Introduction to Fluid Mechanics and Fluid Engineering
Prof. Suman Chakraborty
Department of Mechanical Engineering
Indian Institute of Technology - Kharagpur

Lecture - 51
Introduction to Fluid Machines (Contd.)

We were discussing about some of the characteristics of performance of centrifugal pumps and now we will go ahead with that and see that what are the various losses that maybe incurred as the energy is flowing from the input to the output end.

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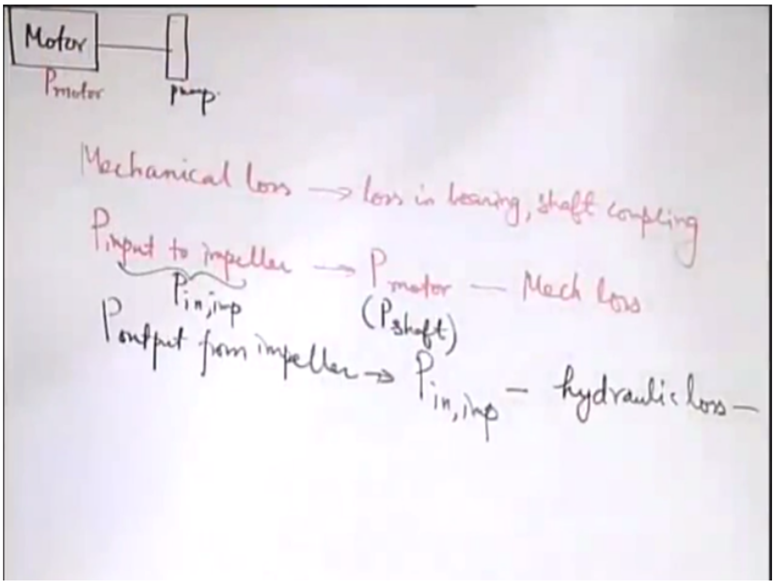

So if you recall that schematically we may consider that you have a motor which is the sort of driver for the pump. So there is a shaft and on this shaft is mounted the impeller of the pump, so you have this as the pump so to say just schematically we may call this as a pump and then there is some energy output from it. So let us just look into it in the form of the power or energy transfer.

So let us say that you have P motor as the output power that you are getting from the motor. Now this entire output power, which you are getting from the motor is not what you are getting as the power input to the pump. So some power that goes into the pump so in between there are some losses. So what are the important losses? So you could have some loss as the mechanical loss.

Mechanical loss is some loss in the bearing, coupling etc, loss in bearing, shaft coupling. So you know that the bearings are there to support the shafts and there are losses in the bearing and not only that. There are some mechanical losses in the shaft coupling. So there is a motor shaft and there is a shaft which is on which the impeller of the pump is mounted and there is a coupling between these 2 shafts.

And there is a loss of energy as energy is being transferred from one to the other. So that is one loss. So when you have this loss that means whatever energy is input to the pump or rather whatever energy is input to the impeller, so energy input to the impeller so power input to the impeller that is nothing but the whatever could be the power output from the motor– some losses.

So one of the losses is –mechanical loss. Power output from the motor that you are getting is the power available to the shaft of the motor shaft. So this may also be called as P shaft. There is an electrical conversion of course relationship between the motor input and output and that may be obtained from the characteristics of the motor that what would be that input output relationship.

But that not being a part of the pumping structure, we are not going into that part. So that is the characteristic of the motor itself. It does not directly fall in the purview of the energy transfer for the pump as the system. So this –the mechanical loss. Then what is this one? So this is the ideal power input, ideally this is the power input to the impeller. Now what is the power output from the impeller?

So let us give it a name P in impeller, so this is P in impeller-some loss. What are the losses? These are losses which take place within the impeller. So there are 2 types of losses and we will name this one by one. One is the hydraulic loss and another is a loss of volume of flow because of leakage of some fluid that we call as a leakage loss. These losses are taking place within the impeller. So the hydraulic loss is what we have looked into the reasons behind the hydraulic loss.

We were accounting for some of the reasons because of which the HQ characteristics of a pump deviate from the ideal one. So what were the reasons behind that, one was the shock at the entry, shock at inlet, another is the slip at the outlet and the third one is friction in the blade passage. Slip at the outlet is not just that affects the velocity triangle of the outlet but it has certain other significances.

So if you see consider the blade like this, so if it is having a slip then we have seen that basically it means that the exit velocity it increases, V2 increases because of slip. So actually there is reduction in pressure on this side of the blade to compensate for that and this side of the blade has a higher pressure and because of that there is some local circulation that is being created around the blade passage and this is one of the reasons behind the losses.

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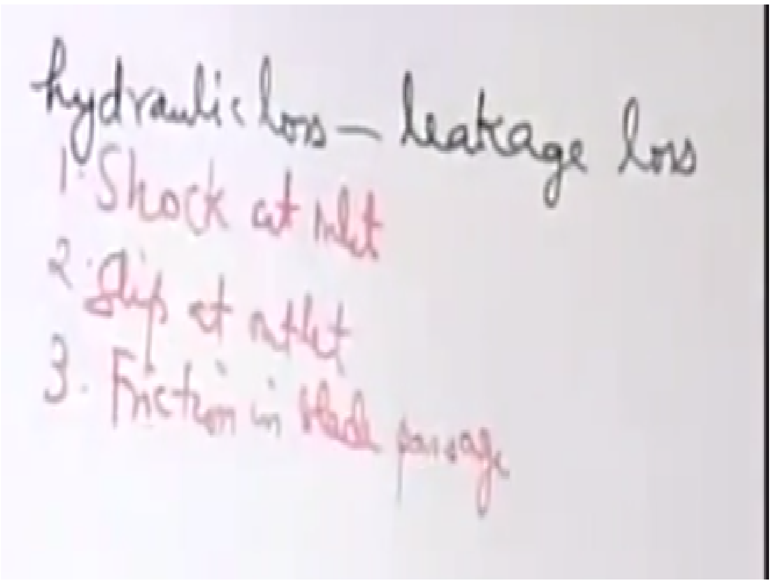

So these are basically hydraulic losses plus there also could be a leakage loss. So in terms of these losses we may determine the corresponding efficiencies. So if we say consider something called as hydraulic efficiency. So what is the hydraulic efficiency of a pump? So all the efficiencies consider certain losses, if there were no losses the corresponding efficiency would be 100%.

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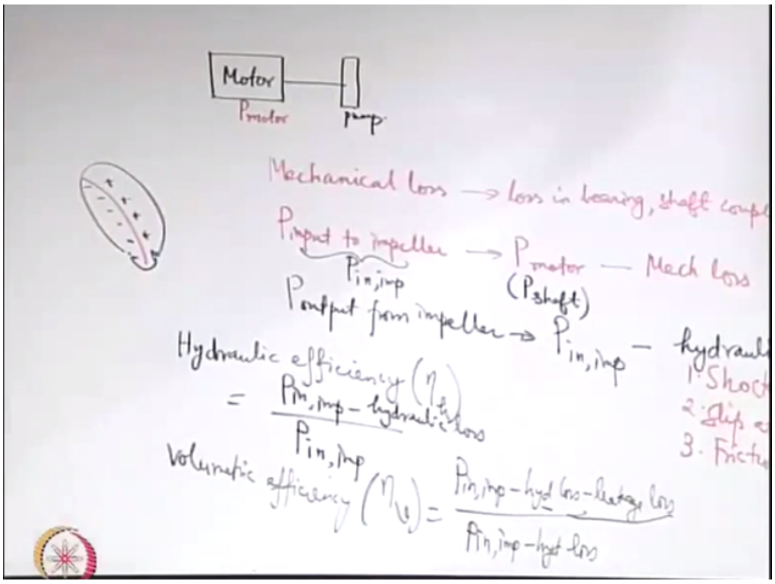

So hydraulic efficiency from the name it is obvious it will concentrate on the hydraulic losses. So it will be the power input to the impeller/power input to the impeller-the hydraulic loss. Then there is something called as volumetric efficiency. If there was no leakage loss then whatever is kept in the numerator of the hydraulic efficiency would have been the output but because of the leakage loss the output is different.

And therefore the volumetric efficiency is defined as power input to the impeller-hydraulic loss that is in the denominator. In the numerator, power input to the impeller-hydraulic loss-leakage loss. So it pinpoints the sole effect of the leakage loss. So there may be some leakage around the impeller passage. So that whatever is the net flow rate that is supplied to the pump the same rate flow rate is not the output.

If Q is the flow that is supplied may be Q-delta Q is the output. So there is some loss of flow because of leakage. Then mechanical efficiency let us say so what will be the mechanical efficiency? So what loss it should consider. So mechanical efficiency should consider this mechanical loss, which is not taking place in the impeller but it is taking place in this shaft like the mechanical losses.

The losses in the bearing shaft coupling etc. So the mechanical efficiency would be you have the shaft input power in the denominator and in the numerator shaft input power-mechanical loss and this is nothing but power input to the impeller that we have to keep in mind. What is the overall efficiency? Overall efficiency is like the net output/net input. So the net output is like whatever.

So this is the net output, this is the P output, input to the impeller–losses in the impeller. So tha tis the P output/P shaft, which is like the input to the system. P input=P shaft, so from these expressions you can clearly see that the overall efficiency is the product of the mechanical efficiency, the hydraulic efficiency and the volumetric efficiency.

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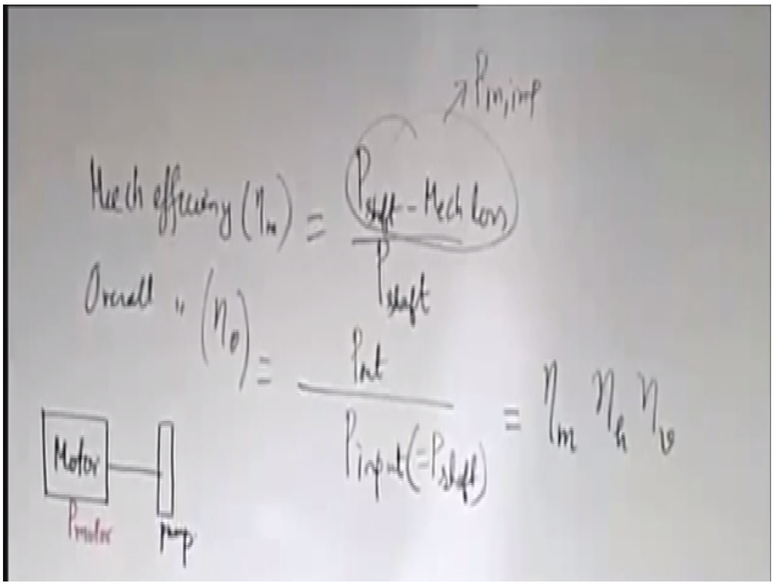

Just if you multiply these things will cancel, so it is quite obvious so the output at one stage is the input to the other. In that way if you consider each stage (()) (10:50) with certain losses right. Now if you plot the overall efficiency of the pump as a function of Q or maybe if you want to plot the power as the function of Q, let us try to make a plot of that and make certain observations out of that.

So if you say our plotting first of all let us plot a HQ curve which you have already seen so HQ curve is something like this. We are considering the backward curve bends for the reasons that we have already explained. If you consider the power versus Q let us say in the same graph with the different scale, we are plotting the power. So what do you expect that the power is nothing but like will it increase with Q or will it decrease with Q?

It should increase with Q so the power characteristic may be something like this. So now the efficiency let us say we want to plot the efficiency, the overall efficiency. Overall efficiency the power output is nothing but the head output*rho g*the output Q. So you can see that the power output and the denominator is sort of the power at the shafts say that is fixed. So the power output when you see you have H and Q.

So that to keep in mind that there is a sort of relationship between these that you have H as a decreasing one with Q as increasing. So this one if you consider the efficiency it will have a sort of a peak before it falls and this point is known as the design point or point of maximum efficiency. In reality, it would have been very nice if one could operate at that point but in reality it might not be possible to operate at that point. Why?

Because these characteristics are drawn forgetting about the system with which the pump is connected.

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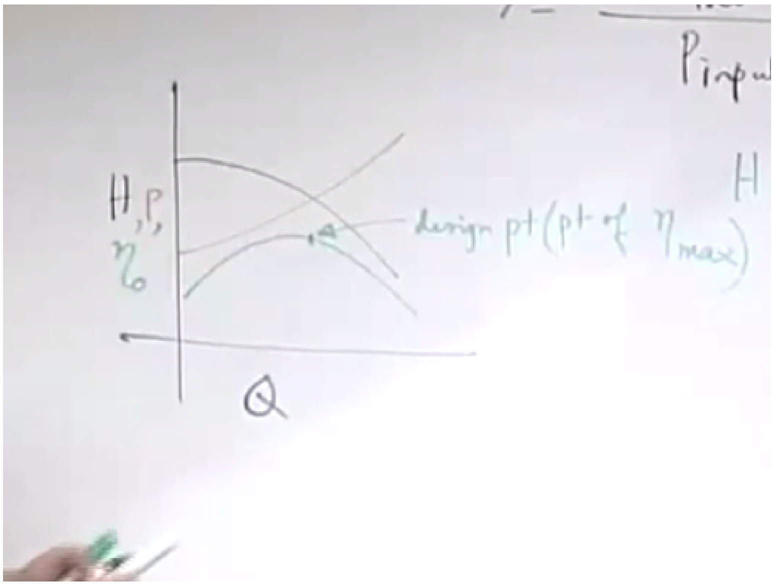

So it is drawn without considering that what are the piping and fittings and all those things which are there in the connecting system that connects from the sum to the supply reservoir. So the system has its own characteristics. What are the characteristic of the system? So if you see the system, so if you have a pump like this let us draw it schematically. Let us say that you have a pump that is having a supply to a reservoir.

So if you think the pump as the source of energy, so just try to understand it like overall picture. So to the system the pump is like a source of energy, which energizes the fluid. So what energy the pump should supply to the fluid? It should be sufficient first of all to have this static lift plus in the process overcome the losses in the pipe. So the head of the pump should be such that it should be the H lift plus some of the head losses in the pipe right.

Head losses in the pipe of course depend on many things for example whether it is a laminar flow or a turbulent flow. If it is a laminar flow it will be proportional to Q. If it is a highly turbulent flow where the friction factor is independent of Reynolds number, then it will be like for a particular surface roughness characteristic it is like a constant. Then it will be proportional to Q square.

So let us say that that is the case that means it is like as an example this is for a highly turbulent flow it is like KQ square of this form where K is some coefficient which will come from many considerations if there are fittings in the pipe line those losses will also come into the picture. So whatever head the pump is developing, the head should match with the head required from the system point of view.

So that this effect of the pump may be achieved, so then what will be that curve? So let us try to draw a system HQ characteristic. So system HQ characteristic you will see that it will increase with Q. So you have a system HQ characteristic maybe something like this. This is system HQ okay, so that is that equation H lift+KQ square. So you can see that what will be the operating point?

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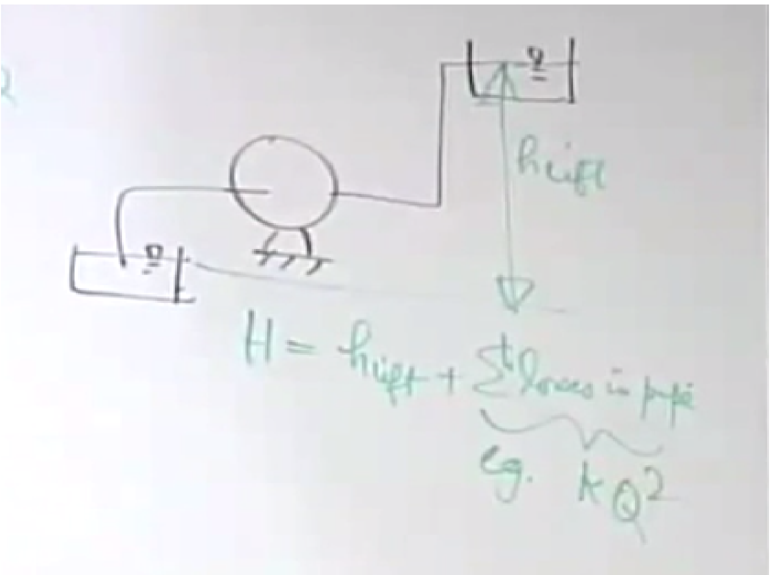

The operating point is the point where the head supplied by the pump is just good enough to achieve this lift and to overcome all the losses in the system. So that will be the point of intersection between the pump and the system characteristic right. So this will be the operating point and the operating point definitely is going to be different from the design point.

Very clever design may have operating point very close to the best efficiency point but it is in general impossible to maintain that and you will always have the operating point deviated or shifted from the maximum efficiency point. Now you also have to consider different types of losses and when you consider the losses you have to keep in mind that there are valves located at these locations.

Now let us say that you want to measure the heads at the suction and the delivery. So the question is that will you keep the suction gauge or the delivery gauge something like this or in the other side of the valve. Let us say this is the suction gauge, this is the delivery gauge. In our previous lecture, we did not bother about that so much but like when we are coming into the losses and all those things, it is important to see that which is the desirable one.

So can you follow my question the other thing is the alternative is this here to the right of the valve in place of that could it be placed in the left of the valve. Here this s is put in the left of this valve could it be possible to put it in the right of the valve. So relative location between the gauge and the wall that is the important concern. If you put it in this side what is the difference?

"Professor - student conversation starts." So when you are writing the head developed by the pump as the difference in head between the d and s. In that expression, we did not account for any loss in the valve right. Therefore, this should be put in other way. There is nothing wrong if you put it in this way fundamentally provided then you consider the losses in these valves into account. **"Professor - student conversation ends."**

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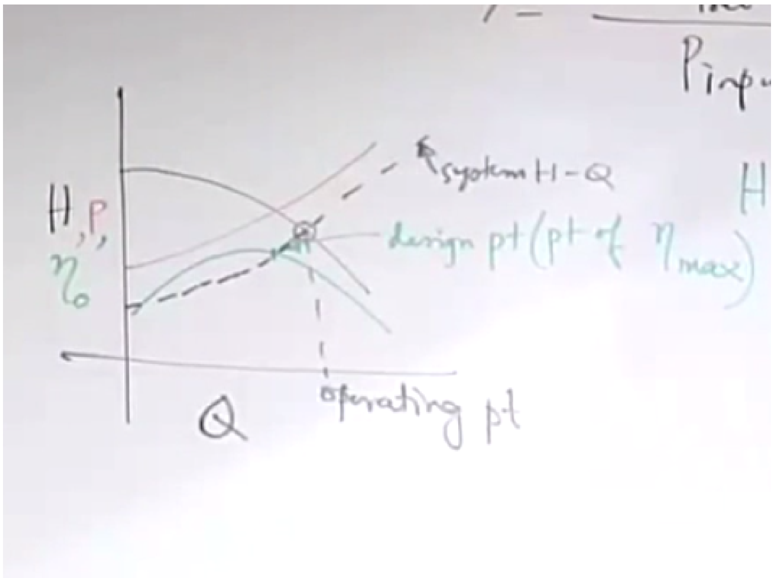

So it depends on like what you account for when you write the head but when we consider the head what we would always like to consider is that something which is solely the difference is being created by the pump and so if you consider for example on this side then whatever is the head between this say this new s point and new d point that is solely attributed to the head developed by the pump.

Otherwise if you consider this in the other side, these losses in the suction and delivery valve have to be taken into account and if you want to avoid that it is better to put in the other way then what it is shown in the figure. So we have got a clear idea of the design point the system characteristics and the pump characteristics and how to get a design point as the point of intersection between the system and the pump characteristics.

Now we will look into some other types of pumps. So before looking into that we will keep in mind that the pump that we have discussed so far has a centrifugal effect but more importantly we have considered that the flow is virtually radial and that is why those are also called as radial flow type of pumps.

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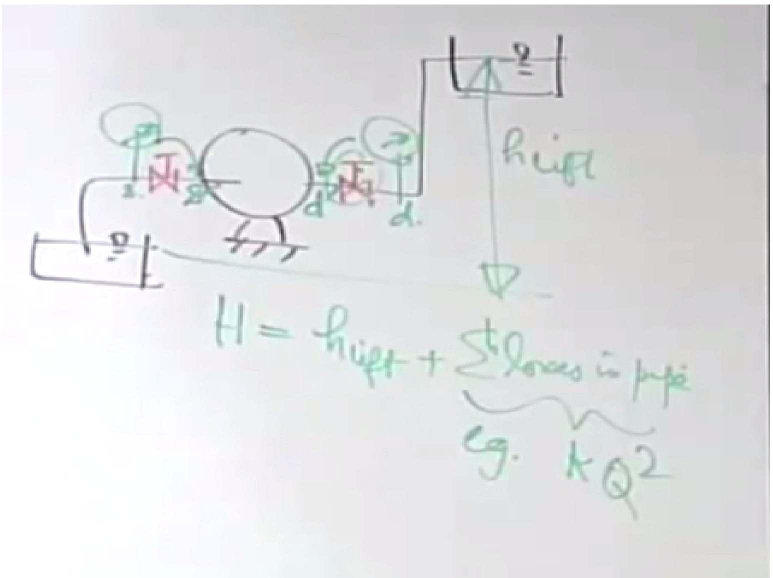

But in general you may have not only radial flow type of pumps but you may also have axial flow type of pumps. What are the axial flow type of pumps? So let us look into axial flow pumps. Axial flow pumps are like propellers and before drawing any sketch in the board maybe let us try to look into some more constructed schematic which will give some idea on this.

So if you look into the radial flow or the centrifugal pump, so this is what we have studied so far. Just try to develop a 3-dimensional qualitative understanding of how the impeller of the pump will look, which is the left hand side picture and the details of the volute casings and all those things, which we have discussed about their importance that is there in the right side.

Now come to our axial flow pump, see axial flow pumps are like propellers so to say. So basically there is something which is rotating with respect to an axis and there are blades which are located on the top of that rotor and these blades if you look into the left hand side picture, it is a sort of a twisted structure. You see that it is not a sort of very regular structure and there are designs that go behind these blades.

Let us not give too much of an emphasize of what should be the design consideration of this blades but these visuals are just to give you an idea of how the fluid flow is taking place across these pumps and if you look into this figure you will see you will look into the direction of the arrows which are given in the right hand side picture, it will give you an idea that now the fluid is flowing coaxial to the rotation of the rotor okay.

And that is why it is called as axial flow pump. So it is now flowing in a direction which is like sort of in a gap in the blade passage between the hub and the tip and it is flowing in that in the axial direction. So now we will try to have a sort of schematic description of that one and we will try to draw velocity triangles for the inlet and the outlet in a similar way as we did for the radial flow pumps.

So let us say that you have sort of stator and so this is just to give the structure of a shaft and then there is a coupling between this one and the shaft of the propeller. So it is somewhat like this and the fluid flow is taking place in the axial direction and there is a rotation with respect to this axis. That is what is the broad picture. So here so we have to first keep in mind see the best way in which you learn different hydraulic machines is by drawing analogy with the first thing that you have learnt.

The first thing we have learnt is a centrifugal pump, so let us try to see that if you want to draw velocity triangles for this case how you can draw analogies. One way you can draw analogy is like this. For the radial flow centrifugal pump what were the directions which were important? So if you use the coordinates then r and theta directions were important. Here you feel what directions should be important?

"Professor - student conversation starts." The z direction will be important. No, see this is rotating like this. So you have a tangential component of the velocity on the top of that there is an axial component.

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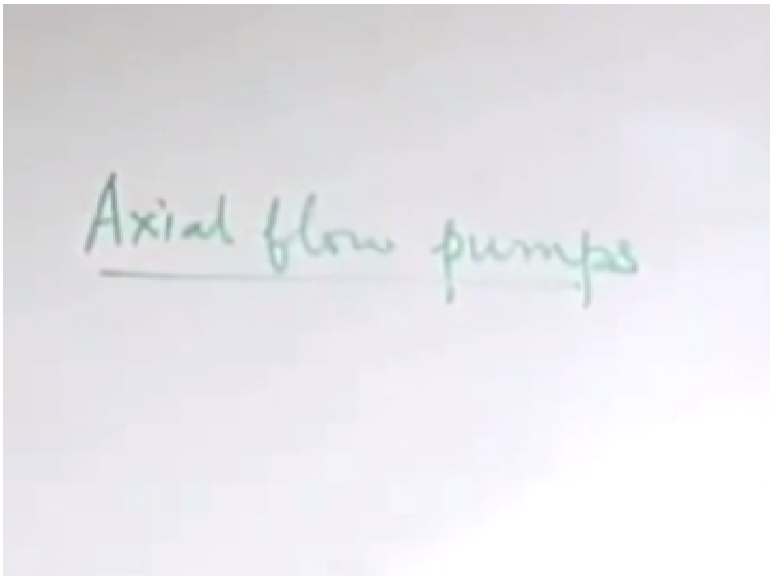

So it is the z component and the theta component, these are important. So these are certain things which we have to visualize from the description. So think that it is rotating so that tangential component is theta on the top of that you have an axial component and the resultant flow is the resultant of that one. So if you want to draw a sort of like a velocity triangle in the blade passage, the blade is typically something like this.

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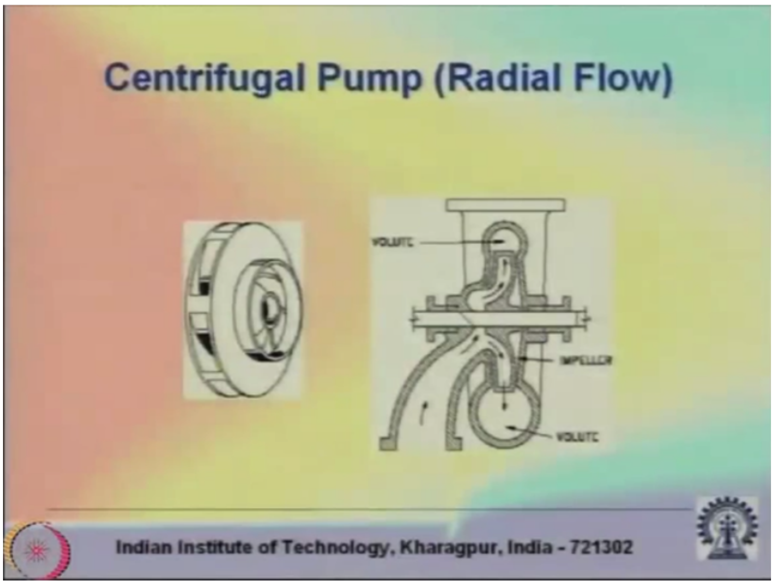

It will remind you of the aero foil section that we discussed about in a couple of chapters back. So if you consider that there is a z component say vz1, say this is 1 and this is 2. Then you have a u1 then you have a w1, so that the resultant is vz1 which is=v1.

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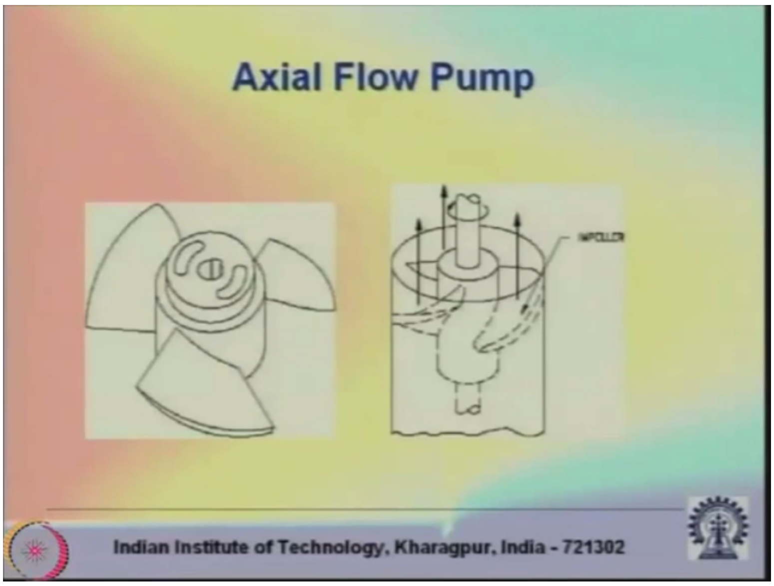

That means at the inlet the resultant flow is in the axial direction, this is like beta 1 the blade angle and this is alpha 1 which we have taken as 90 degree. Just try to draw an analogy replace the r direction by the z direction of what you have learnt in the radial flow centrifugal pump. It is very, very analogous. Now when you come to the outlet, so you have this as u2, u1 and u2 are the same because we are drawing the velocity triangle say 1 and 2 at the same radial location with respect to the center.

So when you are drawing at the same radial location u is like omega*that radius. The angular velocity is the same and the radius at 1 and 2 because they are at the same radial height from the axis, they are the same so you have u2=u1 which is omega*the corresponding radius at which we are drawing it. So this on the top of that you have a w2 and you have a v2. This angle is beta 2 and this angle is alpha 2.

And the axial component of this is vz2, which is same as vz1=v1. Why? Because you are having a flow rate. What is your vz? Let us again do not consider the velocity profile because of viscous effects and all those things. So if you just consider some average velocity that is the flow rate/area over which it is flowing.

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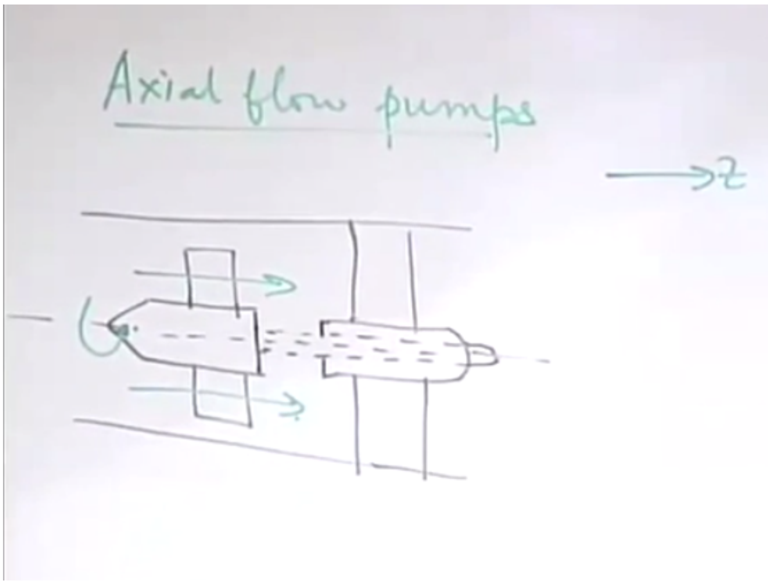

What is that? This is pi/4 diameter of the tip square-diameter of the hub square. So this is the hub and this is the tip okay. So in this passage there are blades and the fluid is flowing. So then this one see the diameters of the tips and hubs are not changing as you are going from from the inlet section to the outlet section. The flow rate is also not changing, so you expect vz also to be the same.

That is why vz1 is same as vz2 and since at one the entire direction of the flow is axial therefore that is=v1 and what is the head developed by this pump? It is same as u2 v theta 2-u1 v theta 1/g the same thing that because the fundamental principle is again the same the change in angular moment and the torque and the power I mean the only thing is that in place of the radial direction of the axial direction has become important.

But at the end you will come up with the same expression and you have v theta 1 as 0 in fact that was the purpose of making alpha 1=90 degree. So that you get the maximum head. Now let us try to look into this that what happens or what are the important relationships between the flow rate and the head? That is is such a machine having a high flow rate or low flow rate?

Is it going to have a high head or a low head? First of all, the inlet area of these types of machines is not restricted. If you consider in place this a radial flow machine, the inlet area is restricted because the inlet diameter is small, the outlet diameter is large and whatever is the inlet flow the same flow will go out because the inlet area is restricted you may only have limited flow.

So one thing we can conclude that if you compare a radial flow machine with this axial flow machine here you expect the flow rate to be higher than that of a radial flow machine. Now let us consider that what should be the corresponding head. So now if you consider this v theta 2, so v theta 2 you can write as u2 what is v theta 2? The v theta 2 is this one.

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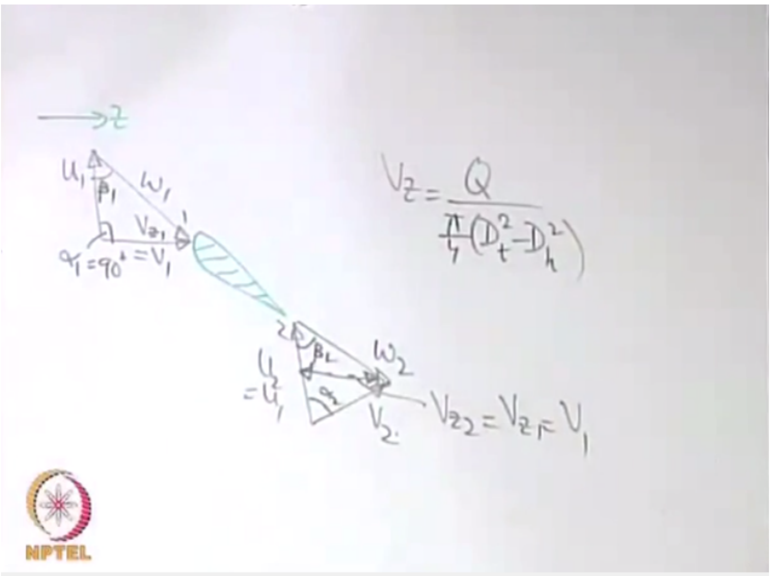

So that is=u2-vz2 cot beta 2 right. This angle is 90 degree so you can clearly write it from the trigonometry and vz2 is like you have this as same as Q/pi/4 d tip square-d hub square okay. So that means how will the power depend on beta 2? So if you increase beta 2 what will happen cot beta 2 will increase or decrease. It will decrease and therefore we expect that the head should be more. So you will have a temptation of increasing beta 2.

In reality, you cannot do that, we have discussed about this why, just think about it, think that you have aero foil section, you have the angle of the blade dot well oriented with the direction of the flow but it is getting more and more deviated from the direction of the flow as you increase beta so that means so this is related to the angle of attack that we have seen for a aerofoil section so more or the higher value of this angle you make, it will come to a state when there will be a very easy flow separation.

And that is known as stalling of aerofoil right. So increase of this is limited by the stalling effect and you cannot increase it indiscriminately to a great extent. That is why you cannot have a very high head in a axial flow machine that is limited by the possibility of increasing it in a way that at least it should avoid stalling, it should not be increased indiscriminately. So that means these devices will operate on high Q but low head.

Remember the expression for the specific speed N root Q/H to the power 3/4 for a pump. So if you have a high flow rate and low head that will mean a high specific speed that is why the specific speeds of axial flow pumps are much higher than those for the radial flow pumps. So from the specific speed you may select the type of the pump even.

If you are having to deal with the certain range of specific speed which is the highest of all possible pumps, then your choice must be axial flow pumps. Your choice cannot be radial flow pumps because of the limits in the Q and H. There is some type of pump which is in between the axial flow and the radial flow and the name itself is like that it is called as a mixed flow pump.

So in the mixed flow pump a part of the flow is axial and the part of the flow is radial. So if you have a mixed flow pump that means you have just I am drawing it very, very schematically, do not think that the mixed flow pump will actually will be like this but the whole idea is that if you consider the incipient flow now if you consider the change in direction of the flow it is neither radial nor axial.

And therefore it will have a sort of in between characteristic between the radial flow and the axial flow. So typically the radial flow pumps will have specific speed say between maybe 10 to 50.

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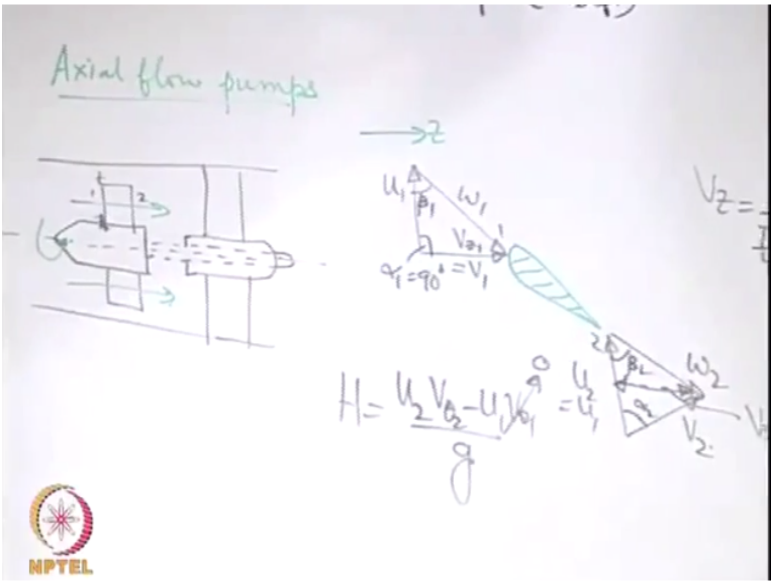

See do not take these as very figures with great sanctity, these are just rough ideas. If you consider an axial flow pump maybe it specific speed will be in the range of maybe 300 to 500 just as an example and so or may be 150 to 300 as just beyond 300 is not too common say 150 to 300, this is we are talking about typical specific speeds and the types of pump, so this is axial, this is radial and mixed flow is something in between say roughly between 50 to 150 like that.

Again these are very rough figures for the specific speeds the units have been put here according to the units that we have mentioned and then these are of course actually this is not dimensionless but the corresponding number by putting those units whatever you get that is coated. So that is one important thing, important thing is not to just be very, very particular about the specific values.

But to understand that if you go for higher and higher specific speeds, it is the axial flow pump that is the characteristics that is going to be more common to that feature or behavior. Now the next thing that we will discuss is that some very important phenomena known as cavitation in a hydraulic machine and as an example since we started with the centrifugal pumps, we will try to understand how cavitation occurs in a centrifugal pumps.

So first of all we will try to understand what is the cavitation and then we will try to characterize it. So cavitation in hydraulic machines in general.

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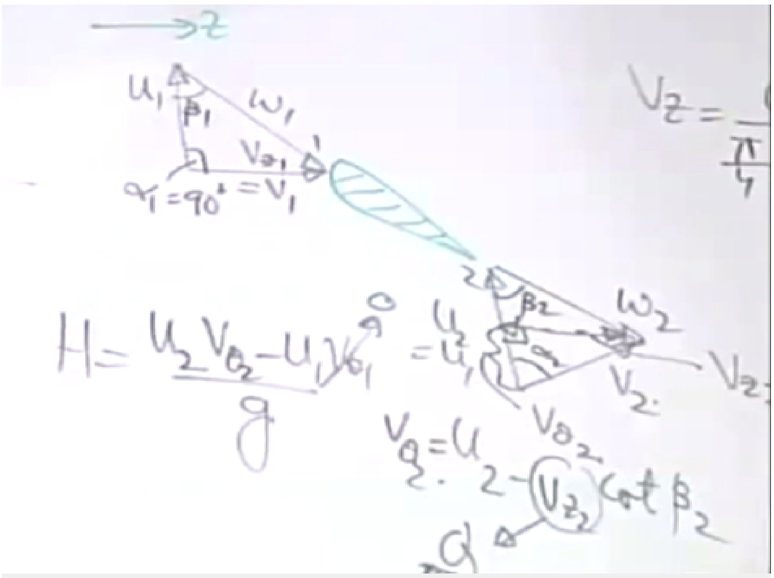

So what is cavitation say you have a hydraulic machine in which at some point the pressure falls below the vapour pressure at the prevailing temperature. Say the machine is handling liquid water, at a given point the pressure becomes low it becomes low enough such that it is less than the corresponding vapour pressure. Vapour pressure is a function of the temperature that is there.

So for a particular temperature you will have a particular vapour pressure. Let us say that the pressure is below the vapour pressure. Then what will happen? Bubbles will be formed. When these bubbles are formed now see these devices are having the flow, so when bubbles are formed these bubbles will move from one place to the other place because of the flow. So with the flow these bubbles are likely to move to a place where the pressure is higher.

And if the bubbles now move to a place where the pressure is higher what will happen? Say the bubble is again getting collapsed. So once the bubble gets collapsed the bubbles were occupying greater volumes because of the formation of the vapour phase. When the bubbles are getting collapsed, then you have having a sort of void that is being created because of the collapse of the bubbles.

Then what will happen, liquid particles or liquid molecules from all sides will try to rush into that space to fill up that void and because of strong collision between those molecules, there will be an extremely large increase of pressure, so that increase of pressure in a typical hydraulic machine if it is not designed properly may be say of the order of 400 megapascal also, it may be as high as that.

This pressure is think how high it is, one atmosphere is roughly 100 kilopascal and this is like 400 megapascal. So it is such a high pressure, it may not last for a long time and its range of operation, it may not be wide but it has its detrimental consequences. What are that? See there is a time scale over which these bubbles are formed and these bubbles are collapsed and accordingly the blades of the fluid machine maybe subjected to a fluctuating pressure.

So because of the fluctuating pressure there may be a failure of the blades and that is known as fatigue failure in design. So one is that there may be a fluctuating force on the blades and the blades themselves may fail to operate.

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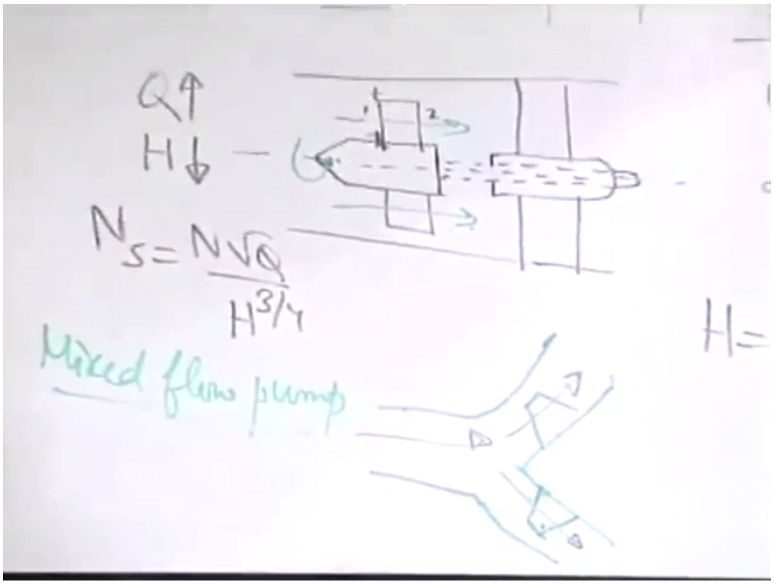

Sometimes the failure is so obvious that this pressure is good enough to take away some material out of the blade. So the blade loses some material this is known as cavitation pitting and so it gives a sort of spongy appearance so because of dislodging of some of the parts of the material from the blade. So that is one of the very detrimental consequences. Not only that there is a lot of vibration and noise that is being created.

So because of this time dependent phenomena there is likely to be a lot of vibration and because of this vibration there may be some instability in the system. There is lot of noise also and if this phenomenon is very, very serious the noise is as if gravels or passing through fluid. So it is such a high noise and the noise maybe of varying frequency like typically small size bubbles will be associated with large frequency noise.

And large size bubbles will be associated with lower frequency noise. So depending on the size distribution of bubbles you may have large wide range of frequency spectrum over which this noise is emitted. So because of this noise vibration and physical loss of material from the blade it is not at all a desirable feature in a hydraulic machine and what is that which has created this? It is not just the formation of bubbles.

If the bubbles are just formed, it is okay but bubbles are going to a place where the pressure is>the vapour pressure and therefore the bubbles have collapsed. So simultaneous formation and collapse of bubbles because of the change in pressure. That is what is the sole reasoning behind this type of like problem in the machine. So we have to understand this is known as cavitation.

So it is not just the inception of bubbles, it is not just the nucleation of bubbles but the subsequent collapse because of migrating to a higher pressure region that give rise to these phenomena. So what is the big origin of this phenomenon? The big origin of this phenomenon is formation of regions of low pressure because if the pressure falls below the vapour pressure then only the bubbles may be formed.

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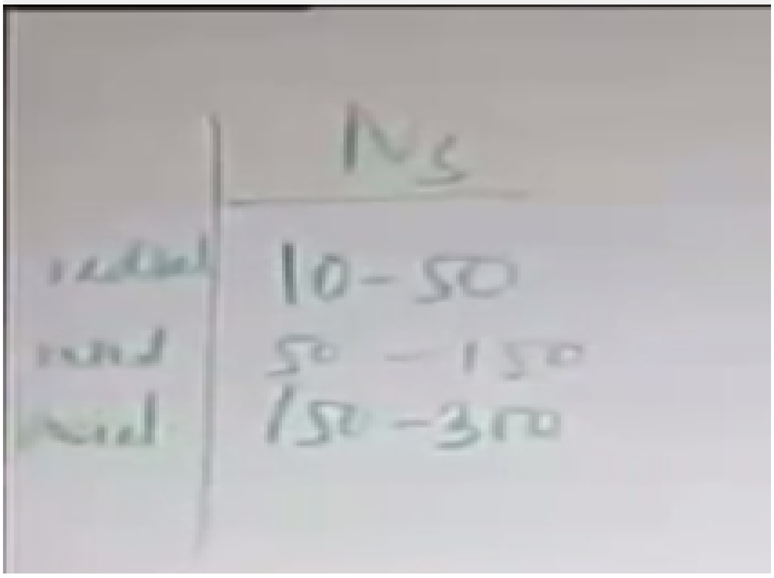

So we have to see that what portions of the devices or what portions of the machines are prone to such very low pressures. So let us take an example of a centrifugal pump. So let us say that this is the schematic of the suction side. So we are not going into the other side but let us just concentrate on a suction side. So this is 1 and let us say this is the point S, so if you apply the energy equation you have p1/rho g+v1 square/2g.

Let us call this height as Hs=Ps/rho g+vs square by 2g+Hs+Hsf. So if you recall that this is small and this is 0 as gauge that means one atmospheric pressure. So what is Ps/rho g? This is –of vs square/2g+Hs+Hsf okay. So we have to keep in mind here that we are talking about the pressure at the point s the possibility of being it very low. See we can clearly see that it is a suction pressure or a negative pressure below atmospheric pressure if you consider this some to be located below the axis of the pump that is in this Hs itself is positive.

Because Hsf is always positive it is a loss, vs square/2g is always positive, Hs may be positive or negative depending on whether this supplied reservoir is placed below the axis of the pump or above the axis of the pump. In some cases, to avoid the strong negativity of this, this supplied reservoir is put above the axis of the pump and in many industries classical example is if you have a condensate extraction pump or may be boiler feet pump in a steam power plant.

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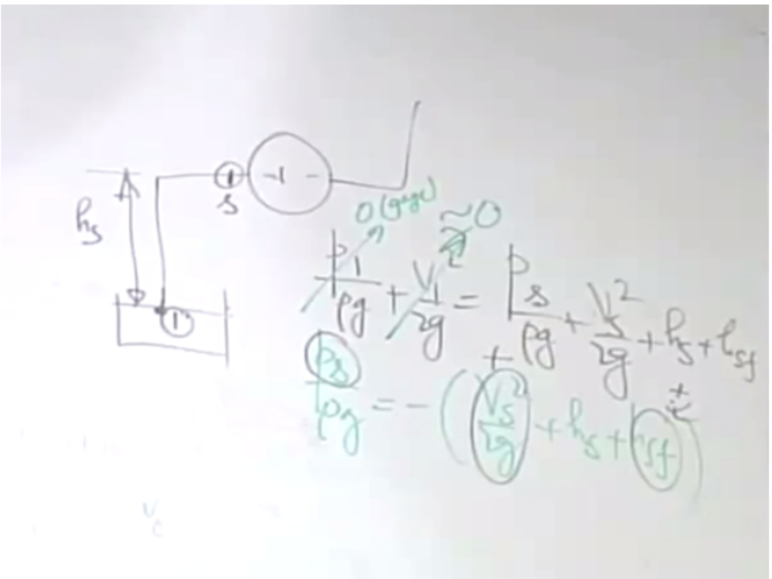

Now one has to keep in mind here that like no matter whatever is the Hs positive or negative, this is the location which is prone to very low pressure. So we have to put a lot of attention on this one and we can infer that if the pressure at this point is<the corresponding vapour pressure then you may have a cavitation. So we may consider that a safety margin. What is that? Ps/rho g-P vapour/rho g. We are talking about head so we are dividing it by rho g.

Typically, in symbolic terms we write rho g by a symbol gamma which is the specific weight. So if this is positive that means more and more positive this is that means more and more safe it is to avoid cavitation. In practice, what is done is a safety margin is defined where you also add a vs square/2g with this one. Because what helps you to have a positive head at the suction is the kinetic energy.

So this is given as a terminology of NPSH or net positive suction head. Net positive suction head is given by Ps/gamma+vs square/2g-P vapour/gamma. Now what is this? This is the expectation from the pump side that is the pump expects that this net positive head of this amount should be there, this should be first positive. So this is like net positive head.

This is physically an indicator of the net positive head over and above the vapour pressure head that is there at the suction that is the physical meaning of it but more importantly see this does not in this particular form when you write this you would say that you have a suction pressure, you have a vapour pressure and you do not have any relation of this equation or this expression with what happens in the system where the pump is there.

So this is the demand of a positive suction head from the pump. So pump expects this net positive suction head. So this is also known as NPSH required. What is the net positive suction head that is available? it depends on the system in which the pump is located. So let us try to relate this with what happens in the system. So in the system see you can write so let us consider this equation.

So if you write it for the system then just let us write one more step you have Ps/rho g+vs square/2g. Now let us just not write it as a gauge pressure, so this in place of writing this as 0 gauge let us write it as P atmosphere/rho g because we want to write an expression which should not be dependent on the way there is a gauge pressure or an absolute pressure. So let us write the pressure properly without considering it as a gauge reference.

So then this expression you from this what you can write Ps/rho g+vs square/2g-p atmosphere/rho g=what? -Hs-Hsf right. So what we want is Ps/gamma+vs square/2g-P vapour/gamma. So Ps/gamma+vs square/2g is P atmosphere/gamma-Hs-Hsf. So this becomes P atmosphere/gamma-P vapour/gamma-Hs-Hsf from this expression okay. So when you write this see the same expression we are writing.

Here we have focused on what is the requirement of the pump, here we are focusing on what you get from the system because now here you have Hs and Hsf, which are dependent on the system characteristic, so what is that part of this lift and what is the head loss at this section? So this we call as NPSH available that is looking it in form of a requirement demand supply situation.

This is what is the NPSH that is demanded by the pump. This is the NPSH that the system gives to the pump that is available to the pump from the system and if whatever is available is>whatever is required then it will be a cavitation free operation. So we can say that for cavitation free operation, you have NPSH available > NPSH required. That means the system must be good enough to give sufficient amount of net positive suction head.

So that it is more than what is required by the pump. So if you make a sketch of this NPSH versus Q or the flow rate, let us say we make a graph of NPSH versus Q. So first of all let us make a plot of NPSH required versus Q. So NPSH required will it increase with Q or decrease with Q? See if you have a higher Q you have higher vs, so that means NPSH required will increase with Q.

So NPSH required will be something like this. NPSH available will it increase with Q or will it decrease with Q. What is the key here? The key is this head loss term. Head loss will increase with Q and it is a –of the head loss therefore NPSH available will decrease with Q. so NPSH available will be somewhat like this.

So you can clearly see that there is a point of intersection, to the right of it you have NPSH required is more than NPSH available that means the system is not able to supply NPSH and therefore this will indicate a cavitation and if NPSH available is more than NPSH required that will indicate that it is a cavitation free operation. So this is sort of cavitation free. When a cavitation has occurred it may be important to have plots of certain characteristics, one is the efficiency.

Say efficiency of the fluid machine, so before that we have to see that there is a very important parameter which is considered to be a cavitation parameter, which in a non-dimensional way determines the extent of the cavitation or the occurrence of the cavitation that is given by a parameter known as Thomas cavitation parameter. This is a non-dimensional form of NPSH available. So it is a NPSH available/total head of the pump.

So if you have sigma > a critical value sigma c then we have a cavitation free operation. Why it is so? Qualitatively understand sigma c is the critical cavitation parameter, sigma>sigma c is as good as NPSH available > threshold value.

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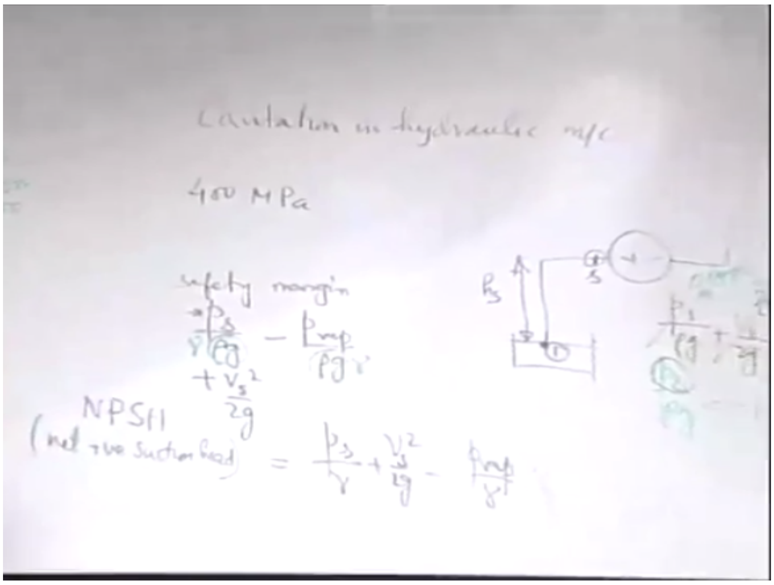

So it is at the end qualitatively saying that NPSH available should be>a threshold value. So that it is always more than NPSH required to overcome cavitation or to avoid cavitation. So if you plot eta versus sigma, eta is the efficiency of the pump. You will have a sort of behavior like this which is typically obtained from experiments. It is like this, so what are the typical features of this graph.

So this is typically the sigma c the critical cavitation parameter. So if sigma is>sigma c, it is not disturbing the efficiency. Now a very interesting thing occurs when sigma just falls<sigma c. So here what happens first bubbles are formed, so when the bubbles are formed these bubbles formed are very nice blanket on the blade. So the blade friction decreases because of that. That is why there is a momentary increase in efficiency.

You can see, so it is not just the cavitation has occurred and therefore it is a reduction in efficiency. So there is an initial inception of bubbles, the bubble layer is now forming as a blanket on the blade, so it is reducing the blade friction but with more and more deviation from sigma c obviously one can see that these bubbles are now all around in the flow and they are creating the catastrophe of cavitation.

And that is why the efficiency is dropping sharply as sigma falls significantly below sigma c. All this results one may also plot in terms of say sigma c versus the specific speed because one may relate the sigma with the specific speed. So if you have this one then the typically this graph is divided into 3 regions, one is a dangerous region, this is a sort of doubtful region and this is a sort of safe region.

Now can you tell that for a system to avoid cavitation sigma c should be less or more? Sigma c it should be less because the sigma has a greater chance of becoming more than sigma c right. So you can see that the safe region is the sigma c.

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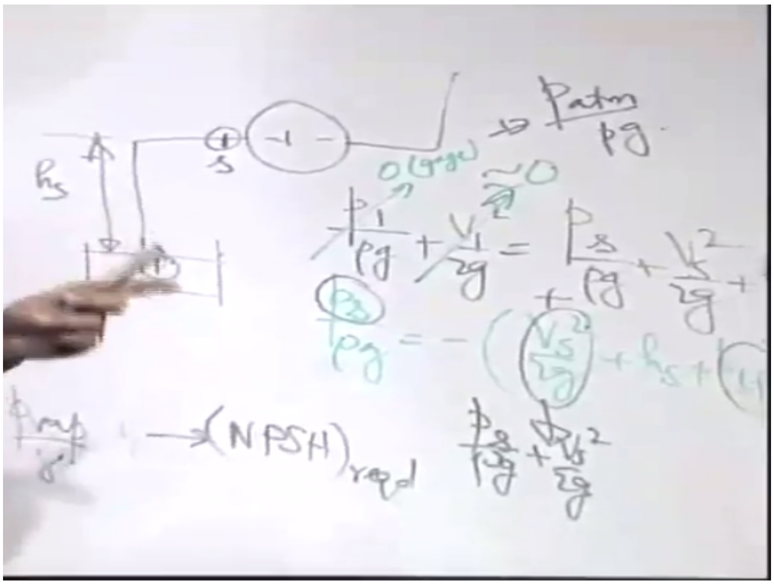

So if you consider that sigma is > sigma c then it is sort of like so if you now see here as you increase the specific speed what happens? As you increase the specific speed, the sigma c increases right. That means the chance of sigma to be more than sigma c will be less and less and that is why you cannot indiscriminately increase the specific speed to have a design of the pump.

So we have not talked about a pump with a specific speed of 1000, 2000, 10,000 like that because such specific speed might have a very high discharge. In some way it is good but with a higher specific speed you will have a higher value of sigma c to be in a safe region and then there will be a less chance of sigma becoming>sigma c and that will have more cavitation prone situation okay.

So these are some of the practical considerations that go behind the design of a pump. In the next class, we will be working out some examples or problems on the features of the centrifugal pump that we have discussed before we move on to the turbines. Thank you.