Fluid Dynamics And Turbo Machines.

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Part C.
Module-2.
Lecture-10.

Cavitation in Hydro Turbo machines.

Good afternoon to all for today's discussion on fluid dynamics and Turbo machines. In this week, prior to this class we have talked about pumps and hydraulic turbines and for both of these hydro Turbo machines, cavitation is a phenomenon and which is very harmful. So today we will discuss cavitation in Hydro Turbo machines. Before we start the discussion, let me ask you, where have you seen the bubbles in water? One common example can be in case of the boiling of water. Let us say you are preparing tea, you are boiling water by heat transfer.

So when you get bubbles by heat additions to the liquid and the phase change takes place, we call that phenomenon as boiling. But cavitation does not necessarily involve any heat transfer or temperature change. More often than not we talk about the formation of bubbles in liquids, not because of temperature rise. One example may come to your mind is when you open a soda water, you see that the bubbles coming. Why does the bubble appear in the liquid? It is because the soda water contains dissolved gases and when the soda water bottle is opened, the pressure is released and the gas comes out of solution.

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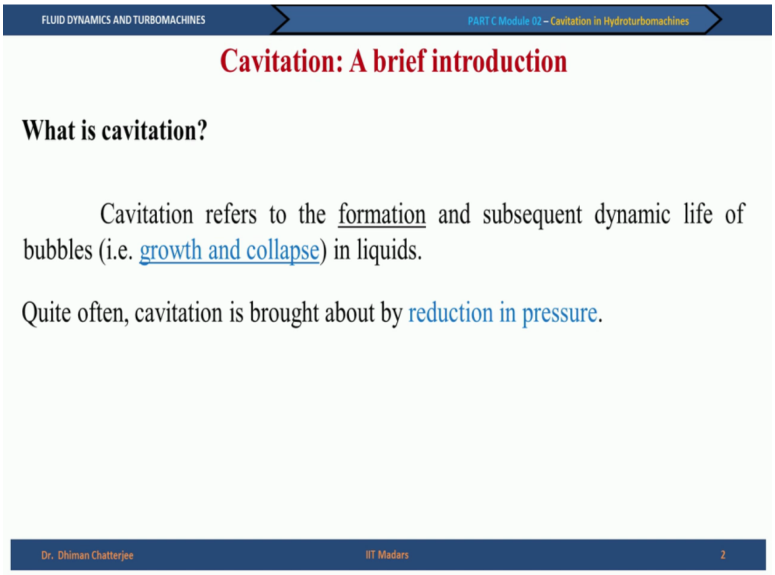

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Cavitation: A brief introduction

What is cavitation?

Cavitation refers to the formation and subsequent dynamic life of bubbles (i.e. growth and collapse) in liquids.

Quite often, cavitation is brought about by reduction in pressure.

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Do these bubbles form as a result of cavitation? The answer is not really. Why, because this phenomenon is known as effervescence or gas coming out of solution. So what constitutes cavitation? And hence in today's discussion we will start with what is cavitation. The definition can be like this. Cavitation refers to the formation and subsequent dynamic life of bubbles that is growth and collapse in liquids. The important terms are formation, growth and collapse. If you take the example of soda water and the bubbles rising in soda water, we do see bubbles forming and the bubbles are growing, bubbles rise, but we do not see the collapse.

Whereas in case of hydro Turbo machines in particular or in other applications of cavitation, it is the collapse phase which is more important. All the phenomena that are associated normally with cavitation are related with the collapse phenomena. So we have to stress words formation, growth and collapse. And this formation can be brought about by the reduction in pressure. What we are interested in today's discussion is the cavitation in Turbo machines and hence there is a flow. So whenever the reduction in pressure is brought about by the flow, we call it a hydrodynamic cavitation.

There are other modes of production of cavitation in liquids but we will not go into that in today's discussion. So we are talking about cavitation, let us have a schematic to understand this phenomena better.

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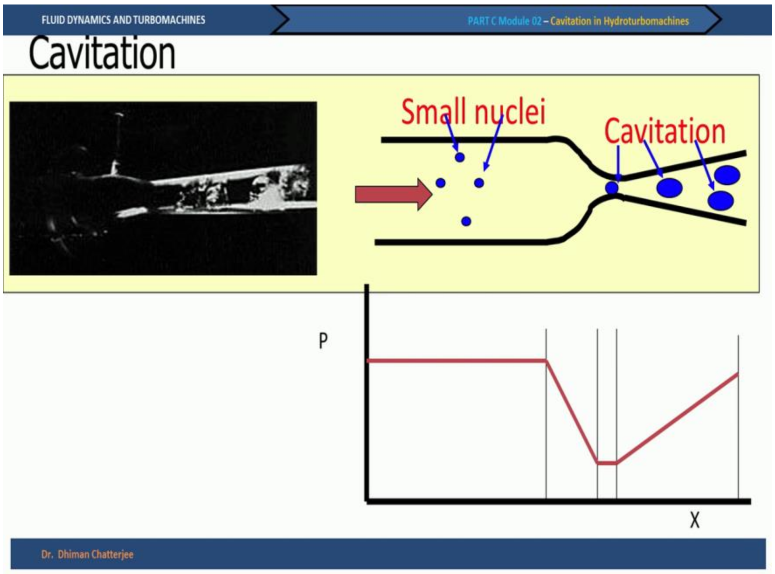

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Cavitation

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So we say, this left side is a photograph of a venturi meter in which the flow is taking place from left to right and we can see the bubbles, the whiteyou can see the white patches on the screen which are the bubbles and to make it clear we have the schematic here. These are the small nuclei which may be present in water but these are not detectable by naked eyes. However, when these bubbles or these nuclei pass through the throat, then we see that at the throat and at the downstream regions, big bubbles are formed just like in the photograph.

The reason is very simple. If we try to draw the pressure variation assuming, even in an idealised condition, if we draw the pressure variation along the flow direction, that is P versus X, we see that in the contraction region the velocity will increase and hence pressure reduces, this is the throat where the pressure is minimum and finally the pressure recovers. So this low-pressure or the lowering of local static pressure brings about a phenomenal or enormous change in the size of the nuclei and these are now detectable by eyes. Of course cavitation is not only detectable optically, we can also hear the Cavitating noise, but more about that little later.

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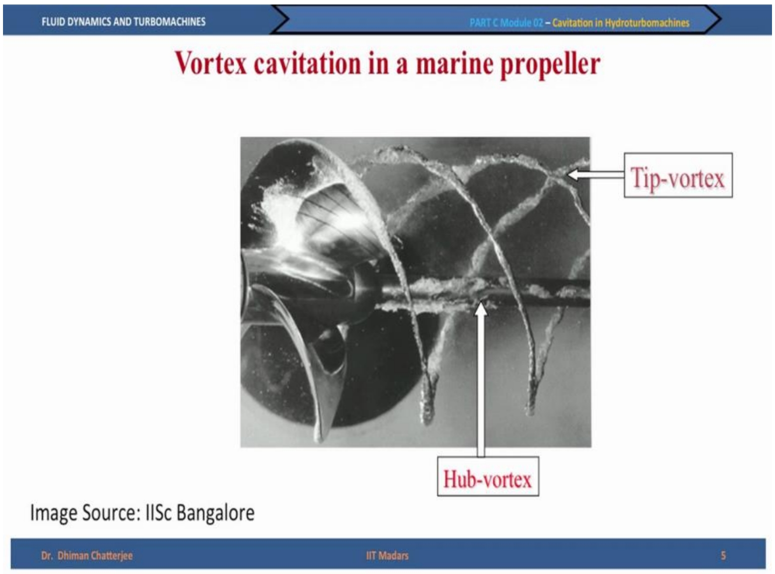
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Vortex cavitation in a marine propeller

Image Source: IISc Bangalore

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The previous example that I had given was for an internal flow but we can also have flows in the external like is shown in this slide. You can see the flow over some external flow over some curved surface. This Red Line indicates the external pressure variation as experienced by any fluid that moves over this surface and this black dashed line refers to the vapour pressure corresponding to the temperature of the ambient condition of the temperature of the liquid.

Now what we see is that in this schematic, that when the external pressure falls below the vapour pressure, we find that small bubbles appear and as the magnitude of this pressure difference between the external pressure and the vapour pressure increases, the size of the bubble grows and when pressure starts recovering, the size of the bubble again reduces and finally the bubbles disappear beyond a point. Such types of flows maybe seen in certain cases and they are called the travelling bubble because the bubbles are more or less spherical and they are travelling along with the flow.

There are other kinds of cavitation in which such clear scenario is not detectable. For example, if we see this marine propeller, it is a typical scenario of marine propeller which is rotating and cavitating, we can see a thread like structure that comes from the tip and it propagates. So this threadlike structure which is marked here as tip vortex is because of the rotation of the propeller blades in an ambient liquid. One nice thing to notice here is that this threadlike structure is actually made of bubbles, not one single bubble as you saw in the previous slide but myriads of bubble, millions bubbles are formed together to give this thread like appearance.

You can see a similar structure not so pronounced at the hub of this rotating propeller. But one another interesting thing that has to be noticed in this case is that rest of the flow field, for example I am putting the cursor here, rest of the flow field along this cursor here or here, there are hardly any bubble. Why is that, it is because at the core of these vortices, the lowest pressures exist and hence cavitation is seen locally in the core of these vortices, it is not seen in the rest of the fluid volume.

Thus it is possible that we may get distinct zones of cavitation like we have shown here, it is possible that we may get distinct bubbles like we saw in the previous slide or it can be even combinations of different types of cavitation. I would be more precise to say the different types of hydrodynamic cavitation. So why should we as engineers be interested in cavitation? The reasons are because of the effects.

And when we talk about effects of cavitation, we have to keep in mind that the fact that I will be listing out here is from the perspective of a Turbo machine person. There are many useful effects of cavitation which are used or whose advantages are taken off by the chemical engineers to bring about many chemical reactions, in the fields of biology or in medical medicinal applications. But as the engineer of handling with fluid dynamics and Turbo machines, what concerns us is the fact that all the effects of cavitation are harmful.

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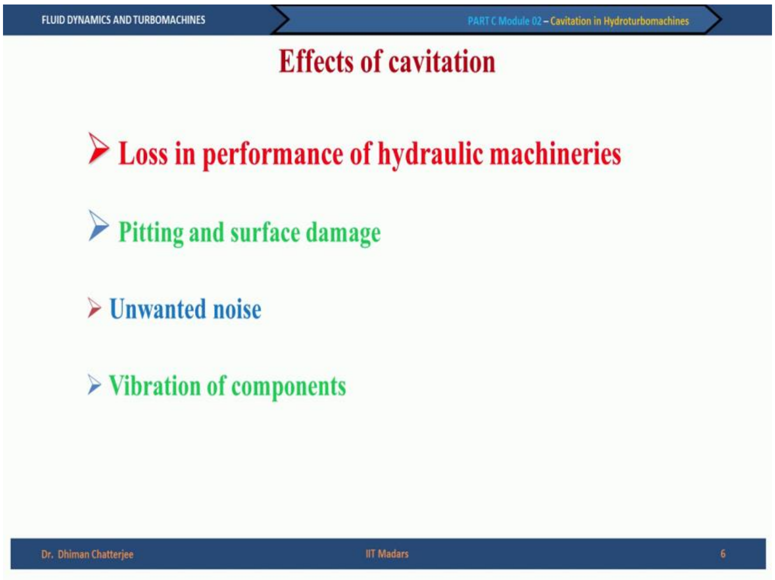

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Effects of cavitation

- Loss in performance of hydraulic machineries
- Pitting and surface damage
- Unwanted noise
- Vibration of components

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The most notable and this, the first point is the loss in performance of hydraulic machineries. When I talk about hydraulic machinery, I mean pumps and turbines both. And this aspect I will stress in the latter part of the discussion. Another thing which is also related with the life of the Turbo machines, for example a turbine blade may be severely damaged because of cavitation and hence its hydrodynamic performance may also get affected resulting in a lowering of the efficiency of the turbine.

So the 2nd point is about pitting and surface damage. Now I will show you one pump impeller to bring out what cavitation can do. You will see in these impellers that small holes are being made as if somebody has taken out the material very minutely. So let us look at the impeller in more detail.

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This is a zoomed view often impeller, first I will show you the view in all and now what you can see is that this wall here, this wall here has a white background, this white background is given because we wanted to highlight that there is a hole present in this region. This hole is present in this region and hence in this metal background you see that only this portion has a material removal. So you can see that there is a material removal in the pump impeller that we are talking about. And it is not just this only one blade, you can see that similar material removal has taken place in other cases, I have not put the white background, or even here.

Another thing you have to note I will come back to this aspect later is the fact that this has happened midway between the inlet and the outlet. It has not taken place right at the inlet, the damages not taken place right at the outlet. To see it more clearly, let us look at another specimen here.

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This is a portion of the impeller and you can see clearly the damaged portions, as if somebody has scooped out this material. Some other aspects of cavitation which are important for different applications is arising because of the unwanted noise and vibration. Particularly for naval applications where stealth is of primary importance, this cavitation noise can be a very undesirable phenomenon. But for this discussion today, we are more concerned and more interested in finding out the loss in performance of hydraulic machineries.

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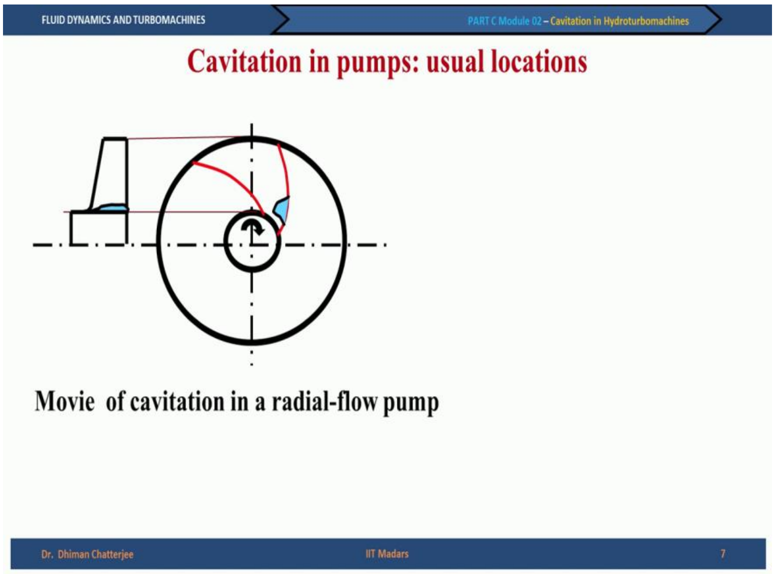

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Cavitation in pumps: usual locations

Movie of cavitation in a radial-flow pump

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So first we are going to talk about cavitation in pumps and we are talking about the usual locations. Where should we expect the cavitation to occur? If we look at pumps, we know that there is a pressure increase, there is an increase of pressure from the inlet of the blades to the delivery side, to the outlet of the blade. So, we told that earlier that cavitation can happen whenever there is a reduction in pressure and hence it is quite obvious to you that cavitation should more likely occur at the leading edge or the suction side of the pump impeller.

Here is a schematic to bring this out. This is just to show that cavitation can occur the region is marked in blue and that it can happen more on the suction side. It is not likely that cavitation should always occur on the suction surface of the blade because you know when the rotation of the blade is as shown, this is the pressure surface, this is a suction surface and when we say suction side and pressure side, we mean the inlet and the outlet. So let us not get confused, we are talking about the fact that cavitation should occur on along the suction side which is the inlet of the blade and more likely to occur along the suction surface of the blade as given by the curvature.

But it is not only possible here, we will see the next slide where else can cavitation occur in the radial flow pumps. So here is a movie that I would like to show you before we discuss further on when we talk about cavitation in pumps, this movie will help us to understand it better.

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This is a clipping of the movie in which cavitation is taking place in a radial flow pump and you should be able to mark the zones of cavitation and let us first see the movie for some time and then we discuss. So you see this movie was taken at a high-speed of 6000 frames per second, that is shown at the top and we have also tried to show down and show you here, you can see the formation of cavities and it is very clear, and you can also see that beyond a certain distance in the vane passage, the cavities do not appear, the cavities have disappeared.

The cavities are present mainly along the inlet edge or the suction side of the pump impeller. This is exactly what I was trying to talk about. Okay, this movie can continue but let us come back to the slides that we were discussing.

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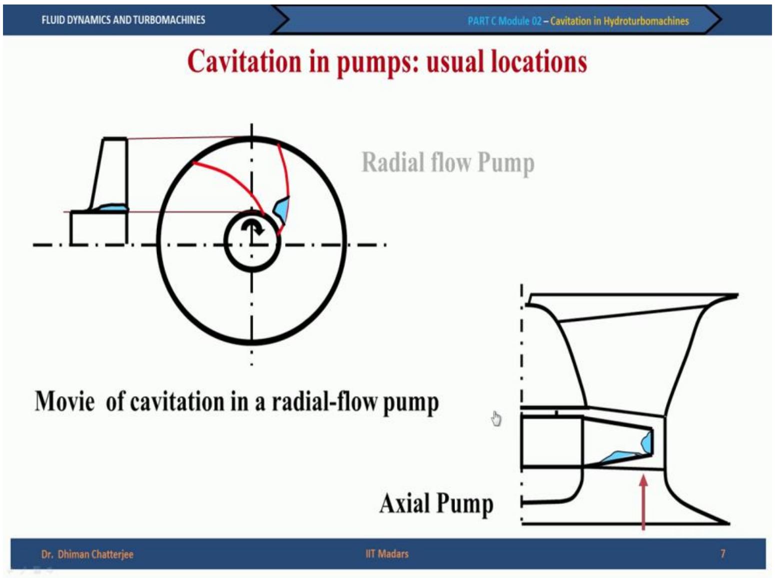

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Cavitation in pumps: usual locations

Radial flow Pump

Movie of cavitation in a radial-flow pump

Axial Pump

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In an axial flow pump, similarly the zones or the possible zones of cavitation occurrence are marked here. Now we will talk about the what causes the pump blades to cavitate and more so what happens with the variation in the volume flow rate. So let us look at the next slide here.

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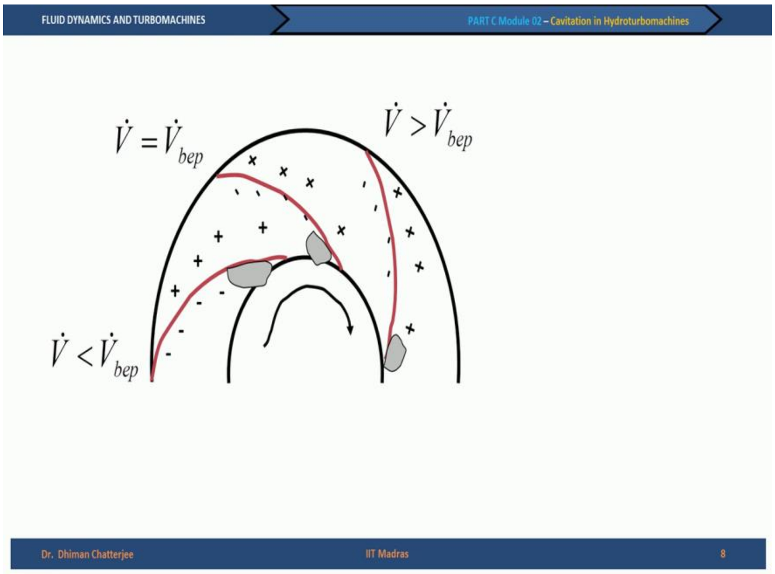

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It is actually not one single blade where you can get simultaneously V dot equal to V dot BEP, BEP stands for best efficiency point. Here we are showing 3 possible scenarios, please note that this is not a schematic showing that in the same pump at the same time you have 3 different flow rates, no. What we are trying to say is that by showing these blades we are trying to show 3 different conditions that can take place in a pump under 3 different times, it is not simultaneously.

So if we look at the Centre one which says that V dot equal to V dot BEP, we mean that the volume flow rate is equal to or very nearly equal to the best efficiency point and we see cavitation such as marked here. When the volume flow rate is less than BEP, the cavitation success is slightly more pronounced but most importantly it is still taking place on the suction surface of the blades as shown by the - sign. The + sign as you remember is the pressure surface of the plate.

However when the volume flow rate is greater than the volume flow rate at BEP, at the best efficiency point, then we will see the cavitation occurs on the other surface. Why is it so, this is because the angle of incidence changes as you have already studied that the angle of incidence need not always be the blade curvature angle. That is the flow angle need not be the blade angle at all flow rates. At flow rates away from the design flow rate, there will be angle of incidence.

Now this angle of incidence can be positive or negative and hence we can have situations when the flow angle is more than or less than the blade angle. And in this case we see that when the volume flow rate has been is more than the volume flow rate at best efficiency point we find that because of the change in angle of incidence or other change in the sign of the angle of incidence, cavity structure appears on the other side, so-called pressure surface.

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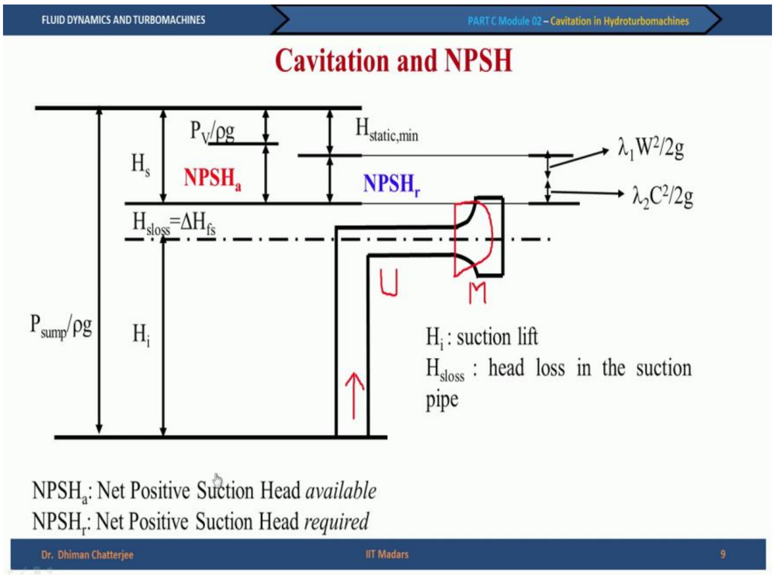
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Cavitation and NPSH

H_i : suction lift

H_{sloss} : head loss in the suction pipe

NPSH$_a$: Net Positive Suction Head *available*

NPSH$_r$: Net Positive Suction Head *required*

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One important parameter that we have to keep in mind while discussing cavitation in pumps is the term called NPSH, NPSH as I will talk about means net positive suction head but before we go into definition of NPSH, let us look at how to find out what NPSH is and what is the reasoning behind such a calculation. So we say that we have a pump impeller, this is my schematic of a pump impeller which is placed at an elevation above the sump, the bottom line is the sump and it is placed above the sump. The sump pressure is P sump and we can say that the head corresponding to this pressure P sump is P sump by rho g.

We can say that H I is a static lift of the pump or the elevation of the pump from the pump Centre line from the sump level, then HS loss is nothing but the friction loss in the suction pipe of the pump. When I say suction pipe, I mean from the side at the sump here to the inlet of the pump, not inside the pump. And we can then define that HI is the suction lift and HS loss is the head loss in the suction pipe. And then we can say that P sump by rho g - H I - HS loss is given as HS.

And we can then say that if the vapour pressure at the water temperature or the liquid temperature is PV, then the corresponding head can be expressed as PV by rho g. So if we subtract PV by rho g from HS, we get NPSHA. This NPSHA, the subscript A stands for available. I will explain these terms again after finishing this picture. So similarly we can think about another term which is called NPSHR, NPSH required, R for required and that is given by some terms. Let us not go into the details this NPSHA, its formulation and NPSH R and its formulation at this point.

Let us try to first understand that why do we need in the first place 2 types of NPSH, why not one NPSH suffice? So to understand this first let us note down that NPSHA stands for net positive suction head which is available, please mark the word available and then NPSHR is the net positive suction head required, again mark the word required. Let us think about a physical situation. You are going to do some experiment in your laboratory or in your workspace. You purchase a pump and install it.

Now there are certain things which you as a user of the pump know. For example you know what is the height of the elevation of the pump Centre line from the sump. The pump manufacturer or the pump designer who has made that pump will not know because the same pump can be used by different users at different locations. Similarly the legnth of the pipe that is required from the sump to the pump inlet is also something which a user decides. The temperature of the liquid, the temperature of let us say water if you are using as a liquid, then the temperature of the liquid is also dictated by the user.

The atmospheric pressure or the location in which the experiment is done, the work, the pump is made to work also depends on the user. So these are some of the quantities on which the manufacturer has no control, whereas what happens between the pump suction side and the suction flange in the pipe end of the pump on the suction side is something which a manufacturer alone knows. For example if we try to understand it, we can say that from here, this is let us say the suction flange, from here upto this point whatever happens is known to the manufacturer.

So this is known to the manufacturer, whereas the rest of the portion, if the water is going along this, what is the height, what is the diameter of the pipe, what are, what is the length of the pipe, everything is known to the user of the pump. And hence we should get these 2 expressions, these 2 information together to find out whether cavitation is likely or not. So I will take you through these definitions now. But let us start with this picture again I will we understand it that NPSH available is nothing but P sump or by rho g - H I - HS loss - PV by rho g.

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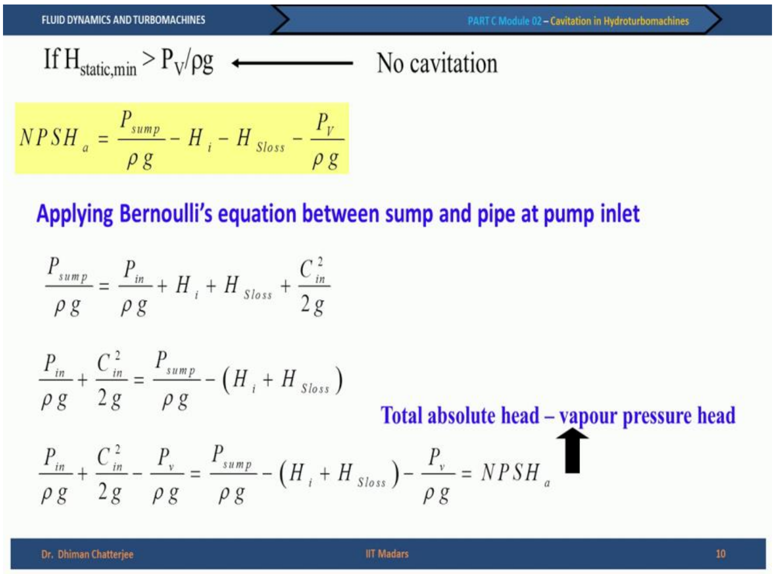

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If $H_{static,min} > P_V/\rho g$ ← No cavitation

$$NPSH_a = \frac{P_{sump}}{\rho g} - H_i - H_{Sloss} - \frac{P_V}{\rho g}$$

Applying Bernoulli's equation between sump and pipe at pump inlet

$$\frac{P_{sump}}{\rho g} = \frac{P_{in}}{\rho g} + H_i + H_{Sloss} + \frac{C_{in}^2}{2g}$$

$$\frac{P_{in}}{\rho g} + \frac{C_{in}^2}{2g} = \frac{P_{sump}}{\rho g} - (H_i + H_{Sloss})$$

Total absolute head – vapour pressure head

$$\frac{P_{in}}{\rho g} + \frac{C_{in}^2}{2g} - \frac{P_v}{\rho g} = \frac{P_{sump}}{\rho g} - (H_i + H_{Sloss}) - \frac{P_v}{\rho g} = NPSH_a$$

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So let us write down these 2 aspects. We say that NPSH available is P sump by rho g - H I - HS loss - PV by rho g. To appreciate this NPSH available better, we can say that applying Bernoulli's equation between sump and pipe at the pump inlet, please remember we are not entering the pump as a user, we are talking up to the suction flange, the vertical line that I have drawn in the previous slide. So we can say that P sump by rho g assuming the velocity is negligible is P in by rho g where P in is the pressure at the pipe in the pump inlet + H I + HS loss + sin square by 2g, which gives me that P in by rho g + sin square by 2g is P sump by rho g - H I + HS loss whole within the bracket.

Now if I compared this expression with NPSH available which is marked above, what we get it is that P in + rho g + C in square by 2g - PV by rho g, that is the vapour pressure head is equal to nothing but NPSH available. And hence NPSH available talks about the total absolute head available at the suction flange just outside the pump inlet and - the vapour pressure head. So we get an idea about what NPSHA is trying to convey. It is related with the pressure in the suction pipe just outside the pump inlet.

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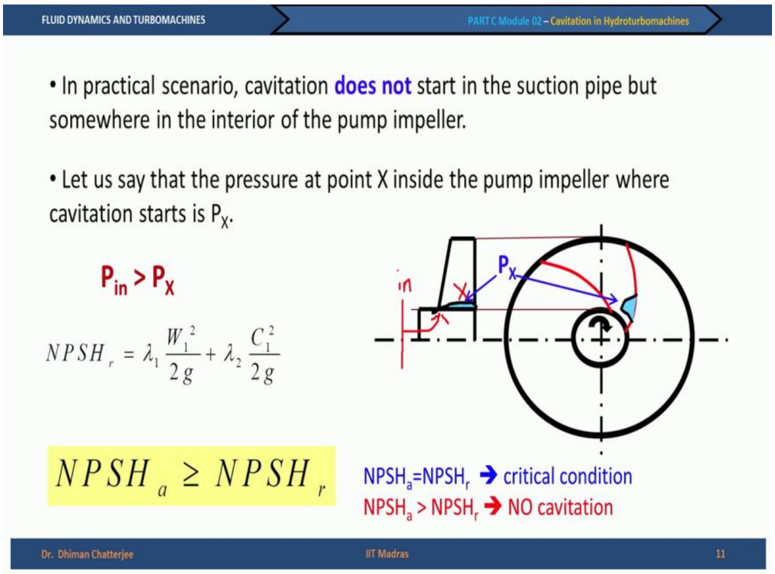

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- In practical scenario, cavitation **does not** start in the suction pipe but somewhere in the interior of the pump impeller.
- Let us say that the pressure at point X inside the pump impeller where cavitation starts is P_X.

$P_{in} > P_X$

$$NPSH_r = \lambda_1 \frac{W_1^2}{2g} + \lambda_2 \frac{C_1^2}{2g}$$

$$\boxed{NPSH_a \geq NPSH_r}$$

$NPSH_a = NPSH_r$ → critical condition

$NPSH_a > NPSH_r$ → NO cavitation

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But cavitation really does not start then, cavitation starts inside somewhere inside the pump impeller. Let us say that the pressure at point X inside the pump impeller where cavitation starts is P X and we know now that P in will be greater than PX, why, whenever there is a flow taking place from P in, that is a suction flange just outside the pump inlet to the suction side of the impeller inside the pump, there is, there are some pressure losses. The pressure losses could be because of for example the flow comes from here, the flow enters here and goes like this.

So this curvature will give rise to loss and please remember that this is your point X. And this is somewhere your P in. So this is where I am talking about P in. So you see that we are talking about this pressure difference P in - PX because of the curvature of the flow taking place as it enters or because of the acceleration of the flow is we find that P in is not equal to PX, in fact P in will be slightly greater than PX. And this difference of pressure is known only to the manufacturer because it is the manufacturer or the design of the pump who has designed the pump internals.

So the usual correlation that is given by the manufacturer will be in the form of lambda 1 some constant, W1 square by 2g + lambda 2 C1 square by 2g. Now in order to avoid cavitation we need to prevent the cavitation to occur at PX which means PX should be greater than equal to the vapour pressure, because at the vapour pressure is this PX should be equal to the vapour pressure. So the condition of prevention of cavitation is the NPSH available should be greater than equal to NPSH required.

This equal to sign deals with critical condition when cavitation has just set in. When NPSH available is greater than NPSH required, then there is no cavitation. How can you remember the situation? If you think that NPSH available is greater than NPSH required to prevent cavitation is something difficult to remember, think about this story. Imagine that you have gone to a shop to buy certain items and let us say you have thousand rupees with you. If the cost of that item 995 rupees, then you can buy that item and come back home happily.

On the other hand if the cost of that item is thousand and fifty, 1050 rupees, then what happens, you are falling short of money, you cannot buy that item, you come back unhappily. So in case of a Turbo machine an engineer is unhappy when cavitation sets in. So now you think that if you are a user, you know what is available with you just like the buyer, as the buyer you know how much money is available with you. The shopkeeper or the manufacturer knows how much money is required to buy that item, similarly here the pump manufacturer or the pump designer knows what is the NPSH required.

So if you have more money, which means if the availability of money is more than the required money, you are happy. Similarly if availability of NPSH, NPSHA is greater than NPSHR, you are happy, which means no cavitation. I hope, even if you forget it, you will be able to reconstruct that NPSHA is greater than NPSHR is a condition of no cavitation using this story. Let us continue. And there are other ways of defining in case of industrial use.

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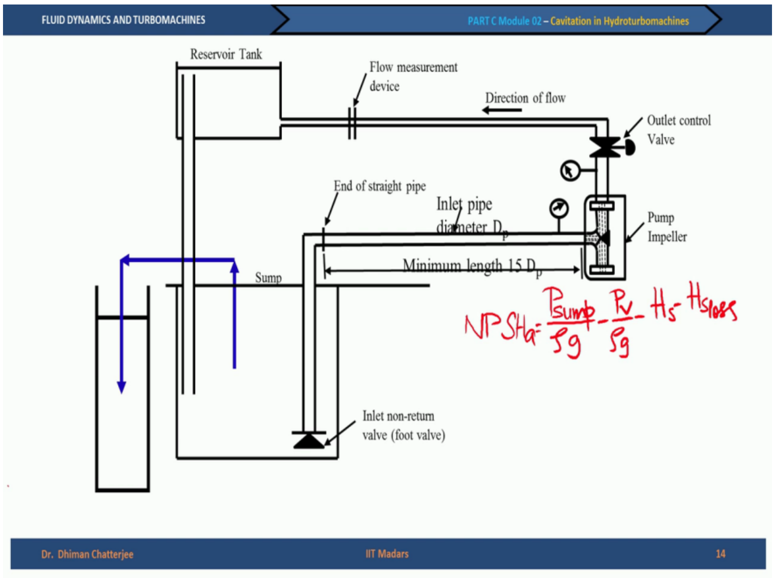
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$$NPSH_a = \frac{P_{sump}}{\rho g} - \frac{P_v}{\rho g} - H_s - H_{s\,loss}$$

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I will not spend much time along the lines of specific speed we can talk about a specific speed in terms of NPSH. Just like we write N under root V dot by H to the power three fourth in case of specific speed, we can define the suction specific speed instead of replacing H by NPSH. And many times in industry this is also used along with NPSH. So how do we do experiments, suppose we want to do experiments in the laboratory? One possible setup is like this.

You have a pump here, you have a sump and you have a nonreturn valve or a foot valve and you have a valve to control the flow rate and you have a pressure gauge, at the suction side you have a pressure gauge at delivery side, you have outlet valve and that goes to the reservoir tank. So what you can do, you are trying to bring in cavitation, please note that this is not an experiment to avoid cavitation which is a real-life scenario, this is an experiment you are doing to find out how badly the pump performs under cavitation. You want cavitation to happen and in order to do that, what you have to do is you have to reduce NPSH available.

So one way of reducing NPSH available is by increasing the HS loss. So if you increase the HS loss, how can you do that, you can throttle this valve more, as you throttle the valve, the valve loss coefficient will increase and hence you will get more losses in the suction side and we can get cavitation at the onset. This method is really little bit problematic because you may end up getting cavitation not in the pump first but cavitation in the valve. The valve may cavitate first and then what will happen, downstream of the valve you will get lots of bubbles, just like the example I showed you with the venturi meter at the beginning, there will be bubbles downstream of the throat.

And these bubbles will be fed into the pump. But that is not what we want to try, we want to try how a Cavit pump performs with normal water, not with water fulfilled with bubbles. So there is another method of doing the same experiment of bringing about cavitation and that can also be done easily in the laboratory is this one. If you recollect the expression for NPSH available, you know that you also have a term - HS which is the suction lift, that means if you can change the elevation of the pump from the free surface of the sample, then you have a chance of bringing in cavitation because of the reduction in NPSH available.

Now lifting the pump is not possible, what is possible lays if we reduce the water in the sump and in this schematic what I am trying to show is that if we can take away water from the sump to some other reservoir, I am not saying throw this water, I am saying store it in later use in some other reservoir, then this sump level will come down and as a result the gap between the pump centreline and the sump surface increases and let us recollect the NPSH available expression once again.

It is P sump by rho g - PV by rho g - HS - HS loss. So you see in the previous example what we have talked about is this one. We have talked about increasing HS loss by throttling the valve, in this example we are trying to increase HS by removing some water, please note that there is no valve here. So there is no possibility of valve cavitating sooner than the pump cavitation.

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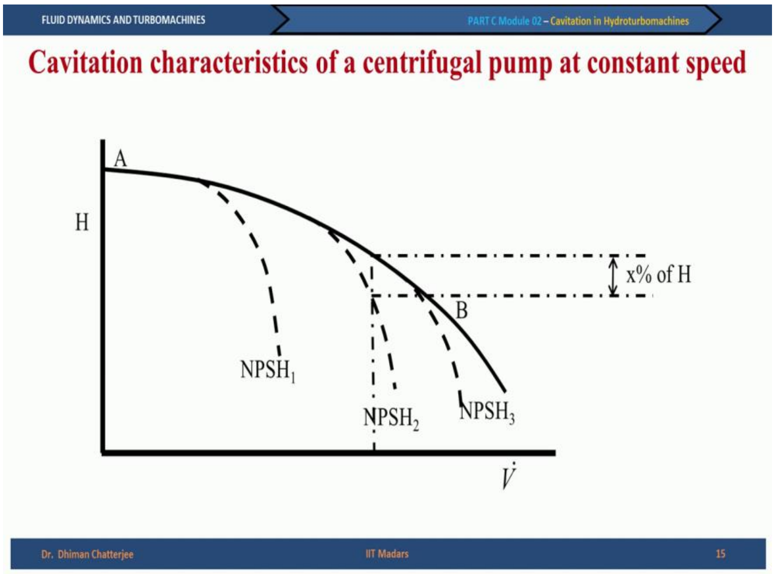

FLUID DYNAMICS AND TURBOMACHINES

PART C Module 02 – Cavitation in Hydroturbomachines

Cavitation characteristics of a centrifugal pump at constant speed

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So cavitation characteristics of a centrifugal pump, how does it affect? Let us say cavitation occurs and how does it affect the performance? So already we have talked about the HV dot pump characteristic curve in one of the early lectures on pump. This line, the solid line refers to the pump characteristic of course at a given speed as you know at constant speed when there is no cavitation. However when we have a lower NPSH available, we find that cavitation starts and NPSH is reduced, you see that there is a Sharper droop in case of the pump characteristic from the non-cavitating one.

And one of the measures adopted by the industry in pumps is how much head drop is acceptable to the industry or to the user. Let us say that is X percent, usually it is 3 percent, so this is a non-cavitating head for this flow rate and for this NPSH 2 which is available, then we see there is this much drop in head which is the X percent head drop. Now if as a user or as a designer you have to decide whether this X percent is acceptable or not. Usually the acceptable number is 3 percent of head drop.

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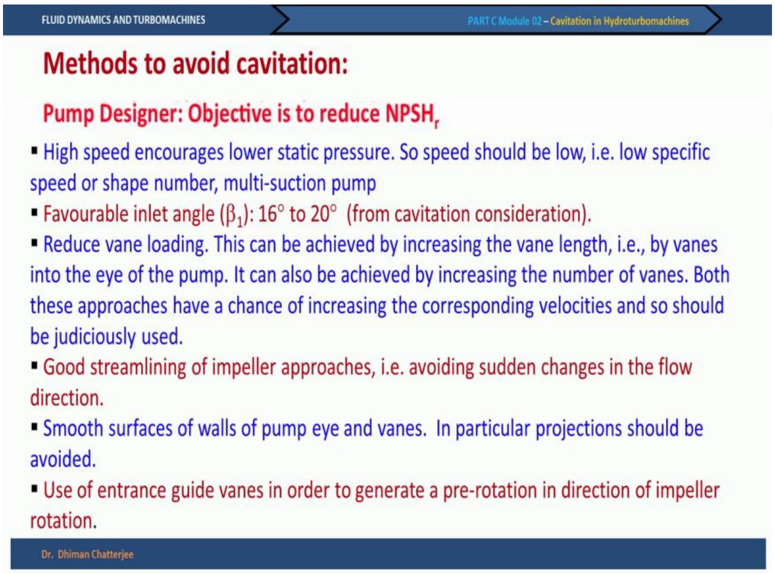

FLUID DYNAMICS AND TURBOMACHINES

PART C Module 02 – Cavitation in Hydroturbomachines

Methods to avoid cavitation:

Pump Designer: Objective is to reduce NPSH_r

- High speed encourages lower static pressure. So speed should be low, i.e. low specific speed or shape number, multi-suction pump
- Favourable inlet angle (β_1): 16° to 20° (from cavitation consideration).
- Reduce vane loading. This can be achieved by increasing the vane length, i.e., by vanes into the eye of the pump. It can also be achieved by increasing the number of vanes. Both these approaches have a chance of increasing the corresponding velocities and so should be judiciously used.
- Good streamlining of impeller approaches, i.e. avoiding sudden changes in the flow direction.
- Smooth surfaces of walls of pump eye and vanes. In particular projections should be avoided.
- Use of entrance guide vanes in order to generate a pre-rotation in direction of impeller rotation.

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So methods to avoid cavitation because as engineers we would like to avoid cavitation as I told you, particularly as an engineer working in the field of Turbo machines. So as a pump designer, we can do it as a pump designer, we can do it as a pump user. First let us look at the pump designer, when I am a pump designer, my objective is to reduce NPSHR. And high-speed encourages lower static pressure, so speed should be low, that is the low specific speed or shape number and multi-suction pump should be used because in that way if you use for example multi-suction pump, then the volume flow rate is less and hence volume flow rate in each of the impellers is less and hence there is less chances of cavitation.

Favourable inlet angle, I have already told you that beta 1 should be between 16 and 20 degrees, I reproduce it from the pump lecture that this is from the cavitation consideration, the blade angle should be lower. Reducing the vane loading, if you remember we have talked about vane loading as nothing but, this can be nothing but the pressure difference from the 2 surfaces of the vanes. Fewer the number of vanes, we can get more vane loading and so if you want to reduce vane loading, one of the objectives can be by increasing the number of vanes.

We can also reduce the vane loading by increasing the vane length but if you remember that if you have more number of vanes, that means the blockage or due of the flow passage due to the vanes, vane thickness will also increase. If the blockage increases, then the frictional drops will increase and the pump will not be able to perform that effectively. So we should use this reduction of vane by either increasing the vane length or the increasing the vane number very judiciously.

Then good streamlining of impellers approaches should be made, that is we should try to avoid as sudden changes in the flow direction as possible and we should have tried to avoid any particular projections, etc. from the pump eye and vanes. There should be no sudden surface roughnesses which are coming as isolated roughnesses, because in the low-pressure region these isolated roughnesses can also give rise to the cavitation. Use of entrance guide vanes can be used in all to generate a pre-rotation in the direction of impellers rotation.

See earlier we have told you that most of the times we can start with the assumption of that inlet whirl or the pre-whirl component of the inlet absolute velocity at the impeller inlet is zero. That is C1U is zero. But if you are designing a pump for a particular application where NPSH available is very restricted, then you may try using the guide vanes to give it a small pre-rotation in the direction of the impeller rotation so that the cavitation is less.

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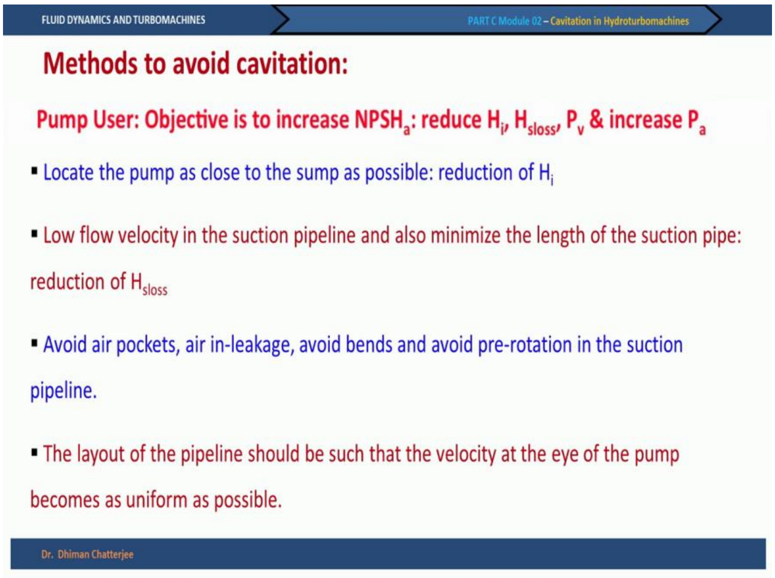

FLUID DYNAMICS AND TURBOMACHINES

PART C Module 02 – Cavitation in Hydroturbomachines

Methods to avoid cavitation:

Pump User: Objective is to increase $NPSH_a$: reduce H_i, H_{sloss}, P_v & increase P_a

- Locate the pump as close to the sump as possible: reduction of H_i
- Low flow velocity in the suction pipeline and also minimize the length of the suction pipe: reduction of H_{sloss}
- Avoid air pockets, air in-leakage, avoid bends and avoid pre-rotation in the suction pipeline.
- The layout of the pipeline should be such that the velocity at the eye of the pump becomes as uniform as possible.

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Similarly as a pump user, you can try to increase the NPSH available when I say increase NPSH available, that means we should reduce HI, we should reduce HS loss and we should also reduce vapour pressure and a possible increase the sump pressure. So we can locate the pump as close to the sump as possible, for example we can bring the pump as close to the sump surface, so that we can reduce the HI or the suction lift, we can say that the low flow velocity in the suction pipeline, so we can increase the pipeline size so that the velocity is less and also minimise the suction pipe, so the objectivity reduce the HS loss.

We can try to avoid air pockets, avoid bends as much as possible, it may not always be possible to completely avoid bends but if you have bends, then give enough sufficient length before the pump is kept and avoid any rotation in the suction pipeline, do not confuse it with the pump. The layout of the pipeline should be such that the velocity at the eye of the pump becomes as uniform as possible. Try to make the pump as, velocity in the pipeline as uniform as possible so the chances of cavitation because of the local pockets of high velocities are less.

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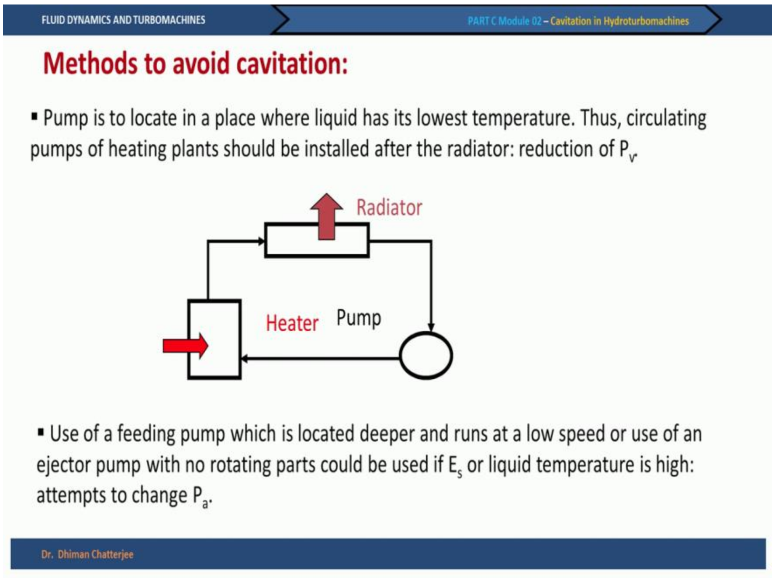

FLUID DYNAMICS AND TURBOMACHINES

PART C Module 02 – Cavitation in Hydroturbomachines

Methods to avoid cavitation:

- Pump is to locate in a place where liquid has its lowest temperature. Thus, circulating pumps of heating plants should be installed after the radiator: reduction of P_v.

- Use of a feeding pump which is located deeper and runs at a low speed or use of an ejector pump with no rotating parts could be used if E_s or liquid temperature is high: attempts to change P_a.

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And if we have to deal with temperatures which are varying, then we should try to locate the pump in a region where the liquid has its lowest temperature. The circulating pumps are heating plants should be installed after the radiator for reduction of the vapour pressure. User of a feeding pump which is located deeper and runs at a low speed or use of an ejector pump or a jet pump which is many times used, ejector pumps or jet pumps are many times used in connection with the centrifugal pumps so that we can avoid a large value of suction lift can be used.

And if possible we can try to change the sump pressure but that is not always within our hand, the other aspects can be tried like changing the suction pipelines or the changing the location of the pumps, which is possible for a user.

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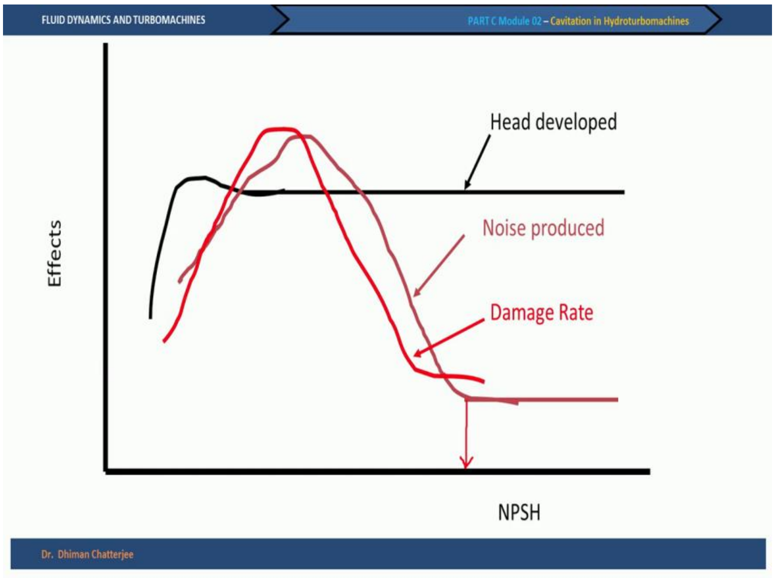

So now to sum up what are the effects of cavitation versus NPSH, we can see that noise produced by the cavitating bubbles starts at the highest NPSH which means the noise is the most sensitive way of detecting cavitation. Cavitation damage actually takes longer time to produce depending on the material characteristics, it can take hours or days or weeks and of course it depends on the cavitation intensity. The head developed by the pump actually shows the effect of cavitation much later.

For example if I say that I have to find out the inception of cavitation, then I can show that this point where actually there is a change in slope, this noise measurement shows a change in slope at the point here, it is an elbow for this noise curve. So what we can say for NPSH values higher than this point, that is to the right of the arrow actually does not show any effect of NPSH. It means that there is hardly any effect of cavitation. Whereas to the left of this arrow we can see that there is significant change in the noise level and that significant change in the noise level take place because of the production of cavitation bubbles and rather the collapse of this cavitation bubbles.

So if we say that is, arrow indicates my critical cavitation number or critical NPSH value, if it shows critical NPSH value, then we find that the effect of pump showing an adverse effect of cavitation is felt much later. And hence we can define one as NPSH which is inception value and one where NPSH really shows up and the pump performance breakdown as called the breakdown performance value. Now as a pump user or as a pump designer you may not be worried about the noise produced and hence whether there is noise or whether there is some traces of bubbles being seen inside the pump passage is not one of concern to you.

What you are more interested in is whether the performance of the pump deteriorates. And hence what the user will like to see is whether there is a breakdown in performance and hence he or she will be interested in this region. So we can say that this is the region which is not acceptable to the, to an user. This is a region which is not acceptable to an user. So this region is what the pump manufacturer would also like to avoid and hence what the pump manufacturer will say is that there is a 3 percent head drop I told you that this is the 3 percent head drop that the pump manufacturer will talk about and this is what the will be considered as critical for a pump user.

However please do not miss this point that cavitation has already set in along this point, so between this point and the cavitation breakdown is the point where even with cavitation the pump performance is not affected and hence as a user of the pump we need not bother.

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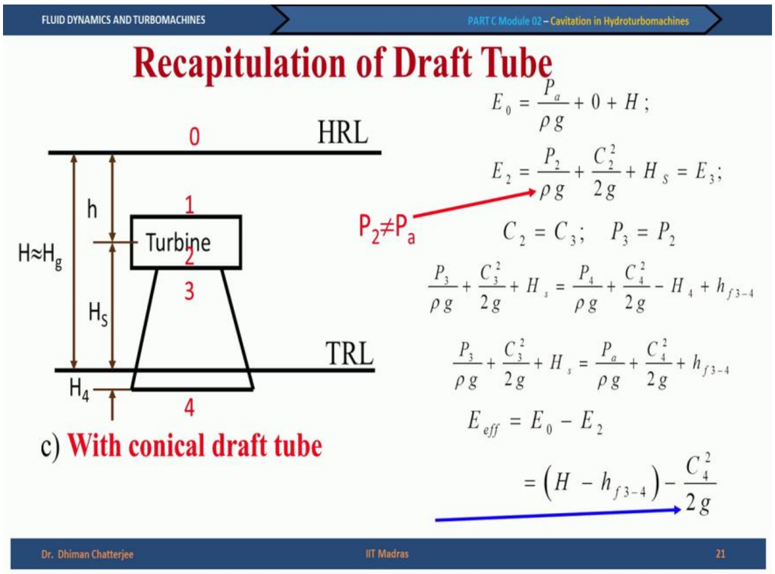
FLUID DYNAMICS AND TURBOMACHINES

PART C Module 02 – Cavitation in Hydroturbomachines

Recapitulation of Draft Tube

$$E_0 = \frac{P_a}{\rho g} + 0 + H;$$

$$E_2 = \frac{P_2}{\rho g} + \frac{C_2^2}{2g} + H_S = E_3;$$

$P_2 \neq P_a$

$$C_2 = C_3; \quad P_3 = P_2$$

$$\frac{P_3}{\rho g} + \frac{C_3^2}{2g} + H_s = \frac{P_4}{\rho g} + \frac{C_4^2}{2g} - H_4 + h_{f3-4}$$

$$\frac{P_3}{\rho g} + \frac{C_3^2}{2g} + H_s = \frac{P_a}{\rho g} + \frac{C_4^2}{2g} + h_{f3-4}$$

$$E_{eff} = E_0 - E_2$$

$$= \left(H - h_{f3-4}\right) - \frac{C_4^2}{2g}$$

c) With conical draft tube

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Now we will talk about cavitation in turbines, particularly we will talk about reaction turbines. But before we go into cavitation and reaction turbines, let me recapitulate what we have studied in draft tube. I will not go into details but I will just talk about the last simple type of draft tube that we have talked about, the conical draft tube and we had said that a draft tube in a reaction turbine is required to reduce the exit kinetic energy loss as well as to enable the turbine to be located somewhere above the tail rest level without a loss in head.

And this we have already done in the last lecture. So here I want to go more into it and find out what is the restriction in the dimension of the draft tube from cavitation. So you know that we have already talked about that the energy that is effectively available is between E0 - E 2 and we are trying to find out the pressure. As soon as we put a draft tube, we find that the P 2 or P3 is no longer atmospheric pressure as shown here, in fact P3 will be less than atmospheric as I have shown in the last lecture. So one point is P3 is less than atmospheric pressure and the 2nd point is the exit kinetic energy laws is C4 square by 2g.

So that means if I have to reduce the exit kinetic energy loss, then I have to reduce C4 further and further. So is it clear that if we have to make this draft tube work effectively, this conical draft tube work effectively, then I should try to reduce C4 further and further, okay. How do we do it and what restriction it brings in the pressure that is available at 3 or 2, this is what we are going to discuss today. So let us look at this again. Let us look at what connects C4 with C2 and what connects pressure with the height and the dimension of the draft tube.

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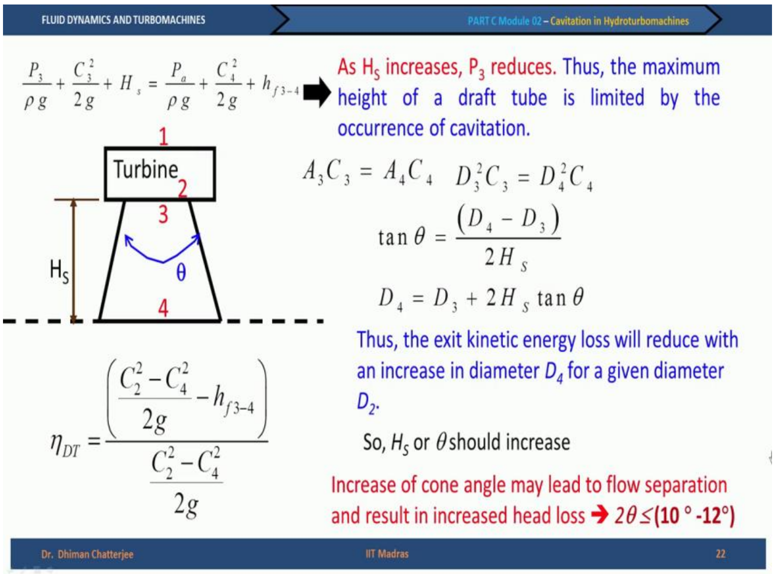

FLUID DYNAMICS AND TURBOMACHINES

PART C Module 02 – Cavitation in Hydroturbomachines

$$\frac{P_3}{\rho g}+\frac{C_3^2}{2g}+H_s=\frac{P_a}{\rho g}+\frac{C_4^2}{2g}+h_{f3-4} \Rightarrow$$

As H_S increases, P_3 reduces. Thus, the maximum height of a draft tube is limited by the occurrence of cavitation.

$$A_3C_3=A_4C_4 \quad D_3^2C_3=D_4^2C_4$$

$$\tan\theta=\frac{(D_4-D_3)}{2H_S}$$

$$D_4=D_3+2H_S\tan\theta$$

Thus, the exit kinetic energy loss will reduce with an increase in diameter D_4 for a given diameter D_2.

So, H_S or θ should increase

$$\eta_{DT}=\frac{\left(\frac{C_2^2-C_4^2}{2g}-h_{f3-4}\right)}{\frac{C_2^2-C_4^2}{2g}}$$

Increase of cone angle may lead to flow separation and result in increased head loss → $2\theta \le (10° - 12°)$

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So we know that P3 by rho g + C3 square by 2g + HS, it is if the height of the draft tube is nothing but PA by rho g + C4 square by 2g + HF 3 to 4. Which means as we have discussed in the last lecture that as HS increases, P3 will reduce. Why, because C4 is less than C3, so this term will be negative and similarly HS is going to be on the other side and ace HS increases, then P3 will reduce. So now as P3 reduces, you cannot go on increasing the HS. Why, because if HS increases, then P3 reduces and you can get cavitation. So the height of the draft tube is restricted by the chances of having cavitation and hence we cannot increase the height.

However if we have to think about the exit kinetic energy loss and if we think of a simple conical draft tube as we have been discussing, then what happens we can write that A3 C3 is equal to A4 C4 and please do remember that our objective is to reduce exit kinetic energy loss which means we want to reduce C4. So C4 is nothing but connected with the D3 and D4. So you see higher the value of D 4, the smaller will be the value of C4 and the smaller will be the exit kinetic energy, which is desirable. Now how can I increase D4?

I can increase D4 by increasing D3 but D3 we strictly speaking we cannot increase because D3 or D2 is dictated by Runner diameter, the impeller diameter or the rotating blade diameter and hence we cannot touch it. So what we can do to increase D4 is either increase HS or increase Theta. So if we increase HS, then what happens, if we increase HS, we know that the P3 reduces, so we have a problem and if we increase the tan Theta, if we increase the cone angle, that may lead to the flow separation and results in the increase head loss and so we respect 2 Theta between 10 degree and 12 degree and we can say that the draft tube efficiency is given by C2 square - C4 square by 2g - Hf 34 whole divided by C2 square - C4 square by 2g.

Now this C2 square - C4 square by 2g is the kinetic energy recovery, thanks to the draft tube. And as a result of the presence of the draft tube we encourage head drop of HF 34. So HF 34 ideally should be zero which is not possible, we should try to reduce it. Now if we increase the cone angle we can reduce C4, true but we also incur higher HF 34 and hence the draft tube conversion efficiency will reduce. So what is not possible is increase in Theta without any bounds, unbounded increase of Theta is not possible.

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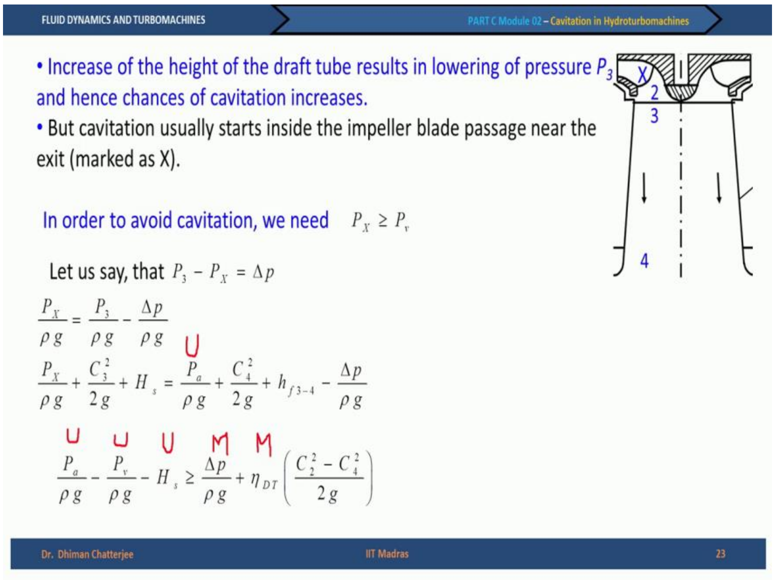

FLUID DYNAMICS AND TURBOMACHINES

PART C Module 02 – Cavitation in Hydroturbomachines

- Increase of the height of the draft tube results in lowering of pressure P_3 and hence chances of cavitation increases.
- But cavitation usually starts inside the impeller blade passage near the exit (marked as X).

In order to avoid cavitation, we need $P_X \geq P_v$

Let us say, that $P_3 - P_X = \Delta p$

$$\frac{P_X}{\rho g} = \frac{P_3}{\rho g} - \frac{\Delta p}{\rho g}$$

$$\frac{P_X}{\rho g} + \frac{C_3^2}{2g} + H_s = \overset{U}{\frac{P_a}{\rho g}} + \frac{C_4^2}{2g} + h_{f3-4} - \frac{\Delta p}{\rho g}$$

$$\overset{U}{\frac{P_a}{\rho g}} - \overset{U}{\frac{P_v}{\rho g}} - \overset{U}{H_s} \geq \overset{M}{\frac{\Delta p}{\rho g}} + \overset{M}{\eta_{DT}} \left(\frac{C_2^2 - C_4^2}{2g} \right)$$

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So if we increase the HS as we have already discussed, the pressure will reduce and we can say like we have discussed in case of pump, that cavitation starts inside the impeller blade passage near the exit. Please note this difference, in case of pump the lower pressure is at the inlet of the impeller, in case of a turbine, the lower pressure is at the exit of the turbine. And hence we should see, expect that if this is a picture of my turbine, then 2 and 3 are the coincident points and X is the point where cavitation is more likely to occur at the exit of the turbine impeller or the turbine runner.

And we can say that PX should be greater than equal to PB. And we say that P3 - PX is equal to some Delta P, now please note that this Delta P is known to the manufacturer or the designer of the turbine, just like we have said in the case of pump. In case of pump we have said that the pressure difference between the pump suction inlet, pipe inlet and the pump impeller inlet is known to the manufacturer of the pump. In this case of turbine we can say that P3 - PX or the pressure that is drop taking place between X and 3 inside the turbine is known to the manufacturer of the turbine.

And hence we can write that PX by rho g is equal to P3 by rho g minor Delta P by rho g. Now we can also write that PX by rho g + C3 square by 2g + HS can be related with PA by rho g which is the ambient pressure at the tail rest level + C4 square by 2g + HF 34 - Delta P by rho g. This is what we have done is exactly in the way of replacing P3 in the previous expression. And then we can say if we group these expressions, you see that PA by rho g is a term which is known to the user. As a user of the turbine you know where you are going to install the turbine, what is the atmospheric pressure.

So this is known to the user. So let us say this is known to the user. Then the vapour pressure is also known to the user because we know that the what is the temperature of the liquid. So this is known to the user, this is also known to the user and HS is where we want to mount to the turbine above the tail rest level. So the left hand side shows all the terms that are known to the user, right-hand side, the first includes the pressure drop inside the runner in a vaneless place inside the runner and then it is known only to the manufacturer.

The draft tube efficiency is also known to the manufacturer and because the manufacturer has defined the draft tube. So we have now said that there are certain terms on the left-hand side which is known to the user and there are certain terms on the right-hand side of the inequality which is known to the manufacturer.

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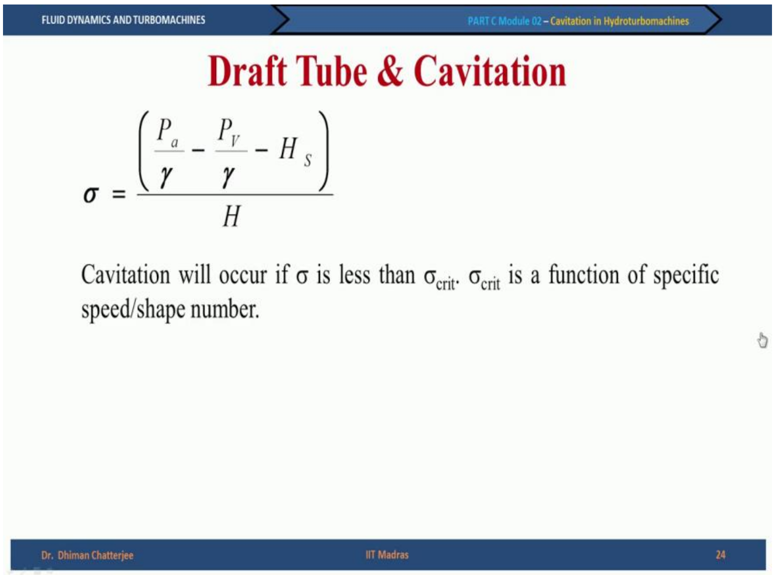

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PART C Module 02 – Cavitation in Hydroturbomachines

Draft Tube & Cavitation

$$\sigma = \frac{\left(\frac{P_a}{\gamma} - \frac{P_V}{\gamma} - H_S\right)}{H}$$

Cavitation will occur if σ is less than σ_{crit}. σ_{crit} is a function of specific speed/shape number.

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So does it not appear very similar to what we have discussed earlier? That NPSH available is greater than equal to NPSH required. You recollect that NPSH available is what a user knows what is available in the system and NPSHR is what the designer or manufacturer knows and what is not known to the user.

So we have a similar situation and we can club these terms to get the and we can define what is known as somas cavitation factor as PA by rho g, then gamma is nothing but rho g - PB by gamma or rho g, whatever you would like to say, - HS, whole divided by H. So cavitation will occur if Sigma is less than Sigma critical, just like we said that if NPSH is less than NPSH available, we say cavitation can occur. Then similarly we say that a cavitation will take place if Sigma is less than Sigma critical. And this Sigma critical is a function of specific speed or the shape number or the type of turbine.

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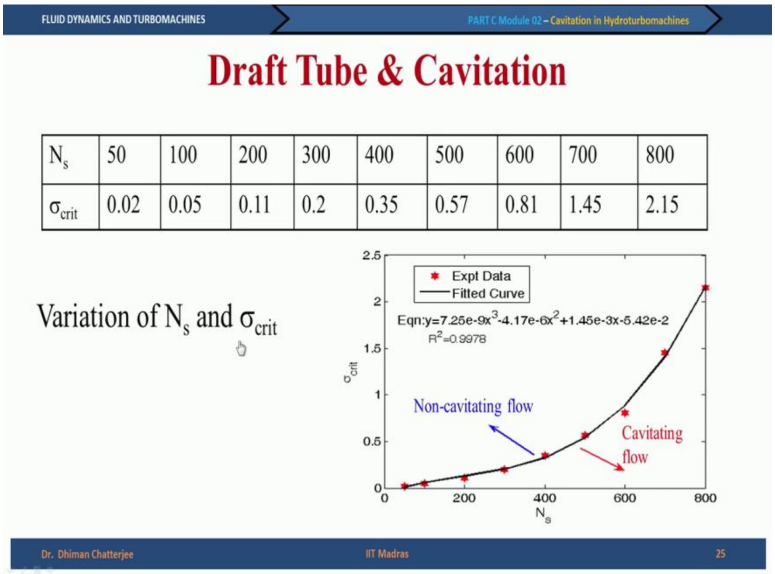

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PART C Module 02 – Cavitation in Hydroturbomachines

Draft Tube & Cavitation

N_s	50	100	200	300	400	500	600	700	800
σ_{crit}	0.02	0.05	0.11	0.2	0.35	0.57	0.81	1.45	2.15

Variation of N_s and σ_{crit}

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So this is a characteristic curve from the experimental data obtained. So you see that this x-axis is the specific speed of the turbine, so when we are talking about a Francis turbine, we are typically in the lower range of this NS, let us say up to 250, 300 at the most and we are talking about Kaplan turbine from the higher ups. And as we said that this is the line which is a critical cavitation numbers so that means if you have a cavitation value at the line above the critical cavitation number, then there is no cavitation. If you have cavitation number less than the critical cavitation number, you will get cavitation.

So you can see that from the design perspective the Kaplan turbine design will be more challenging because there is a more region which is more susceptible to cavitation. This same data is also given in the form of a table. Thus we can say that in order to avoid cavitation we have to respect the height of the turbine. When we discuss the tutorials and we give you some tutorials on this week 7, we will give you some problem for you to solve in cavitation involving draft tubes as well as pumps.

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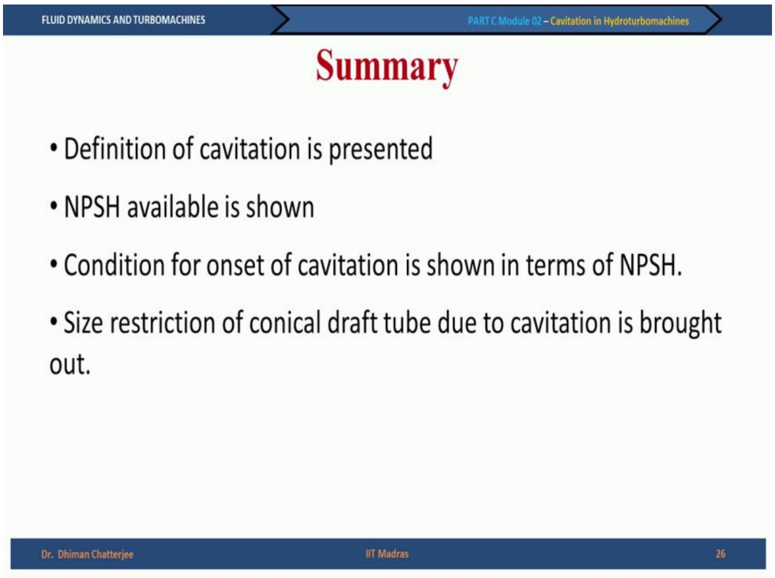

FLUID DYNAMICS AND TURBOMACHINES

PART C Module 02 – Cavitation in Hydroturbomachines

Summary

- Definition of cavitation is presented
- NPSH available is shown
- Condition for onset of cavitation is shown in terms of NPSH.
- Size restriction of conical draft tube due to cavitation is brought out.

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So to summarise, we have defined cavitation here, particularly we have distinguished cavitation from boiling, though both are essentially formation of bubble in liquid but the path of one through retardation, so increase of temperature and the path of the other is through pressure reduction, though at times there could be presence of temperature increase but that is not the essential criterion for cavitation to occur, pressure reduction is the essentials criterion. NPSH available is shown and we have talked about the condition for the N N onset of cavitation, that is NPSH available should be less than the NPSH required in order to cavitation to start.

Or in other words cavitation can be avoided if NPSH available a greater than equal to NPSH required. We have also talked about the size restriction of the conical draft tube in a reaction turbine due to cavitation. In the next lecture we will talk about the some of the problems that we can come across while handling pumps and turbines. We will do some numerical problems so that we can get familiarised with the theories and then we will conclude this week’s discussion on Hydro Turbo machines. Thank you.