Fundamental of Fluid Mechanics for Chemical and Biomedical Engineers
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Lecture: 43
Cavitation and NPSH

Hello, So, in this module we have been talking about pipe flow. We talked about for the pipe flow, the losses major losses and minor losses. So, when we want flow to happen continuously in long pipelines, the head losses or the energy losses that occur because of major and minor losses, we need to provide energy to the fluid. So, that the fluid can be flowing continuously at the given flow rate and for that, we need pumps.

Sometimes it may be sufficient that the gravitational head can be provided by the higher elevation of the supply side, one might get the enough energy because of the elevation, but in most of the cases we require the pumps. So, in today's lecture, we will be looking at briefly the calculations in pipe flow which are relevant to the pump. Though the pump itself is a topic and it can be a different module, but looking at the course structure, we will be just briefly describing what pumps are and what is the pump head and other relevant things.

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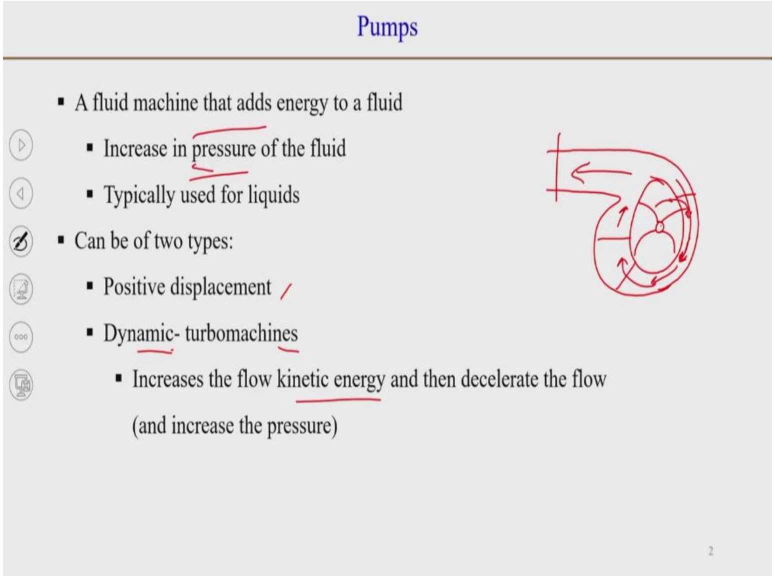

So, to start with pump is basically a fluid machine that adds energy to a fluid. You have another counterpart of pumps what is called turbine. So, there the useful work can be extracted from the fluid, but we will restrict ourselves up to pumps. So, pumps are what add energy to the fluid and that addition in energy comes with increase in pressure of the fluid. The flow rate at the inlet and outlet of the pump side will be same, there will be change in energy or the change in the velocity of the fluid but then that will come back to the original velocity.

So, if we look at the pump inlet and outlet what will change dominantly or predominantly is the pressure at the suction side and discharge side of the pump. They are typically pumps, the term pump is used for liquids and when we use the fluid machine to increase the energy of a gas then we may call it fan, blower or compressor depending on the pressure head and flow rate requirements.

So, the calculations that we discuss here, some of those calculations are of course, valid for gases when we talk about say NPSH that is specific to liquids only, but the pump head calculation and the useful work calculation they are valid for gases or fans, blowers, compressors etcetera as well. Now, the pumps can be categorized in two major categories. So, one is what is called positive displacement pump and another is dynamic pump or what is part of turbo machines.

So, positive displacement pumps are what we see, say for example, cycle pump that we use or the hand pump in various places we see to extract water from ground, they work on the principle that there is a volume of a chamber and when the chamber expands it takes water from one side and then it its volume decreases and the fluid is pushed along. So, there can be different mechanisms for it.

One example is where you have a peristaltic pump for that matter heart is also a positive displacement pump. What we will be talking about here in general is what is called dynamic pump and specifically centrifugal pump which we use say in our day-to-day life for increasing the head of water. So, in the centrifugal pump, basically what you have is. So, in the centrifugal pump the fluid will enter from here and then you have impellers here, impeller blades so, and it will be connected with a rod.

So, the fluid comes in and then it is provided energy because it is rotating and then the fluid goes through this vein, and then it adjusts from here. So, when it comes in contact with the impeller and because impeller is rotating with a certain speed or certain angular speed, so the impeller provides kinetic energy to the fluid. So, the velocity and the kinetic energy of the fluid is increased and then in this passage, as you can see the area is increasing, so the fluid starts decelerating and when the fluid decelerates the velocity decreases and its pressure increases.

So, eventually when it comes out the velocity of the fluid is the same at which it entered if the inlet and outlet cross-sectional area are same or at least the flow rate of the fluid is same at the inlet and outlet because fluid is liquid which is incompressible. So, the flow rate has to remain same. Now, the fluid when it exits, the flow rate is same, but the pressure would have increased.

So, what happens that the kinetic energy is imparted to the fluid by the impeller and this kinetic energy is converted to pressure energy when the by decelerating the fluid. So, that is the basic principle how this say dynamic pumps or centrifugal pump work.

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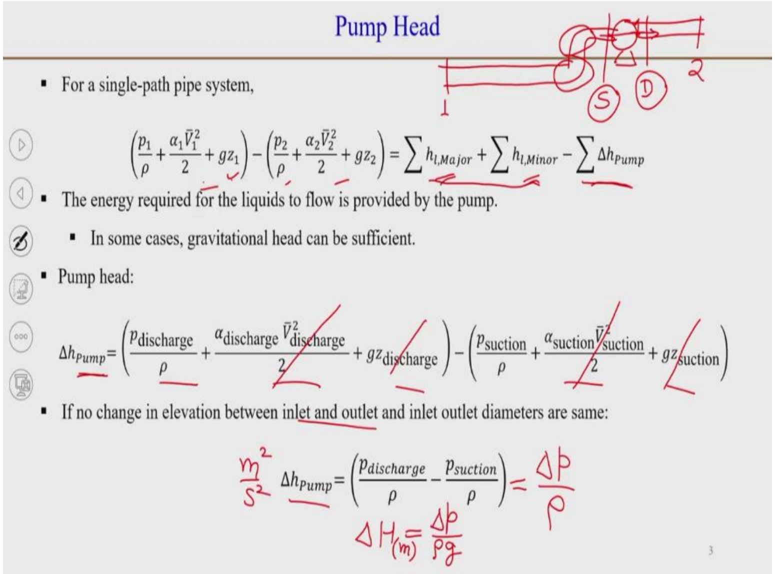

Now, let us get back to the equation that we have been talking about for pipe flow we have, let us say if you have a pipeline. So, you have some bends where there are minor losses and then the energy pump and the fluid goes out. So, from point 1 to point 2 flow is happening, so you can say that the mechanical energy at point 1 minus mechanical energy at point 2 will be the total major losses in this pipeline plus total minor losses.

For example, minor loss here and here and other minor losses if they are present and a minus Δh which is the pump head. Now, for this pump, you can have the suction side where the flow is entering into the pump and you have the discharge side where the flow is going out of the pump. So, you can see here that if the fluid energy is to be kept constant, if the fluid energy at point 1, a mechanical energy of the fluid point 1 and point 2 if it is to be same, then whatever losses has happened, they have to be compensated or that much energy to the fluid needs to be provided by the pump.

So, that is the function of pump. In some cases, as I said earlier that the gravitational head might be sufficient. So, g Δ z can be sufficient to provide for the losses. Now, if we look at the just the pump itself, so if we take our two points at suction and discharge side, then we can write down this equation when there is suction and discharge only then what you will have is there is no major losses no minor losses it will be Δ h pump and that will be discharge minus suction because there is a minus.

So, you will have 2 - 1. So, Δ h pump is equal to mechanical energy on the discharge side and mechanical energy on the suction side. So, that is the pump head or that will be the head that is generated by the pump. And if the inlet and outlet area of the pipes are same. So, because the flow rate is same and A 1 and A 2 are same, so V 1 V 2 V or V at discharge and V suction side will be same V.

If we say that the flow is turbulent then alpha will also be 1 and that will be true for most of the common pipelines we encounter. Now, there will be the elevations between discharge and suction that difference will be very minor if at all any. So, we can neglect the change in elevation between suction and discharge. So, basically the pump head or Δ h pump =Δ p/ρwhere Δ p is pressure at the discharge minus pressure at the suction.

So, pressure rise per unit density is what is head and this is in terms of meter^2 per second^2. We can also write the same equation in terms of Δ h where the units are in meter and that will give us that Δ p/ρ g. Generally, you will see that the head is written, the pump head is given in terms of meters. So, we might need to use this equation and where Δ h remember is discharge pressure minus suction pressure.

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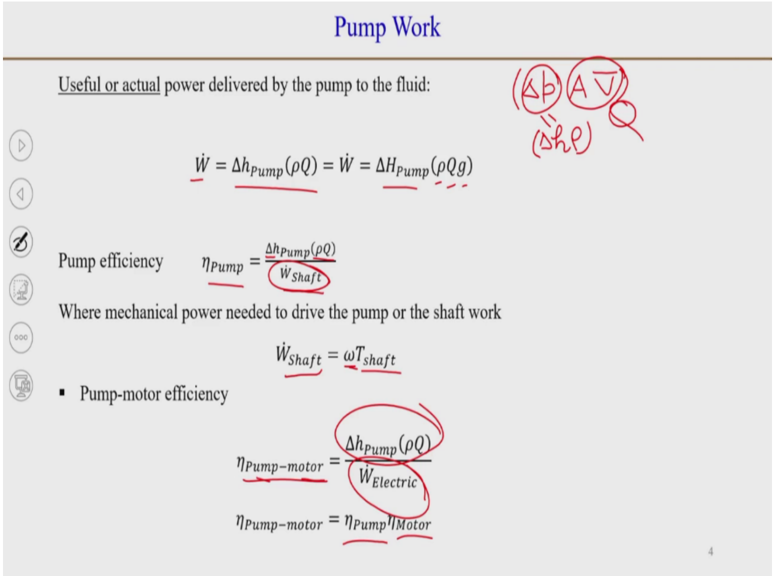

Now, we can calculate pump work or the power required. So, when we talk about the work, work is force into displacement, force multiplied by displacement. So, the work that needs to be done by the pump on the fluid, there is pressure change Δ p and if you multiply this by the cross-sectional area and so, that gives you force. So, Δ pA is force and when you multiply this force with velocities a mean velocity, so that will give you force into displacement per unit time. So, that will become or the energy per unit time or power.

So, rate of work done by the pump on the fluid is Δ p A V bar, where A V bar is nothing but Q flow rate and Δ p, we saw from the previous slide that it is Δ h ρ. So, the pump work we can write that Δ h or the pump head into ρQ or if the pump head is in terms of capital H, in terms of units of meter, then it will be Δ capital H ρQ g.

So, that is the useful work or actual work that the pump will do on the fluid for a pressure rise of Δ p or when the pump had Δ H. Now, we need to calculate pump efficiency or we might need to calculate the work depending on, work efficiency is given. So, the efficiency of the pump itself will be, because all the work that is being done by the impeller on the fluid will not result in or will not transfer as the actual work on the fluid because there will be losses in terms of viscous losses and other losses in the pump.

So, that will be not be 100 percent transfer, there may be say 60-70 percent transfer. So, the work that is being done by the shaft is, what we call $\dot{W}$ shaft and this is the useful work or that is the work that has been transferred to the fluid to increase the head of the fluid. So, this mechanical work, we can because it comes by rotating the impeller. So, we can calculate it by multiplication of torque that is being applied on the shaft and omega which is the angular speed or angular frequency by which, angular speed by which this is rotating in in radians per second. So, that is my shaft work.

Now, again this shaft is being provided the electrical energy from a motor. So, then there will be another efficiency which is efficiency of the motor, that will be that how much, what fraction of electrical energy is being converted to this mechanical work. So, we can say that the pump motor efficiency, overall efficiency will be that the what fraction of electrical energy provided to the pump is being converted to the useful work. So, we call it pump and motor efficiency combined where it is multiplication of pump efficiency and motor efficiency of course, motor efficiency will be $\dot{W}$ shaft /$\dot{W}$ electric. So, these are efficiency etcetera.

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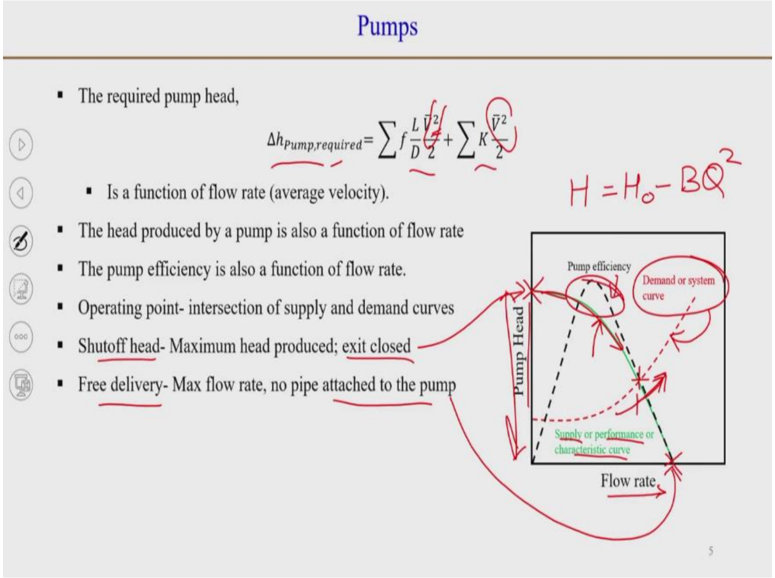

Now, if we look at the required pump head. So, we said that the pump head is required to overcome the losses. So, if we say that the pump head is equal to the major loss plus minor loss, minor loss is K $V^2/2$ and f L/D $V^2/2$ is our major losses and both of them are function of V^2 here. So, that means V^2, we can write in terms of flow rate per unit cross sectional area.

So, h is a function of flow rate or the average velocity. So, we can plot on x y plot, where on the x axis we have flow rate and on the y axis we have the pump head. So, this red curve here it shows the demand curve that means, as the flow rate or the velocity increases, the head required increases. As you can see from here, when the flow rate is increasing the head required is increasing. So, that is required head.

Now, the head that is produced by the pump that is also a function of flow rate and when you buy a pump and along with a manual comes, so the manufacturer he will provide the data about the pump. So, that is called characteristic or pump performance curves it can be called supply or performance or characteristic curve. So, this is what is required for a particular system and this is what a pump can provide in the green colour.

So, it decreases, you can see here that the pump head decreases with an increase in flow rate and this is typically given by say some H_o -, say some constant B Q^2. So, that using a parabolic type of correlation in general it can be fitted, but this curve is generated by the manufacturer in their testing facility by doing the careful experiments etcetera. So, the point where you have both demand and supply curves intersecting that point what we call is the operating point that is for a given flow rate the head required and the head provided by the pump will match.

Now, you can see here that this is decreasing with the flow rate. The point here where the flow rate is 0, so that means, the pump exit is close because there is no flow happening. So, at this point the pump will provide maximum head and it is called shutoff head when the pump is not operating. So, this is the point where you have the maximum head. Then another point when you have maximum flow rate and when will that happen. Maximum flow rate at this point and at this point you can see the head is 0.

So, head required will be 0 when you do not have any major and minor losses and that will happen that there is no pipeline downstream of the pump. So, that is that low pipe attached to the system, you call it also free delivery. So, that is pump performance curve, then you have the efficiency of the pump. So, this black line, the black dotted line shows the pump efficiency and you see that the efficiency first increases with an increase in flow rate and then it decreases. So, there might be an optimum flow rate that you would like your pump to operate, so that the efficiency is significantly higher.

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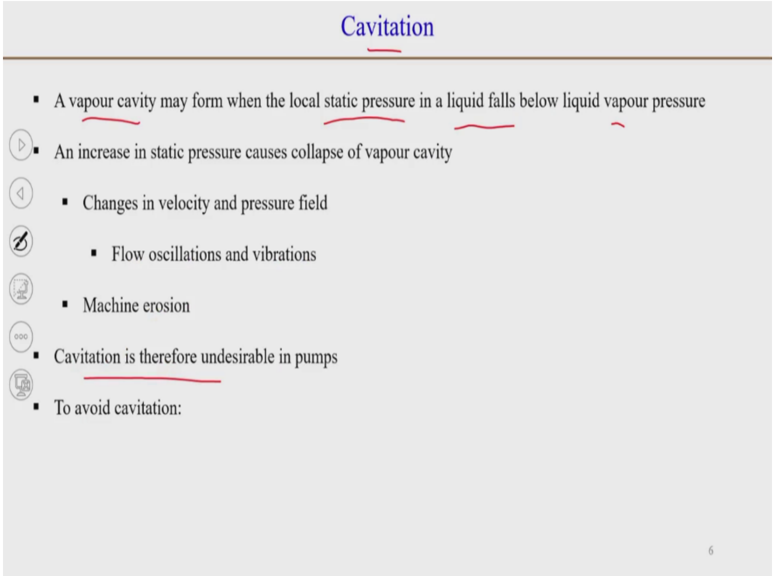

So, the next point comes what we call NPSH or net positive suction head. When we talked about that in the centrifugal pump, the kinetic energy of the fluid increases, the velocity of the fluid increases, when the velocity of the fluid increases, there will be some decrease in pressure. So, when the pressure decreases inside the pump, it should not happen that it evaporates or it changes into vapor.

Now, if you go back to your thermodynamics, you might remember that a fluid can or a liquid can turn into vapor for two reasons; one is that you provide it heat or you increase the temperature at a fixed pressure, so atmospheric pressure, if you keep increasing the temperature of a liquid it will start evaporating and it will turn into vapor that is what we call a boiling point.

The other way to turn a liquid into a vapour is that at a fixed temperature if the pressure is getting reduced and if it goes down or if the pressure above the liquid goes below the vapor pressure of the liquid at that particular temperature then the evaporation start. So, in the pump, if the pressure at any point locally decreases below the vapor pressure of the liquid, then the vapor cavity will form and that is what we call cavitation. So, it says that a vapor cavity may form when the local static pressure in a liquid falls below liquid pressure.

Now, when the vapor cavity form suddenly there is a lot of discontinuity, the density changes from say 1000 to say 2 or 3 or at least 2 order of magnitude decrease in the density. Correspondingly, there will be large changes in velocity, large changes in pressure, and then the pressure is only at some place is very small and when this vapor is transported or is convected to a different place where the pressure is high, suddenly this vapor cavity will collapse.

So, this collapse is not good for the machine, it is not good for the flow, you will have lots of oscillations in the flow and those oscillations can damage your machine, can damage your impeller. So, it is it needs to be avoided. So, the cavitation is avoidable or it should be avoided in the pumps. Now, if we need to avoid cavitation in the pump, we need to make sure that we make calculations that what is the minimum pressure at the inlet that should be present at the inlet, so that the cavitation does not occur in a pump.

Now, this will depend on the fluid, because different fluids have different vapor pressure, it will also depend on the temperature because the vapor pressure at a particular temperature it is the saturation pressure at that temperature. So, the vapor pressure of a liquid is also a function of temperature. So, we need to maintain this.

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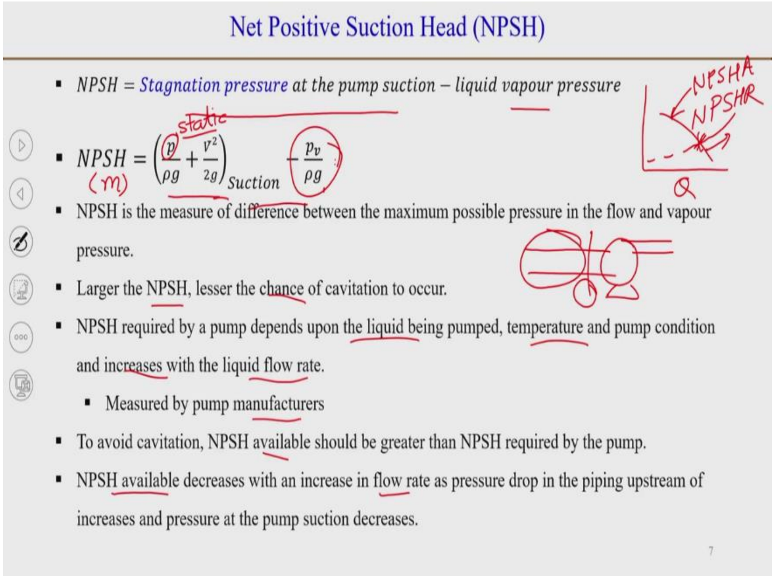

So, when you buy a pump, the manufacturer will also provide you a data about NPSH or net positive suction head. So, that means, because when you measure pressure, you will be able to measure pressure at the suction side of the pump, you cannot measure the pressure everywhere in the pump.

So, what can be done is when you install a pump somewhere you can make calculations that what is the pressure at the suction side and is it sufficient that it provides you a net positive head at the suction side so that the cavitation can be avoided. Now manufacturer will provide as a function of flow rate, because NPSH or net positive suction head is a function of the flow rate.

So, he will provide that for a particular pump, what is the NPSH? What is the net positive add that as required, so that the cavitation not occur? So, how do we calculate that, it is NPSH or net positive suction head is the stagnation pressure at the pump suction minus liquid vapour pressure. So, the stagnation pressure if you remember that if the fluid is being brought to rest isotopically. So, that means, if the entire kinetic energy of the fluid can be converted to pressure energy, then that pressure when the fluid is brought to rest without any irreversible losses, then we call that stagnation pressure.

So, the stagnation pressure at the pump suction will be a static pressure, this p is static pressure. Everywhere what we have been talking about p is the static pressure. So, p/ρg. So, when it in terms of ρg then we call the unit side in meter. So, p/ρg + V^2/2 g that is the stagnation pressure at the pump suction - p v/ρg that physically means, what is the difference between the stagnation pressure at the suction minus vapour pressure.

So, if this number is sufficiently high then the chances of cavitation occurring in the pump is minimized. Now, what should be this value is provided by the manufacturer So, that we call NPSH required or NPSHR. So, larger this NPSH lesser will be the chances of cavitation to occur. It will depend on because it is a function of vapour pressure. So, it will depend on the temperature, it will depend on the liquid that is being pumped, it will also depend on the liquid flow rate, and this required NPSH it will actually increase with the flow rate and this will be provided by the pump manufacturer.

Now, to avoid cavitation the NPSH that is available. So, for a particular pump you will have this at your disposal, the NPSH required and when you are installing it in a pipeline you need to calculate that the point where I am installing where the pump will get its suction from what is the pressure there, is the head available or NPSH available there is it greater than NPSH required?

Now, this NPSH what is available, it will decrease with an increase in the flow rate. So, if you have a pipeline and a pump is being installed in the pipeline, if you increase the flow rate, then the losses here will increase. So, when the losses here will increase that means the pressure at the suction side will decrease, the more flow rate the more losses, more the losses lesser the suction side pressure.

So, that means the NPSH available because vapor pressure at a particular temperature for a particular fluid is fixed, so NPSH available will decrease. So, you will see that NPSH available is decreasing. So, our flow rates should not go beyond this point. So, that the cavitation does not, to avoid cavitation in the pump. So, let us look at a problem.

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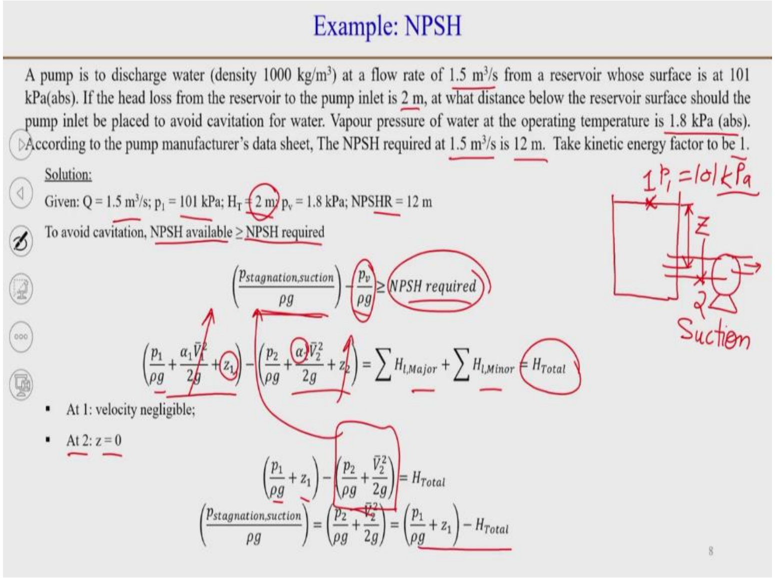

What is given that a pump is to discharge water at a flow rate of 1.5-meter cube per second. So, we have been given the flow rate from a reservoir whose surface is at 101 kilo Pascal absolute which is the atmospheric pressure. So, if we draw a reservoir and from this reservoir the liquid is to be drawn by a pump. So, we can consider the reservoir surface to be point 1 and this to be point 2, which is the suction of the pump. If the head loss from the reservoir to the pump inlet is 2 meters, so the total head loss between point 1 and 2 is given as 2 meters.

At what distance below the reservoir surface, so we need to find this distance, let us say z, should the pump inlet be placed to avoid cavitation for water. We have also been given the vapor pressure and the flow is turbulent, so the kinetic energy factor can be taken as 1 and the NPSH required that given by the manufacturer at this flow rate 1.5-meter cube per second is 12 meters. So, we can list down all the quantities that have been given.

Now, what we need is that in order to avoid cavitation our NPSH available should be greater than NPSH that is required and NPSH available we can calculate that at the suction stagnation pressure minus vapor pressure should be greater than the required pressure. Now, we know vapor pressure and we know the density and acceleration due to gravity. So, this thing is known to us.

NPSH required is given to us what we need to know is what is the stagnation pressure at the suction side. So, we can use our equation for pump and apply it between, not the equation for pump but the energy equation and we can apply it between point 1 and point 2, in this line we do not have any pumps.

So, we can write this simply mechanical energy at point 1 - mechanical energy at point 2 is equal to major plus minor losses which is the total losses because we have been given the total loss of 2 meter. So, in this equation now, at the reservoir surface the velocity will be negligible. So, we can neglect this term we can say that z 1 =15 meters. So, z 2 will become 0 or z 1 is what we need to find. So, we can say z 1 is z and at point 2 z =0 we have taken.

So, our equation simplifies that p 1 + ρg where p 1 is the pressure here 101 kilo Pascal we know already, - p 2 + alpha we have taken 1 p 2 + V $2^2/2$ g and that is the suction side because 2 is whatever suction side of the pump. So, this term is what we are looking for, stagnation pressure at the section by side by ρg. So, that gives us what we can calculate that p 2 or suction pressure =p 1/ρg + z 1 - H total.

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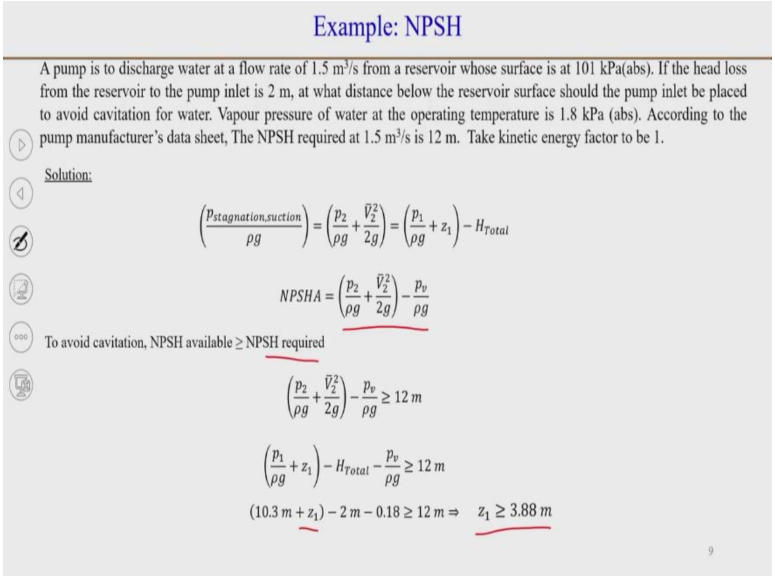

So, that is the p/ρg at the suction side, we can substitute it here and that will give us the required NPSH, we can substitute and in the equation here, so when we solve, we will get that z 1 is equal to should be greater than 3.88 meters. So, you can substitute the values and calculate it for yourself.

So, in this problem what we needed to calculate what is the pressure available or what is the stagnation pressure had available at the suction side. So, once we calculate NPSHA and from that we could calculate in the equation what is z1 and what side below the reservoir surface is used to be installed. So, we can also see from this equation, what is the use of NPSH. It will tell us that at what location can we install it, what location it is not possible or if you installed it there will be problems in the system.

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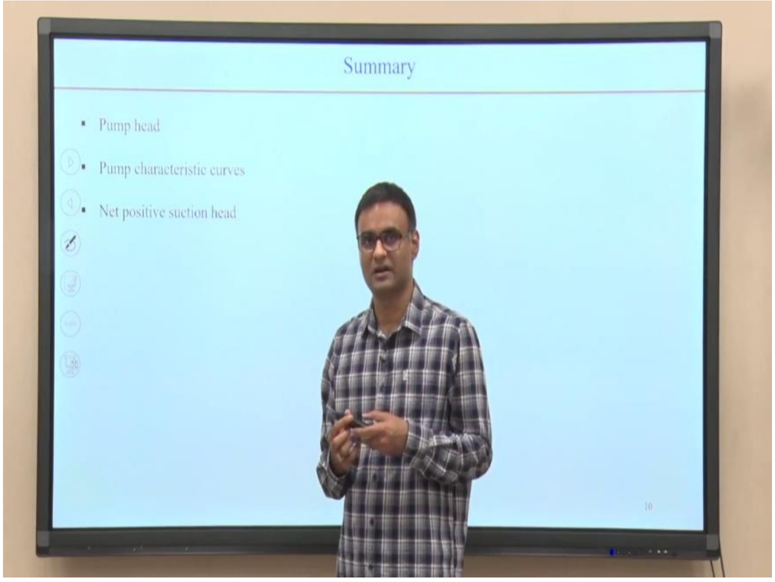

So, in summary what we looked at today is that what are the things that we need to understand or know about pumps. We looked at how we can calculate pump head in terms of meter^2 per second^2 or in terms of meters. And then we briefly looked at what are the pump characteristic curve, how it changes with flow rate, how the efficiency of a pump changes with flow rate. And then we looked at what is net positive suction head, the cavitation, and how we can calculate the available net positive suction head. So, with that, we will stop here and that is also the end of this module and end of the course as well. So, thank you.