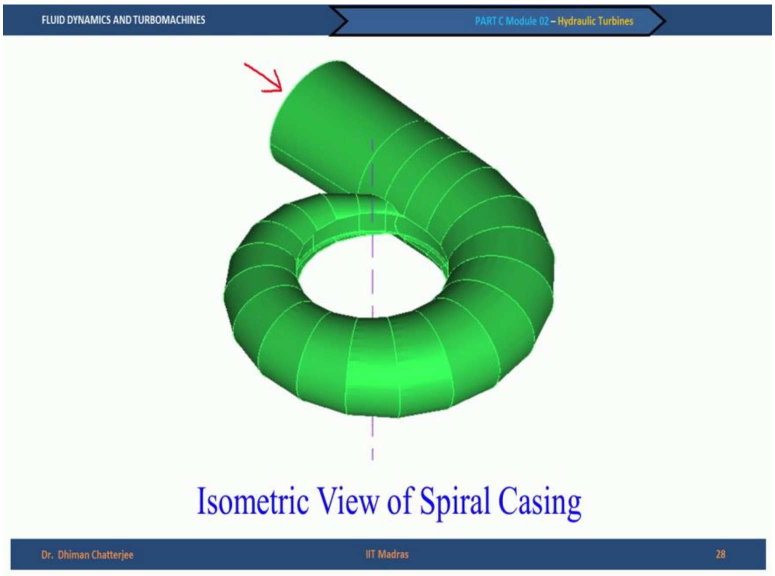

And this is the picture of a casing. The fluid flow from the penstock enters here and flows around it, it actually the water will come out here radially and you can also see that the area of the passage as it starts from here goes on decreasing till it reaches the other end. Why is that? It is because as the water, portion of the water leaves, so you say that initially there is a V dot volume of water entering the spiral casing from the penstock. Now we know that V dot Theta is the volume of water that will come out at any location, angular location Theta. So what happens, the volume of water handled by the remaining portion of the spiral casing reduces.

And in order to keep the mean velocity constant or the mean velocity going to all the blades will be same, we need to have a reduction in area. If you recollect the discussion on pumps, this is just the opposite. In case of pumps, in the volute casing the water was collected as we have shown in the earlier slides and this goes and leaves the pipe. So I repeat, in case of a turbine, in case of a reaction turbines, the water enters in this direction and flows here. So we can show it with this arrow. This is the direction in which the fluid enters, you have to keep this in mind.

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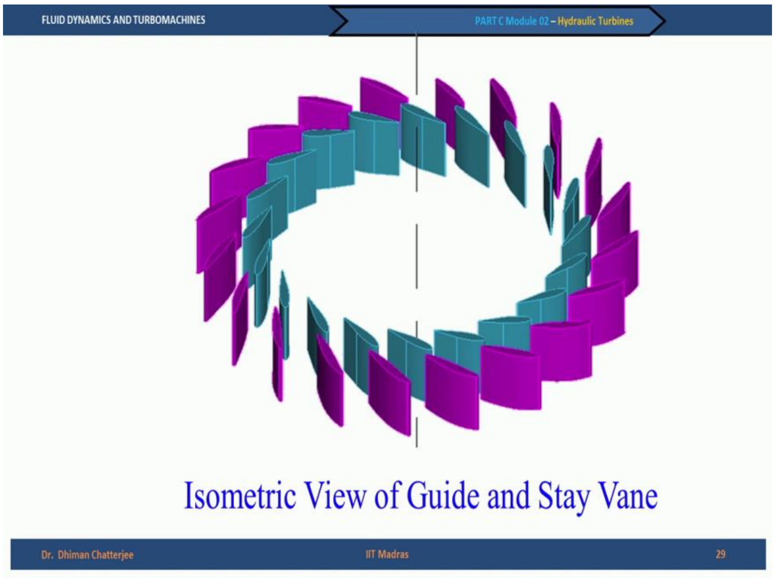

Next the flow will see the guide vanes and the Stay vanes, the so-called the distributor systems, you can see that these are essentially the hydrofoils or aerofoils with a rounded leading edge and a sharp trailing edge. So the flow enters here through the guide vanes and Stay vanes and goes inward. So this we are again we are talking about an inward flow reaction turbine and you know the reason why did inward flow, that is why it goes from a higher radius to a lower radius, that is because we are trying to make use of the centrifugal forces, centrifugal pressure rise due to the blade rotation as we have discussed earlier.

So week, here we have a inward flowing turbine and the disc Stay vanes and guide vanes, particularly the job of the guide vane is actually twofold. One it increases the velocity of the flow because the passage area is reduced from the inlet to the outlet, so it acts like an accelerated duct, the velocity increases and 2nd it direct the flow at an appropriate angle onto the runner. In case of Francis turbine, these guide vanes are adjustable. What I mean by that? By that I mean that whenever there is a higher flow rate you can have a larger opening, whenever you have a lower flow rate you can slide and change the position of the orientation of the blades and reduce the opening.

And thereby you are actually doing 2 things, you are maintaining, trying to maintain the velocity and also give the direction. Because you know that the velocity that leaves the guide blades tangentially is the absolute velocity and that is dictates what is the absolute velocity angle alpha. So this is a very important component of the reaction turbine.

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And this is a typical single runner blade. I will show you how these are blades are arranged or stacked in the turbine.

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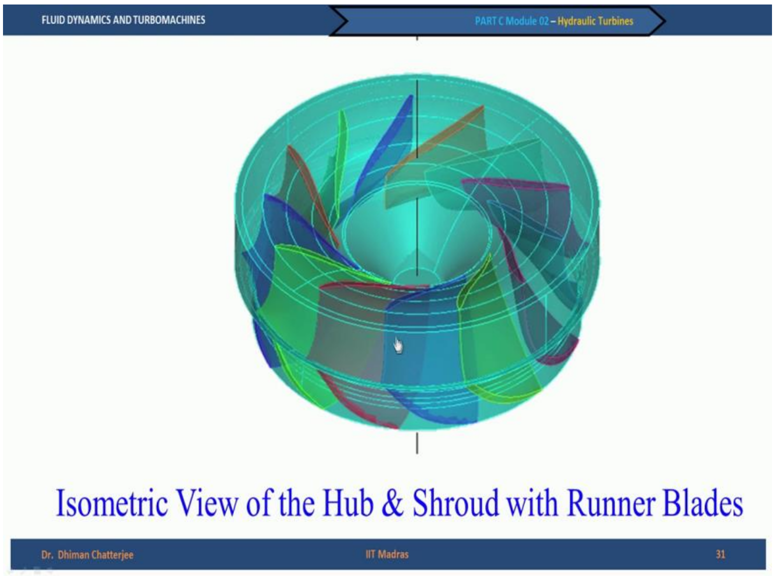

And this is a schematic of the different blades, you can see that these are mixed flow machines, the flow enters here and goes inward and these are the different passages. For example you can see clearly that the fluid will enter all round it and going inward. So this is the isometric view of the hub and shroud with the runner blades. I am taking you through different components as we see, if you imagine that we are taking out the turbines.

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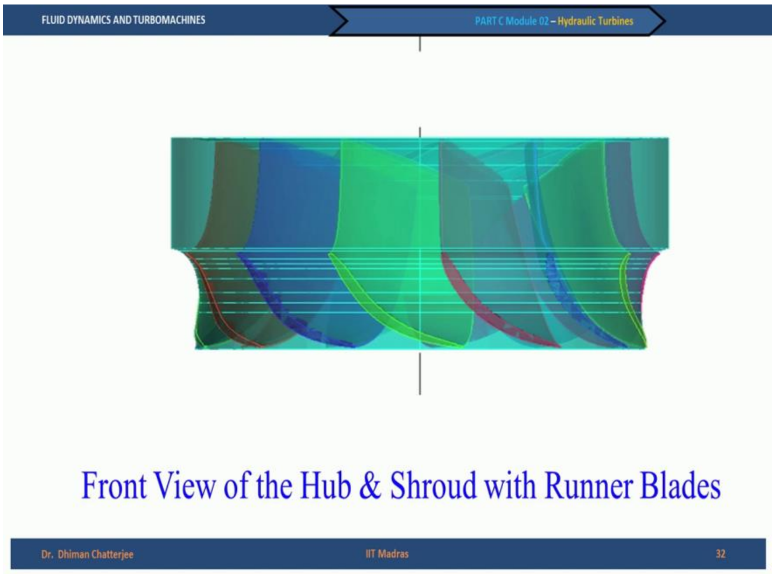

Then we can also show it in the front view but this view is not so meaningful, we can see still the only the inlet edge or the leading edge.

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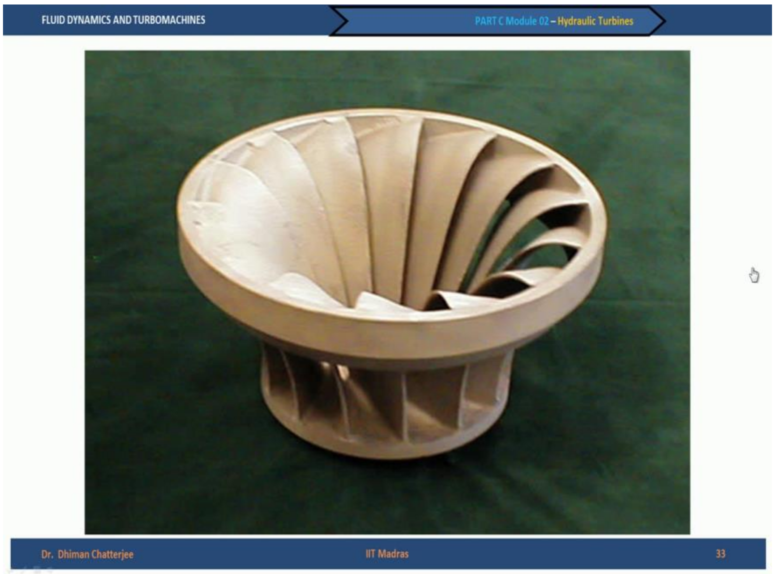

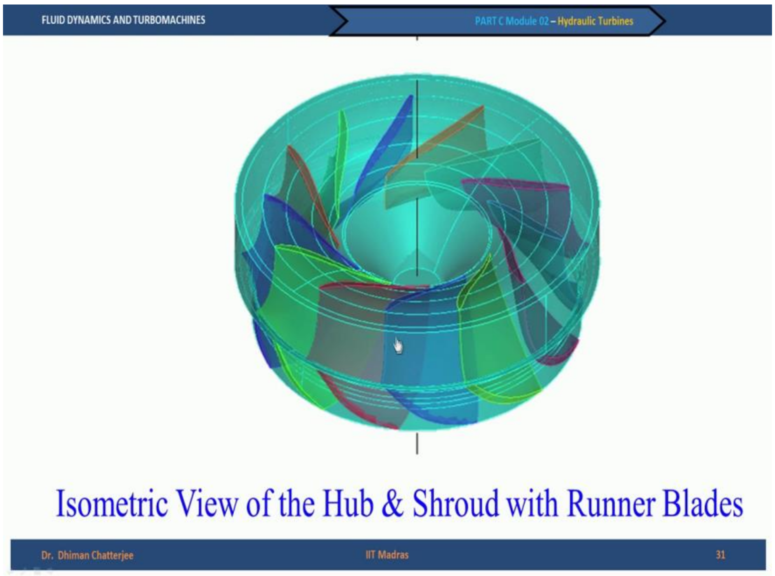

And then this is the model which was taken in a photograph and we can see that how the actual model looks like. Of course you can compare it with the picture that we have shown here, this will be the picture if you make the hub transparent.

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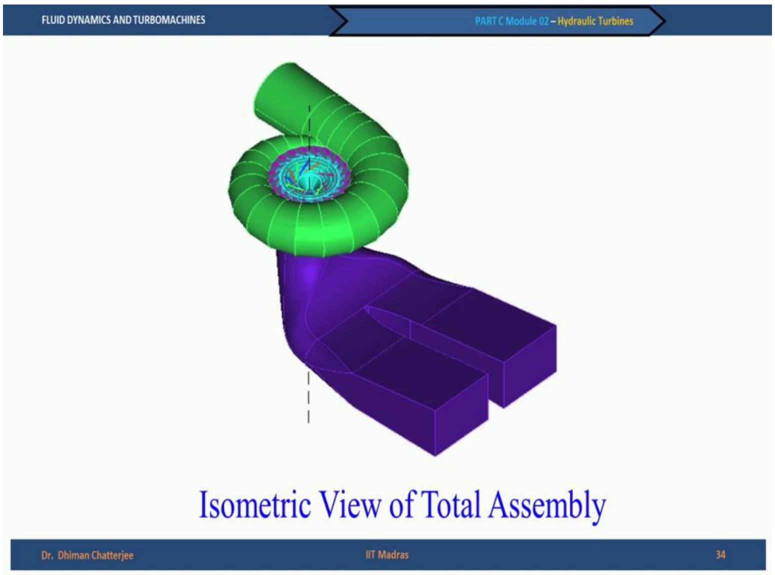

And this is the final assembly. So you see the fluid flow enters in this direction, goes radially inward, it goes inside and comes out through the blue structure. This blue structure is called a draft tube which I will talk about. Of course this is a particular type of draft tube which has 2 separations, there is a pad here which separates the flow. I will talk about the function of this draft tube shortly after presenting the structure of Kaplan turbine. So to sum up, we can say that Francis turbine is a reaction turbine in which the guide blades are adjustable, the runner blades are fixed and it is a mixed flow type of an impeller. Okay.

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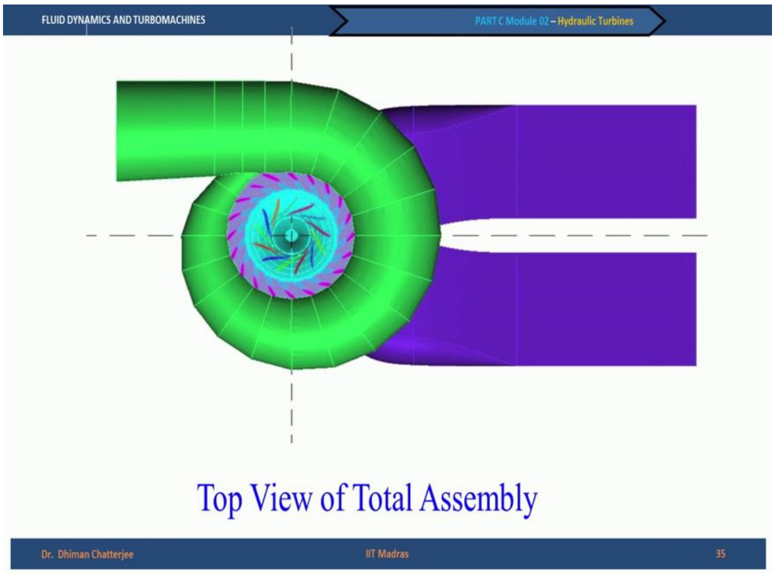

Now we will see more closely the other turbine which is the Kaplan turbine. This is of course another way of showing the top view.

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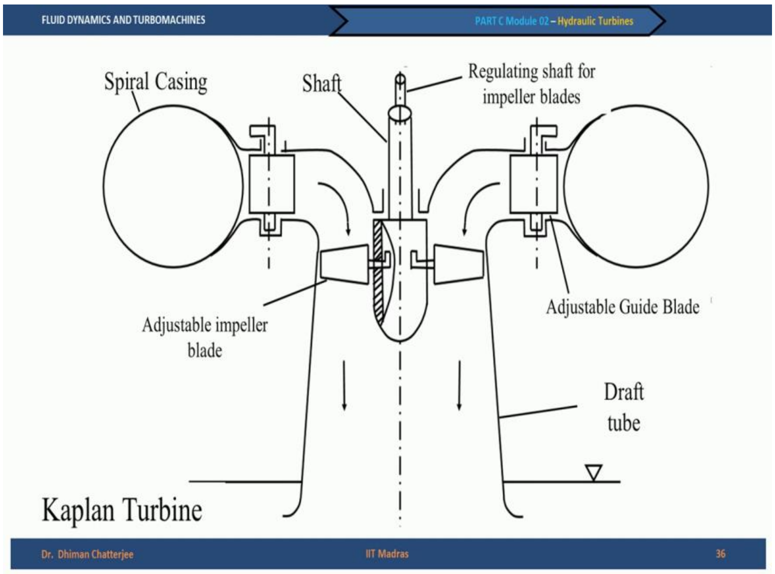

And let us come to Kaplan turbine. In case of Kaplan turbine, you can see the spiral casing as in case of Francis turbine and then you see the guide blades and then there is a vaneless passage, the flow turns and to remind you that this is an axial flow machine, why, because in the runner passage, in the impeller blades, the flow direction is parallel to the axis, please do not get confused about this arrow as I have been saying time and again in this course that for next year flow machine the flow should be parallel to the axis inside the impeller blades and then we have the draft tube.

But what is important here is this distinction, that like Francis turbine, though we have an adjustable guide blade, in case of Kaplan turbine we have adjustable runner blades or impeller blades also. So what it means, it means that when there is a change in volume flow rate for example the volume flow rate may not be constant throughout the year and the turbine may need to work over a certain range of volume flow rate. So when this volume flow rate changes, you may try to adjust the guide blades both in case of Francis turbine and Kaplan turbine.

But in case of Kaplan turbine, over and above this adjustable guide blades, you can change the blade setting angles with the help of these adjustable impeller blades. In this point let me also tell you that there is yet another type of axial flow machine, axial flow hydraulic turbine called the propeller turbine. The propeller turbines are also axial flow turbines but they differ from Kaplan turbine in a very significant way, in the sense that they do not have adjustable impeller blades. Their runner blades or impeller blades in case of propeller turbines are fixed.

So you may imagine that a Kaplan turbine is like several propeller turbines depending on the operating condition. This is very important from the perspective of the performance of a turbine and I will come back to it later. So we see the components and like we have done in case of Francis turbine, let us go through it for the Kaplan turbine as well.

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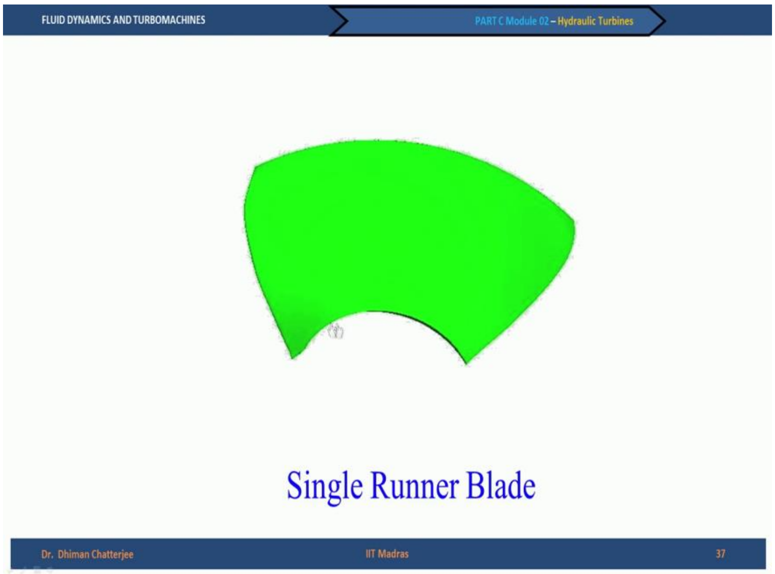

This is the single runner blade and if you remember in one of the earlier classes, I have shown you an axial blade and I told you that you cannot make this blade directly from the hub to the tip, so what to do is, you break it into small radius and you make these smaller radius and you talk about, let us say radius R here and a neighbouring radius DR of thickness and then you try to generate the blade profile. These profiles are of aerofoil shape but these blades are twisted. So we cannot design right from the hub to the tip.

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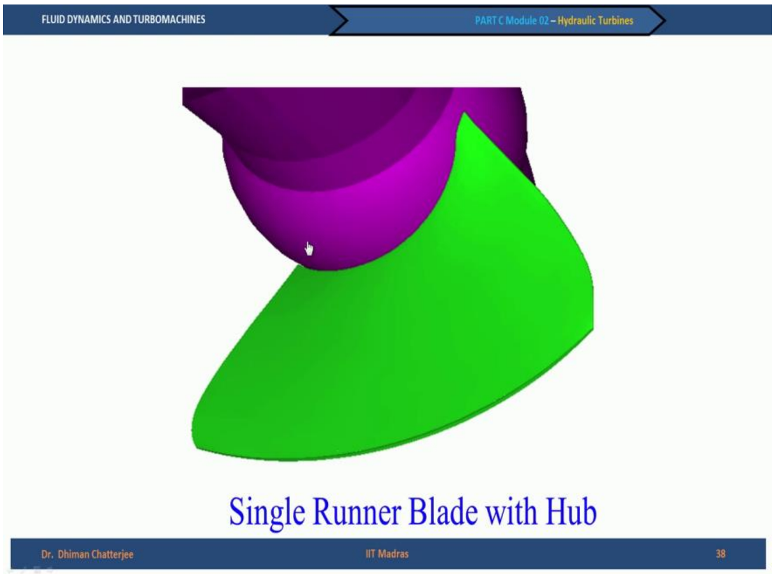

So you see that you have the matching here and the curvature is matched with the hub, also you have this curved here so that it can go inside the casing. This is a zoom view of a single runner blade with hub, just to show you how this mating of the surface is coming.

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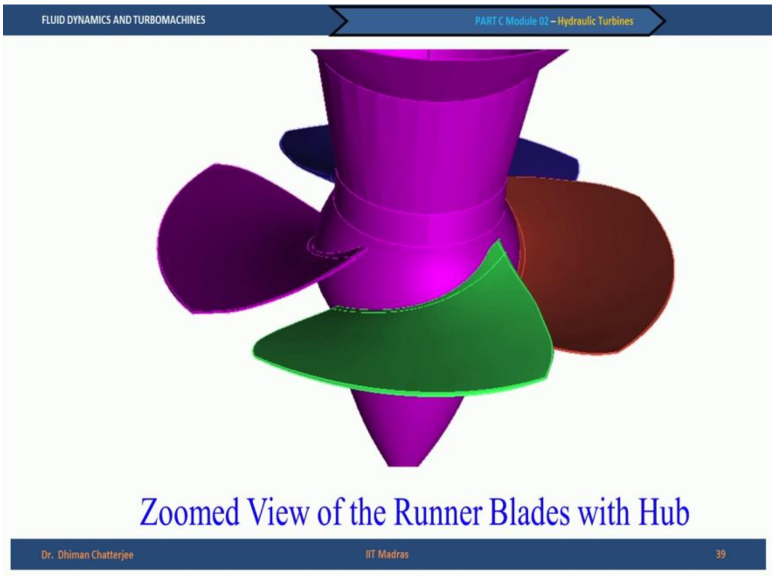

And this is the picture of the runner blades we are showing you here with the hub and this entire thing is fitted inside the casing as shown here.

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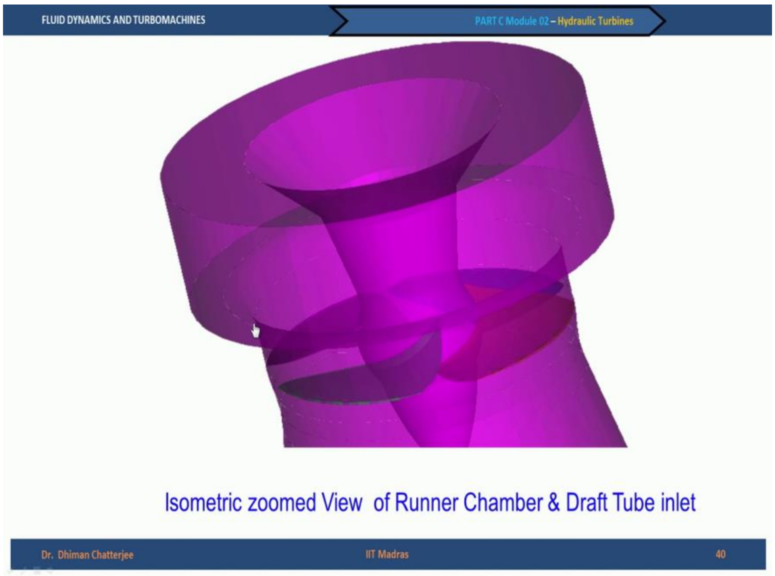

You can see that the casing has been made transparent and this is the hub and these are the blades. Of course the portion of the draft tube is also visible.

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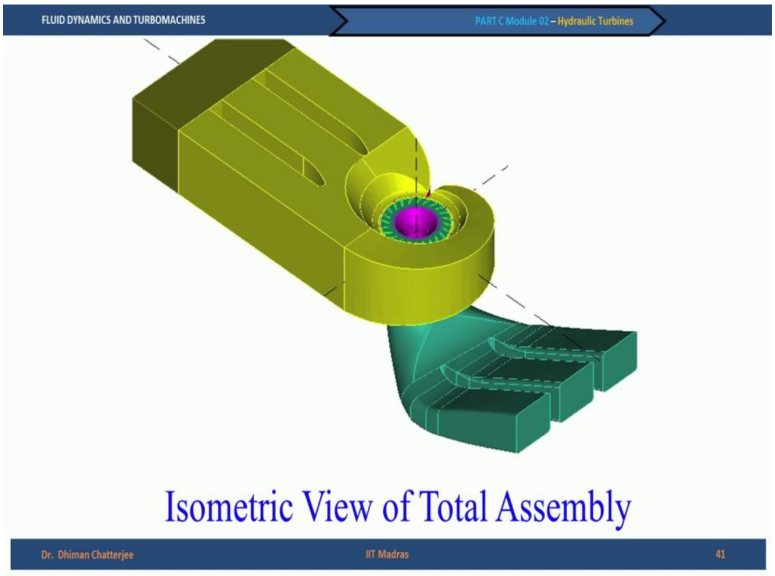

And this is the assembly. Before we conclude the discussion on Kaplan turbine, we just revisit the concept of casing. So you see in this case the flow comes from the inlet, which like in Francis turbine is here, then it goes through the spiral casing, it goes inward and then comes out parallel to the axis to the impeller blades and into the draft tube. So what do we see? Unlike the Pelton turbine in which case the casing has no hydraulic requirement, not related with the hydrodynamic performance of the turbine.

In case of Francis and Kaplan turbines, this is a very essential component. This is because in case of reaction turbines like Francis and Kaplan turbines, there is a pressure variation inside the runner passage and hence the runner cannot be kept exposed to one fixed pressure, let us say atmospheric pressure, so this is a closed one. And in order to get a proper efficiency, this contouring has to be done and this is a part of the detailed design analysis. The 2nd important component where we differ, these Pelton turbinesdiffer from the Francis and Kaplan turbine is in the presence of a draft tube.

In case of the Pelton turbine, the entire runner is open to atmosphere, whereas in case of Francis or Kaplan turbine, its pressure can be different from that of atmosphere. So what is the use of draft tube, we will take up. But whenever we talk about the turbines, we also have to talk about its performance and that brings me to the comparison of efficiency of the 2 different groups of turbines, one side we have a Pelton turbine which is an impulse turbine and the other side we have reaction turbines like Francis and Kaplan.

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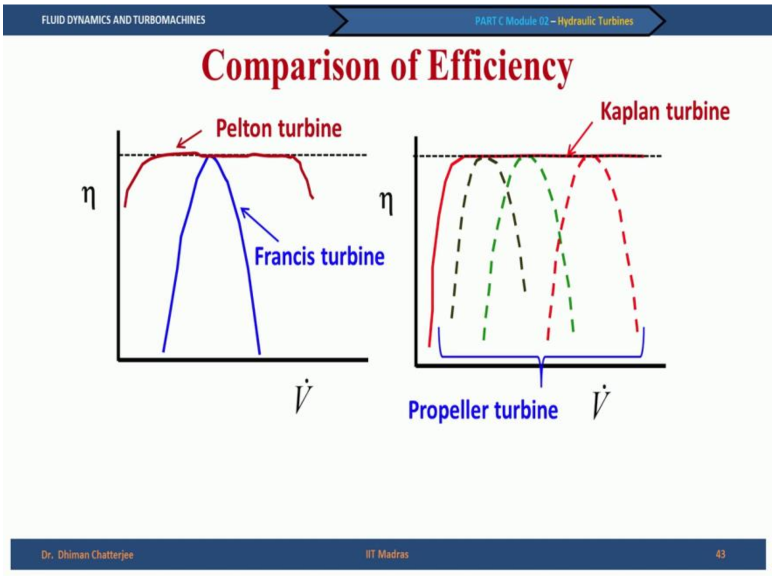

First we will compare the efficiency characteristic, I am not talking about the values, we are talking about the efficiency characteristics of Pelton and Francis turbine. So this is the volume flow rate and Eta is the overall efficiency and let us say for the our discussion, I am not interested in the maximum value, so the maximum value for every time of turbine is given by this dashed line. And the right-hand side will talk about Kaplan and propeller turbine, I am keeping this also same.

These values need not be same but this is just for our reference because we are more interested in the nature of the curve. So this curve shows that this is very flat, where only at the edges for a very low or very high volume flow rate, there is a small droop in efficiency. Which type of turbine do we associate such an efficiency characteristic and why? This is applicable for Pelton turbine. Why, because let us recollect what we have learnt in the discussion of efficiencies. Efficiency means it is intricately related with the losses. So what are the losses about about?

We have talked about, let us say hydraulic losses only, we are talking about the hydraulic or the friction losses and we are talking about the shock or incidence loss. Right now let us assume there is no disc friction loss, no return flow loss, I will bring that soon. So in case of Pelton turbine, what happens, irrespective of the flow rate, irrespective of the flow rate that is accomplished by the positioning of the Spear, as we have discussed in the last lecture, the flow that leaves the nozzle is in one direction and it hits the bucket which is at the bottom of the runner.

So what it means, for all volume flow rates, irrespective of the volume flow rate, the angle at which the jet strikes the bucket does not change. It depends only on the splitter angle beta S. Right, because we know beta 2 is nothing but 180 degree - beta S. And hence it cannot approach the runner at any other angle. So what we expect, the incidence loss to be minimal or negligible. So it does not depend on the volume flow rate and hence we get a flat curve. Over and above we also keep have to keep in mind that Pelton turbine buckets are rotating in air, and hence the disc friction losses are also negligible.

But that is not the main point in this curve, the main point in this curve I repeat is that the Pelton turbine does not have any incidence loss. But if we take the Francis turbine, yes Francis turbine has a set of adjustable guide blades, it tries to accommodate some volume flow rate variations. But beyond it, it is bound to shore off. And we can say that this is a typical characteristics of a Francis turbine. It is not necessary I am try to show, I repeat that the efficiency maximum efficiencies are same, but what I am trying to show is the nature of the curve.

So you see in case of Francis turbine because the runner blade is fixed, we see that incidence loss or shock loss comes in and we have a sharper peak. What happens in case of Kaplan turbine? In case of Kaplan turbine I told you that not only the guide blades are adjustable, the runner blades are also adjustable depending on the volume flow rate. And you can imagine that this also should have a reasonably flat efficiency volume flow rate curve. This is important because we can think about the different beta values that we get by the setting angles of the runner blades as different propeller turbines.

So we can say that if this is a Kaplan turbine efficiency curve, then the envelope of all of these efficiency curves, individual efficiency curves is the Kaplan turbine efficiency curve and this individual efficiency curves are like individual propeller turbine efficiency curves because propeller turbine has a fixed runner blade. So it has a limited or restricted range of operation over a volume flow rate. So you can think about this propeller turbine with a particular blade setting, particular runner blade setting is this Kaplan turbine.

Next time when you change the blade setting, it becomes another propeller turbine and so on and so forth. So we get a much more flatter curve. And hence if we see that there are zones of operation where both Francis and Kaplan turbines can be used, you know that Kaplan turbines are much better. So here we talk about the efficiency. The next thing that I want to bring in is the notion of draft tube and do simple calculations and calculations to show why draft tubes are essential for reaction turbines.

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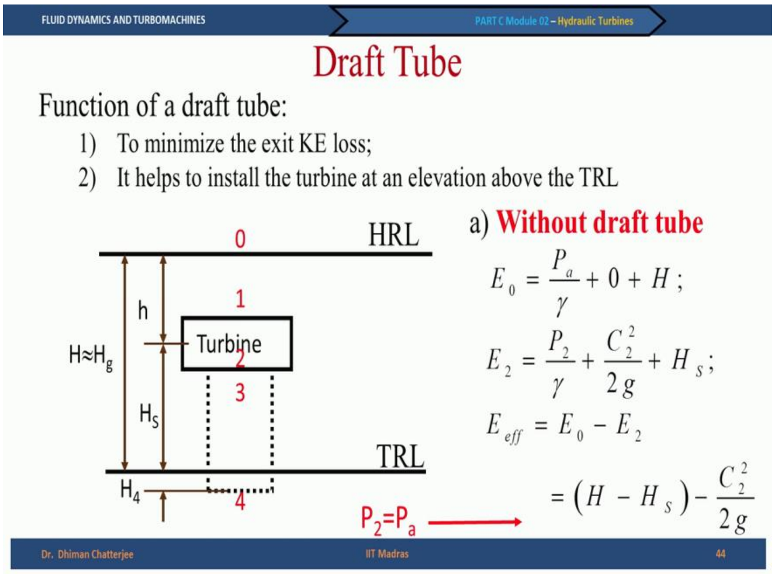

So draft tube, draft tube does 2 purposes, first, it minimises the exit kinetic energy loss and 2nd it helps to install the turbine at an elevation above the tail rest level. If you remember, we have shown in the last class the headrest level and the tail rest level, so we revisit these concepts are and try to see how draft tube actually helps in minimising the exit kinetic energy loss or it helps to install the turbine at an elevation above the tail rest level. So this is the schematic, we have the headrest level or H RL and the tail rest level or TRL and this is the turbine.

Let us start with the case where there is no draft tube and we number it as zero at the headrest level, 1 just before entering the turbine, 2 just at the turbine leaving, 3 outside the turbine as the same location and 4 is somewhere in the tail rest level. We will define 4 with respect to draft tube in the next. And right now we are also ignoring that any losses, and we say that the net head is approximately the geodetic head. This is not required but we are taking it for our simplistic analysis.

We say that the turbine is located at an elevation HS about the tail rest level. Why do we need to put in HS, we will come to that later. So let us assume right now that the turbine is located at an elevation HS above the tail rest level which means the height difference between the headrest level and the turbine location is given by small h. Of course the small h easily did with H - HS. So we can say that without the draft tube, we can write that the energy that is available at the headrest level is the atmospheric pressure head + the elevation which is given by H. And since we have neglected losses, we can say little E0 equal to E1.

E 2 is P2 by gamma + C2 square by 2g + HS. This gamma is nothing but row time G. And we can say that E effective is E0 - E2. Now when you do that are E0 - E2 you are saying that how much of the energy that can be extracted in principle from the fluid. Here we have said that that the P2, what is P2, P2 is at the exit of the turbine and there is no draft tube, so that means that the exit of the runner itself, it is open to atmosphere. And hence P2 is equal to atmospheric pressure, so these 2 gets cancelled.

We say that that the P2 is equal to PA and hence we get H - HS - C2 square by 2g. We get it under the assumption there is no draft tube P 2 equal to PA. What we find that our effective energy that is available is reduced from H by a term HS which is the elevation of the turbine above the tail rest level. Had the turbine been kept at the tail rest level, this term would have gone to 0. What is the problem of keeping the turbine at the tail rest level, that is the maintenance problem. So we would like to keep the turbine above.

And hence H - HS is typically going to be nonzero. And then the 2nd term comes from the exit kinetic energy. So this exit kinetic energy that is living the flow is wastage, can we not recover some portion of it? So now you see the draft tube can actually effectively address its stated functions, then essentially what it is doing, it is reducing this H - HS, the 2nd function and reducing the exit kinetic energy loss C2 square by 2g. So we will address these 2 issues one after another.

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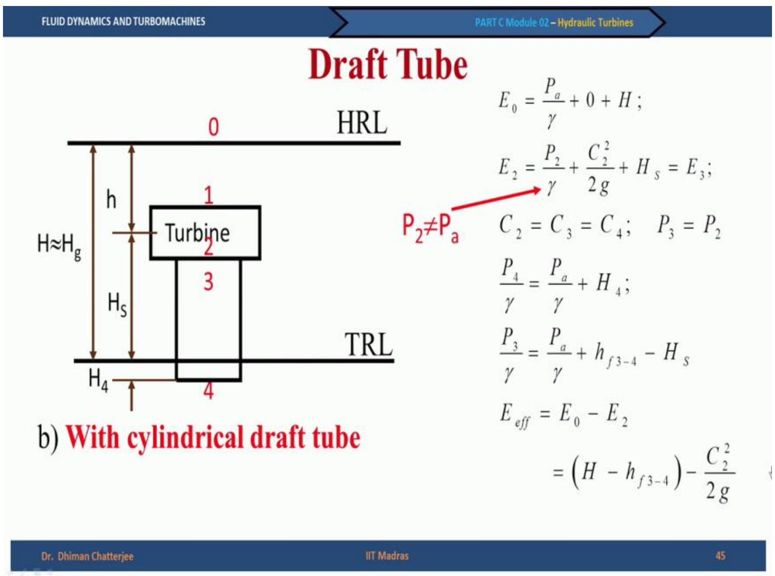

So we start with the cylindrical draft tube. We say that we fix a pipe, simply let us say we will fix a pipe and in this case now we have to remember that 2 to 3 is not going to be the atmospheric pressure, the pressure P 2 or P3 is not atmospheric pressure because you have a pipe. So under that condition, we can again write that E0 which does not change a P A by rho g + H and E2 is P2 by rho g + C2 square by 2g + HS which is now we are saying that 2 and 3 are coincident points and it is 3 but 3 is inside the draft tube, otherwise there is no difference, we are talking about coincident points.

And we can say that P2 is not equal to atmospheric pressure and we say that C2 equal to C3 equal to C4 how do we say that, it is from the conservation of mass or continuity equation, says the area is same, so the velocities have to be same and since 2 and 3 are coincident points, so P2 equal to P3. We can also write P4 as atmospheric pressure + this head due to this under the tail rest level, we are saying that the draft tube a is end isunder thetail rest level and we can get that P3 by rho g or P3 by gamma is PA by gamma + HF 34, HF 34 is the friction will head drop inside this cylindrical draft tube.

It is akin to the pipe friction loss - HS. And then we can say the effective head is now E0 - E 2 which is nothing but E1 - E 2 because there is no loss we have said taken H is almost equal to HG which means under this assumption, E 0 equal to E1 so the energy that is available across the Turbo machine from the fluid is E1 - E2 or E 0 - E 2 and we get H - HF 34 - C2 square by 2g. So what has happened, even a simple introduction of a cylindrical draft tube has changed this bracketed term from H - HS to H - HF 34.

Now think about it, you have a pipe of some diameter and let us say it is 5 metres in length. You have some flow rate through this, flow rate of water going through it is V dot. Now if we have the frictional head drop, it cannot be as much as 5 metres of the length of the pipe. So what it simply says is that H - HS has been now replaced by H - HF 34 and HF 34 is a smaller quantity. By the introduction of the cylindrical draft tube, we are incurring a frictional head drop but what we have saved is we can now place the turbine anywhere above the tail rest levels without any loss of these potential energy terms of which were earlier present.

We have served the 2^{nd} objective or the 2^{nd} function of the cylindrical draft tube. But conical draft tubes will be better because then if we have the conical draft tube, we can have C2 square by 2g. And we can say that we will change now the address the question of exit kinetic energy loss from the turbine. So let us look at how a conical type of draft tube works.

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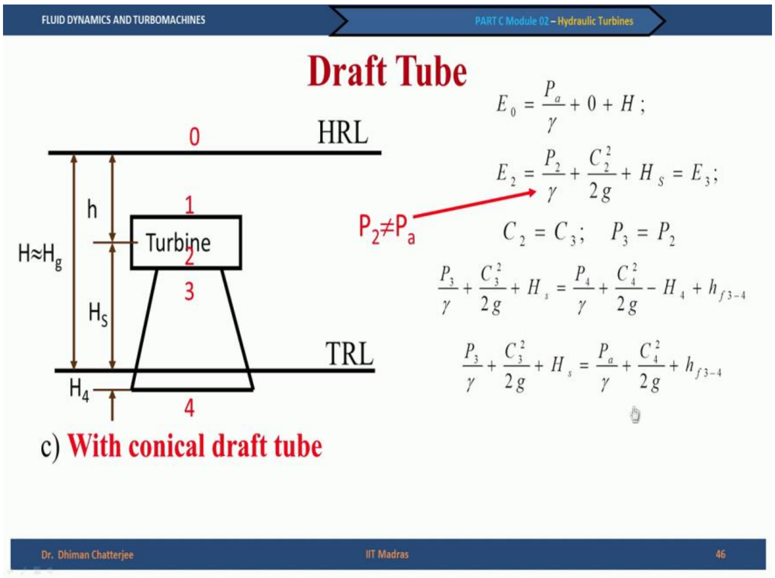

So this is a conical type of draft tube and as before we have given the numbers 0, 1, 2, 3, 4. Our assumptions of H is almost equal to HG, that is there is no loss in the approach and the exit in the penstock or has been maintained, and hence E0 equal to E1. We also say the same thing like we have said last time that HS is the elevation of the turbine above the tail rest level. In this case the first important difference is that C3 is not equal to C4. C2 equal to C3 is fine because they are coincident points we have taken but C3 is not equal to C4 because C4 has a larger area.

If there is a larger area, we know the velocity has to be less because you are talking about an incompressible flow found from observation of mass. So we can write that E0 is P A by rho g or PA by gamma + H. And E2 is P 2 by rho g + C2 square by 2g + HS which is my E3 as well. And hence in this case also we have to note that P 2 equal to P3 but that is not equal to atmospheric pressure just like we had for the cylindrical draft tube. We can say that P3 by rho g + C3 square by 2g + HS is equal to P4 by rho g + C4 square by 2g - H4 + HF 3 to 4.

So I repeat P3 by rho g + C3 square by 2g + HS is equal to P4 by rho g + C4 square by 2g - H4 + HF 3 to 4 and hence we can write that this P 4 by rho g - H 4 is nothing but my atmospheric pressure PA by rho g and we can say that PA by rho g + C4 square by 2g + HF 3 to 4 is equal to P3 by rho g + C3 square by 2g + HS. Now if we do the same way the E0 - E 2, we get that the first term remains unchanged, it becomes H - HF 3 to 4 but the 2nd term, now the exit kinetic energy as loss has become C4 square by 2g.

Note earlier case it was - C2 square by 2g, now it has become C4 square by 2g and because of this conical nature of the draft tube, C4 will be less than C2. What we have achieved is the kinetic energy loss has been reduced. The exit kinetic energy loss has been reduced. So now you see in this case the effective energy, that is available across the turbine with the fluid has increased. And if we assume that the turbine efficiency remains constant so that means the power output will be more.

Thus we see that the introduction of draft tube in case of a reaction turbine serves both purposes of positioning it above the tail rest level and as well as reducing the exit kinetic energy loss. We may say that this draft tube is a very simple one, it is true, and the example that I showed you, the models that I showed you about the Francis and Kaplan turbines, they had a different type of draft tube, I will come to that soon.

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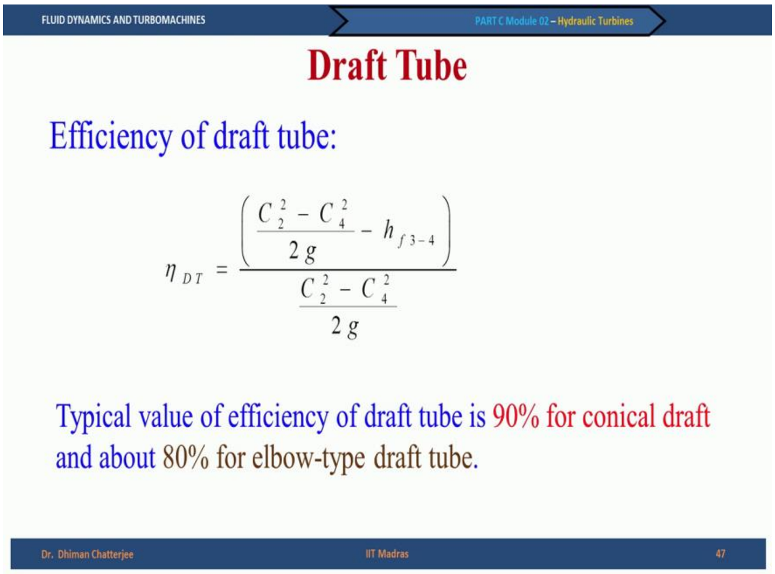

Before do we do that, we can also define that efficiency of draft tube. It is nothing but how much of the energy that we are trying to recover. So you see the first term in the numerator is C2 square - C4 square by 2g. And this is the kinetic energy that we are recovering. But of course the penalty that we pay is a some frictional head drop HF from 3 to 4 and the ideal energy that we could have recovered is C2 square - C4 square by 2g because in the ideal world there is no frictional head drop because we are not talking about viscosity.

So this is the definition of the draft tube efficiency, I will talk more about this aspect of draft tube when we talk about cavitation and hydraulic turbines in my next lecture. But right now you can note down that the typical value of efficiency of the draft tube is 90 percent for conical draft tube and about 80 percent for the elbow time draft tube which I showed you earlier in connection with the Francis turbine model or the Kaplan turbine model and I also show it here.

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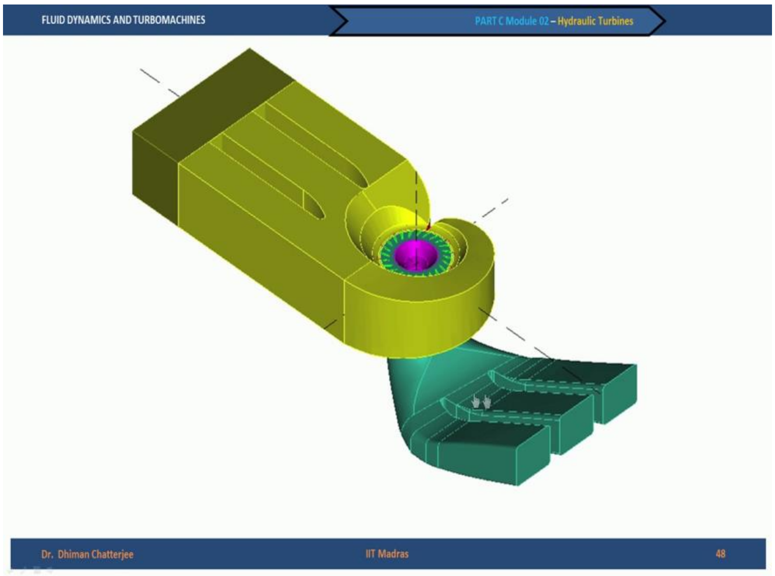

So here you see that the flow comes from here and as if there is an elbow and there is a bend, the necessity for this type, why we have an elbow type of draft you will be brought out more closely when we talk about the discussion on the cavitation in turbines where we talk about the restrictions that we impose from the cavitation perspective on the draft tube dimensions. One more thing you have to keep in mind is that you may say that the draft tube is a stationary component, it is not transferring energy, so how does it improve the efficiency.

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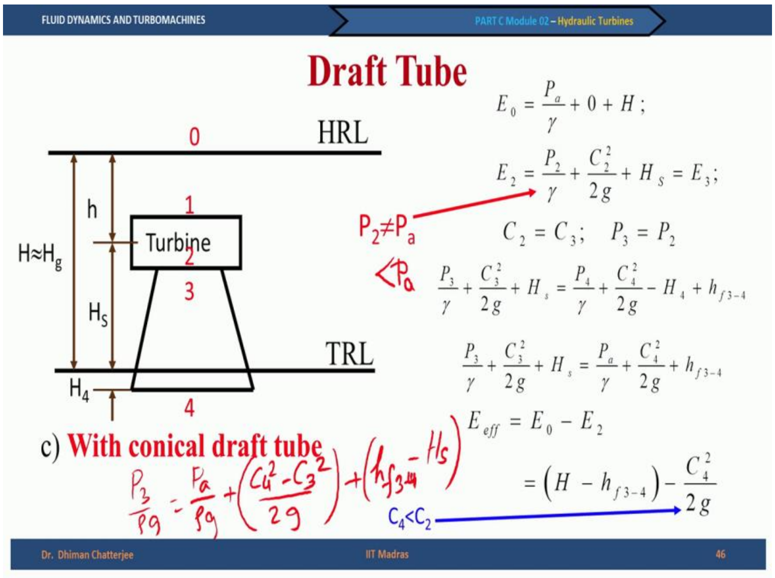

It is because it creates a pressure, you can calculate the pressure P2 or P3, in this expression if you see P3 is equal to P A by rho g + C4 square by 2g + HF 34 - C3 square by 2g - HS. And as a result P3 by rho g or P2 by rho g is less than atmospheric pressure because this is atmospheric pressure head and we have a term HS which is bigger than HF 34. So if we take it to the other side we can say that P3 by rho g is equal to PA by rho g + C4 square - C3 square by 2g + HF 3 to 4 - HS. Now let us look at these terms. C4 is less than C3 and hence this bracketed term is negative.

Similarly HF 3 to 4 is less than HS and hence this summer is also negative, what it shows is that P2 is not equal to PA, P2 is actually less than PA. So what we have created effectively is actually a point where we are getting that the pressure across the turbine has pressure difference has increased. So this is beneficial for the turbine operation and hence the reaction turbines always have draft tube. So you understand that though draft tube directly does not take part in the energy conversion, but it helps in this fashion that it produces a low-pressure compared to the atmospheric pressure that you will get in the absence of a draft tube.

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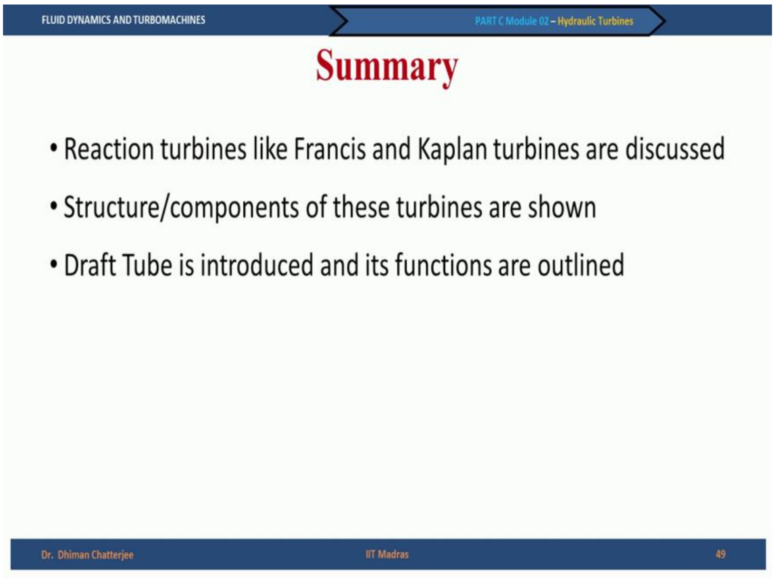

So I come to the summary of today's discussion reaction turbine like Francis and Kaplan turbines we have discussed, I have talked about the different components and in particular I talked about the draft tube which is very important and integral part of the reaction turbines why it is required. The geometric restrictions on the draft tube is not covered in today's discussion, that we will take up in the next class when we talk about cavitation in Turbo machines. When we talk about the cavitation in hydraulic turbines, we will talk about the draft tube aspect once again. So in the next lecture I would talk about cavitation and we will continue this discussion of draft tube as well. Thank you.