Momentum Transfer in Fluids
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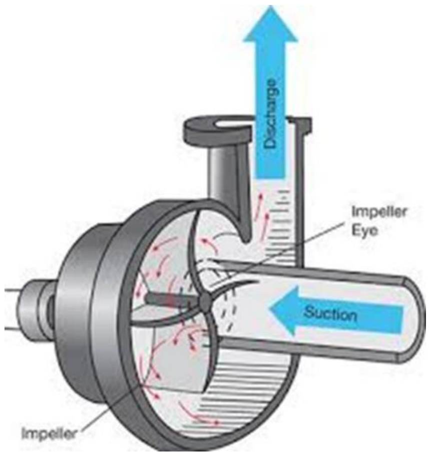
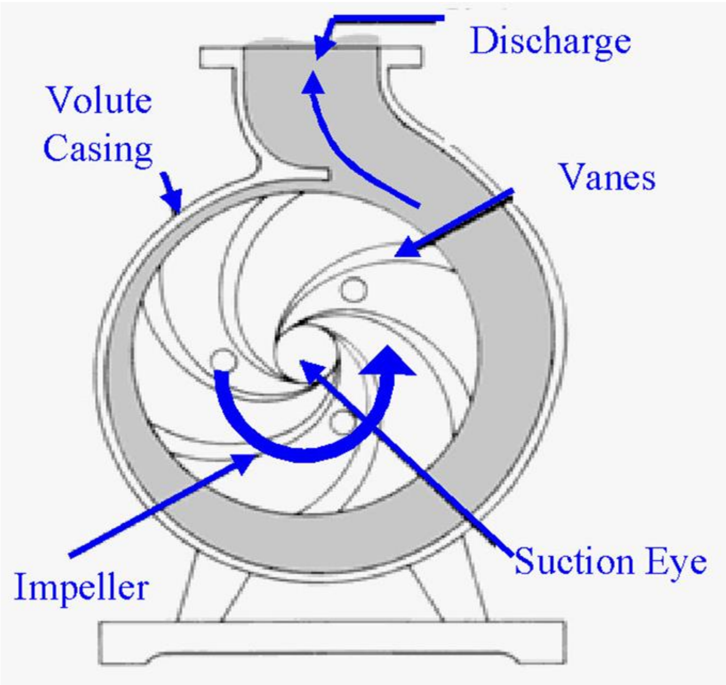
Week-11
Lecture-53

Good morning. The last topic that I would like to cover in my part of the course is something extremely important. So, far we have calculated or we have seen how what is the pump power necessary to make fluid flow from one point to the other and in its path, there could be various bends, flow measuring devices, flow controlling devices for example, valves and so on. And each of them can result in some pressure drop. So, whatever pump that we decide or whatever pump that we choose must be able to provide the pressure drop necessary, pressure drop that the fluid is going to encounter in its flow pump. So, we are going to talk more about the pump characteristics and what are the factors that we must keep in mind while selecting a specific pump.

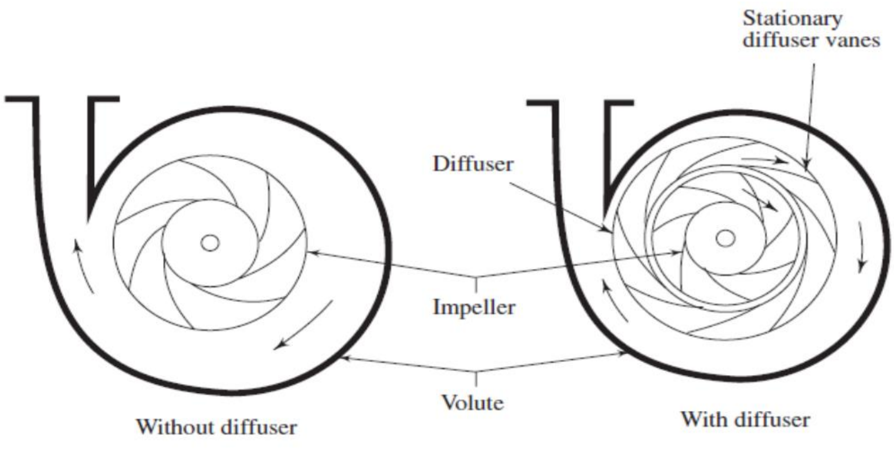


So, the most common pump that you would see in which we generally encounter in most of the flow situations for household use and wherever when we do not require a very high pump head is the centrifugal pump. Now, as you can see that the liquid is going to be the liquid is going to be sucked into the liquid is going to be sucked into a chamber in which there are going to be rotating propellers which are going to direct which are going to direct the fluid towards the edge. And this force is going to give rise to some head at the discharge end of the pump. So, there is going to be suction where the fluid is going to be rotated and because through because of these blades and they are going to push the liquid up the discharge line with a higher pressure than where than the supply one.

So, obviously, the pressure that can be generated in the discharge of a centrifugal pump depends on various factors. And one of them is going to be the design of these impellers which propels the liquid in a specific path. So, when you think about the detailed cross section of a centrifugal pump you have these impellers and you have the you have the vanes there is going to be the region where the liquid is going to be sucked into and the liquid is going to rotate at a very high speed and because of centrifugal action it is going to go out and this is where the discharge it discharges location is which is at a higher pressure. Now, the centrifugal pumps when we think about the factors which we are going to be concerned with or one is going to be what is the pressure head that is going to be generated in such a in such a pump. How much of pressure we are going to get at the discharge end that means, at this end.



The second is what is going to be the flow rate that we want at the discharge. So, there are two things one is the pressure head and the second is the flow rate. Now, we can intuitively see that these two are inversely proportional I mean there is an inverse relation not exactly directly inversely proportional, but there is an inverse relation between the amount between the head generated and the flow rate. It is easy to imagine why the head generated would be lesser when we increase the flow rate. So, there must be a balance between the flow rate and the pressure head generated and any pump will have certain efficiency.

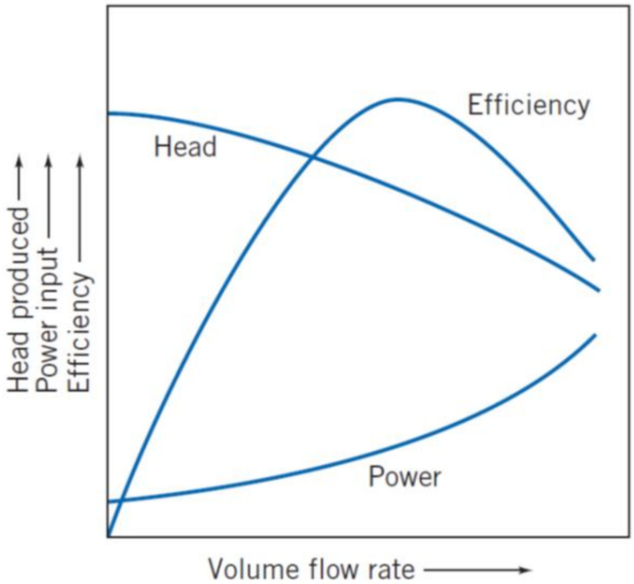


Now, how would that efficiency would change when we change any one of these three. So, there this has led to the characteristic curves of a centrifugal pump where you would see that the in because of the flow pattern which is changing with the volumetric flow rate the performance of the pump is going to be affected. So, the performance parameters as I have said are the head developed, how much of power you want, how much of power you need to provide for the pump to work and the efficiency of the machine under specific operating conditions.

So, it is the head the power and the efficiency, how do they vary when you change the volumetric flow rate. So, we take the volumetric flow rate as the x axis of a curve and in the y axis we plot together the head developed, the power input and the machine efficiency, the efficiency of the pump.

> Efficiency is defined as the ratio of power delivered to the fluid divided by input power, $\eta = P/P_{in}$.
>
> For incompressible flow, the energy equation reduces to $P = \rho Qh$ (when "head" h is expressed as energy per unit mass) or to $P = \rho gQH$ (when head H is expressed as energy per unit weight).

This curve which is specific to each of the pumps which could be provided by the manufacturer or you can you have to do experiments to figure out what would the characteristic curve of a specific pump look like are known as the characteristic curve of the specific pump. The efficiency is defined as the ratio of the power developed to the fluid divided by the input power ok. So, let us look at how the typical characteristic curve of a centrifugal pump looks like. So, in the in the y x axis you see that we have plotted the volumetric flow rate and on the y axis we have the head produced, this is the head produced how much of head is produced by the pump. The power input how much of power we have to we have to input to the fluid input to the machine as we increase the volumetric flow rate.



Now, it is obvious that as the volumetric flow rate increases the power should increase ok. To have more flow through the pump we need to provide more power. So, there is a monotonic increase in power with increase in volumetric flow rate. So, that is the power one. The head the head produced by the pump will decrease as we increase the volumetric flow rate.

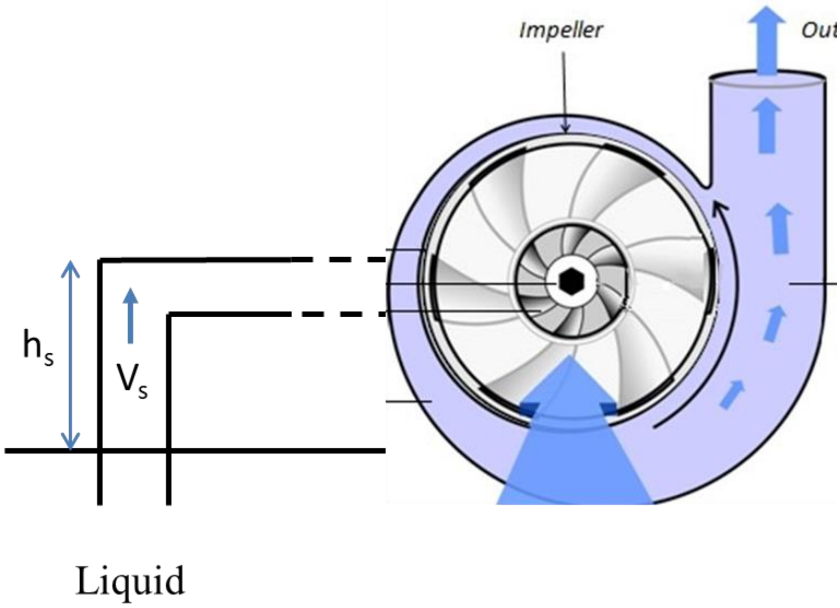
So, if for some specific flow rate, we have certain heads and it is also clear that if we increase the flow rate the head must decrease. So, therefore, head is going to have a monotonic decrease in with the volumetric flow rate. So, you would like to figure out by analysing these two curves the power and the head that how much of head would you need and that would raise at a specific volumetric flow rate and what kind of a power would you have to provide to the pump to make that possible. So, the volumetric flow rate head and power are intrinsically connected to each other. Now, the interesting thing happens when we when you look at the efficiency curve the efficiency passes through a maximum.

So, there is a certain combination of head and power and volumetric flow rate at which the pump is going to be going to operate at the maximum efficiency. So, it is this region towards the top where you do where you would want your pump to operate. So, the characteristic curve or curves of a specific pump provide you the right operating range for the pump to operate in which it would provide sufficiently high head at a lower power with a high value of efficiency. So, anyone who is planning to design or planning to purchase a pump would have to look at what is going to be the head developed near the maximum efficiency, what is the power that is required and what is the volumetric flow rate. So, based on the combination based on your choices or rather your requirements or flow rate head what is the corresponding power and everything should fall into the top part of this efficiency curve such that it is going to operate in the most efficient manner.

So, these are collectively known as the characteristic curves of a centrifugal pump and they are tested as the title mentions at a constant speed and they are mostly experimentally obtained. There is a certain there is a certain other issue that we must keep in mind which is known as the cavitation and then what is first let us say what is cavitation. Now, if you are if you think about the suction side of a pump the pressure is going to be less than that of the atmospheric. Now, the pressure in that supply line must be above the vapor pressure of the liquid at that specific condition. If not the vapor the liquid is going to flash into its vapor and the supply line is going to be filled with the vapor of the liquid and not the liquid creating a condition which is known as cavitation.

So, cavitation can take place anywhere whichever any equipment that is dealing with liquid. So, this local pressure at any point in the supply or suction side of the pump is going to be less than the vapor pressure of the liquid. So, as I mentioned the liquid will turn into vapor and it is going to form a vapor cavity in the path of the fluid. And of course, the flow is going to become unsteady there is going to be lot of vibration, noises, the flow is going to oscillate between conditions where there is only liquid, where there is liquid and the vapor coexisting with each other and there would be significant vibration in the machine which is going to be detrimental to the long-term health of the pump. So, we should always be careful that the at any point of time anywhere in the supply side anywhere in the inlet side of the pump the in that pipe in that path the pressure is always above the vapor pressure.

So, it if that does not happen it is clear based on the discussion that we had so, far that it is going to reduce the performance of any pump or a turbine. Now, we must have no cavitation for efficient operation of the pump. Now, and as I said that cavitation is to be avoided to do that the pressure everywhere in the machine must be above the vapor pressure of the operating liquid. So, there must be a quantitative way by which we can ascertain that the pressure everywhere is above the vapor pressure of the liquid at that specific condition which brings us to the concept of net positive suction head or in short NPSH. So, what is NPSH? In NPSH is defined as the difference between the absolute stagnation pressure in the flow of the pump at the suction side and the liquid vapor pressure it is expressed at the as the head of the flowing liquid.



So, in meters its unit would be meters of the flowing fluid. In the subsequent slides I am going to discuss about what is NPSH, how it can be calculated and what is the what is the value of NPSH or what is the range of NPSH that we must consider before using a pump in a specific in a specific in a specific pipeline. So, NPSH the more the value of the NPSH the higher would be the region of applicability zone of applicability or ease of use of that pump. So, let us start with a very simple figure of and to try to get some idea of what is NPSH. So, if you look at this figure this is the liquid and the pump the centrifugal pump this is the suction side of the pump the entry of the pump is some distance h s above the datum line.

So, I take the free surface of the liquid as my datum line let us call this point as a and L is the point which is at which is at the entry of the pump on the suction side. And let us also assume that the velocity with which the liquid flows through the suction pipe is V s. So, essentially, I am I am fixing what is going to be the flow what is going to be the flow rate for this case. So, with a head static head of h s it is going to suck the liquid with a velocity V s that means, with certain flow rate and it is going to the liquid path is going to be out of the pump at a higher pressure through the discharge side. So, h s is the suction height and V s is the velocity.

Now, what I am I what I am going to do is I am going to apply Bernoulli's equation between this point the free surface of the liquid free surface of the liquid in the reservoir and at point L the entry point at the pump and then try to see what is the condition that must be maintained to have no cavitation in the path of the fluid. We will because this is the high-pressure side. So, the and this is the low pressure. So, whenever you are sucking liquid out of the reservoir there is a possibility that the local pressure is going to be less than the vapor pressure and therefore, cavitation may occur in this case. So, this is this is something which we must which we have to consider.

So, this the same figure over here and I am writing the Bernoulli's equation between point A which is at the surface and point L which is at entry. The alpha 1, alpha 2 as you know are the kinetic energy correction factors and they can be approximately taken to be equal to 1 which should be true for the case of turbulent flow as we have discussed before and h L t being the total loss in the path of the fluid from the reservoir up to the entry of the up to the entry of the pump. So, P A is the pressure at the free surface P 1 is absolute pressure P 1 or P L is the absolute pressure at the inlet of the pump Z A is 0. So, we take datum at this point. So, therefore, Z A the head at A must be equal to 0 Z L is the height of the inlet pump.

$$\left(\frac{p_a}{\rho g}+\alpha_1\frac{\overline{V_a^2}}{2g}+Z_a\right)=\left(\frac{p_l}{\rho g}+\alpha_2\frac{\overline{V_1^2}}{2g}+Z_1\right)+h_{LT}$$

$$\left(\frac{p_a}{\rho g}+0+0\right)=\left(\frac{p_l}{\rho g}+\frac{\overline{V_s^2}}{2g}+h_s\right)+h_{fs}$$

$$\left(\frac{p_l}{\rho g}\right)=\frac{p_a}{\rho g}-\left(\frac{\overline{V_s^2}}{2g}+h_s+h_{fs}\right)$$

So, therefore, the Z L is simply equal to h s and V 1 the V L the velocity in the pipe is equal to V S and h f s let us denote h f s as the loss of head in the valve in the pipe and any other fittings that are in the pipe and any other fittings that are there in the path of the fluid before it enters the pump. So, h f s is the total loss that is present in the system because of the pipe friction and the valve and other fittings which are present in the path of the fluid. So, by V A, V A over here is going to be 0 since it is a reservoir. So, the fall of the level at the reservoir the rate of fall of the level at the reservoir is going to be very small as compared to the velocity head generated inside the pipe. So, this is going to be 0 Z A this is also going to be 0 because since A is my datum level alpha 2 is taken to be equal to 1 V L is essentially V S the velocity h s is the height the Z 1 over here and h f s stands for all the losses in the suction side of the pump in the suction pipe.

So, this P L minus divided by rho g this head is essentially can be expressed in this form. Now, when we write this in the in the specific form let us try to figure out what is the physical significance of each of each of these terms. First, P A by rho g is the atmospheric pressure head let us call it as h A and it is in meter of liquid. P V by rho g is the vapor pressure head h V meter of the liquid. So, what is P V let us go back to this thing once again this P L the pressure at this point at the max it can be equal to or less than the vapor pressure of the liquid at that point.

$$\left(\frac{p_a}{\rho g}\right)=\frac{p_v}{\rho g}+\left(\frac{\overline{V_s^2}}{2g}+h_s+h_{fs}\right)$$

$$\frac{p_a}{\rho g}=Atms\ \mathrm{Pr}.\ Head=H_a,\ m\ of\ liquid$$

$$\frac{p_v}{\rho g}=Vapor\ \mathrm{Pr}.\ Head=H_v,\ m\ of\ liquid$$

$$h_s=H_a-H_v-\frac{\overline{V}_s^2}{2g}-h_{fs}$$

So, what we are going to say is that the in the limiting condition this is simply going to be P V P L is going to be equal to P V which is the vapor pressure head let us call it as h V. So, we understand that P L is the in the value in the maximum the lowest pressure that it can sustain without having any effect without having any cavitation is the vapor pressure any pressure less than that will give rise to cavitation. So, P V by rho g is the vapor pressure head also in meter of liquid. So, therefore, h s the height to which the liquid can be transported the height above the datum from the reservoir which can be transported can be given by this equation where h A is the atmospheric pressure head h V is the vapor pressure the vapor pressure head V s is the is the kinetic energy of the liquid in the pipe and h f s stands for all the losses that the liquid will encounter as a result of its flow through the pipe and through all the fittings and other attachments which the fluid will encounter as it flows through the pipe. Now, if I write that equation once again.

$$h_s = H_a - H_v - \frac{\overline{V}_s^2}{2g} - h_{fs}$$

So, it is h s it is an important equation that it as it gives us the value of the head static head that the pump can generate. Now, h s is the as I said is the maximum suction lift for a centrifugal pump. If you need to have a higher lift then you must use a different centrifugal pump. So, we are trying to figure out a quantitative way of saying that a specific pump is going to work for lifting the liquid up to a certain height. And we also understand it is not only going to be a function of the design it will also depend on the properties of the liquid which is being pumped.

So, the vapor pressure the cavitation is more likely to occur for a liquid that that that is easy to evaporate. So, whichever has a higher vapor pressure it is going to it. So, that there is a possibility that it could give rise to earlier cavitation. So, suction height as I said should not be more than h s else the liquid is going to vaporize and it would lead to cavitation. So, what is the quantitative way by which we can express the amount of suction that the pump can provide and whether the pump will work.

$$(NPSH) = \frac{p_1}{\rho g} - \frac{p_v}{\rho g} + \frac{\overline{V_s^2}}{2g}$$

$$\left(\frac{p_l}{\rho g}\right) = \frac{p_a}{\rho g} - \left(\frac{\overline{V_s^2}}{2g} + h_s + h_{fs}\right)$$

So, this is why we have the net positive suction head. It is defined as the absolute pressure head at the inlet of the pump minus whatever be the vapor pressure head plus the velocity head which the liquid is going to generate while flowing through the through the suction pipe. So, this N p s h is simply then going to be as part the definition is the absolute pressure head p 1 by rho g at the inlet of the pump. We know at the inlet this is L. So, p L by rho g that is the that is the pressure head p v is the vapor pressure.

$$(NPSH) = \frac{p_1}{\rho g} - \frac{p_v}{\rho g} + \frac{\overline{V_s^2}}{2g}$$

$$\left(\frac{p_l}{\rho g}\right) = \frac{p_a}{\rho g} - \left(\frac{\overline{V_s^2}}{2g} + h_s + h_{fs}\right)$$

Therefore,

$$(NPSH) = \frac{p_a}{\rho g} - \frac{p_v}{\rho g} - h_s - h_{fs}$$

So, p v by rho g is the vapor pressure head and the velocity head we know the velocity in the suction pipe is v s. So, it is v s square by 2 g and that is how N p s h is defined. Now, from our earlier relation we know the connection between the p L by rho g p absolute by rho g which are connected by Bernoulli's equation. So, this is the suction height and these this is the loss in the in the path. So, I am going to combine these two equations to get a better idea of what N p s h is.

I have not done anything new I have just used the definition of N p s h and the relation between p L and p A the velocity the losses and this static head using simply the Bernoulli's equation as we have done in the earlier slides. So, this is N p s is the same thing. So, therefore, N p s h can be defined can be expressed by combining these two equations as the atmospheric head, the vapor pressure head, the static head, and the losses in the path of the flow. So, this is the complete definition of N p s h in a specific piping system. So, N p s h is therefore, h A the atmospheric pressure head h s the static pressure heads the h f s the losses and the vapor pressure head.

$$NPSH = \left[\left(H_a - h_s - h_{fs}\right) - H_v\right]$$

So, N p s h is just the algebraic sum of all these all these four quantities. The r h s therefore, is the total suction head. So, N p s h is defined as the total head to make the liquid flow total head necessary to make the liquid flow through the suction pipe to the pump impeller without having any cavitation. So, that is what N p s h is all about. So, N p s h gives us a quantitative idea of how much leeway we must suck the liquid to greater heights.

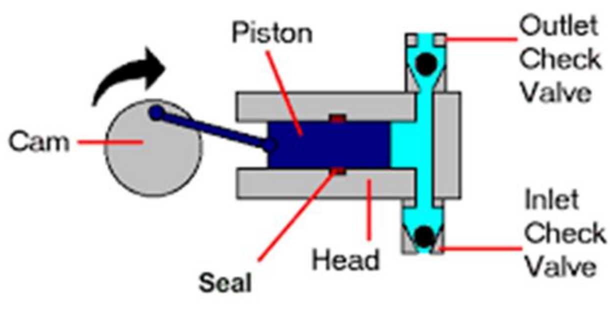
So, that is what that is the relation between N p s h and all these different four different quantities. So, this required N p s h is given by the pump manufacturer. So, the pump manufacturer through their design and extensive studies experimental studies can give us that this much of N p s h must be present in the in the in the path for the pump to operate without any cavitation. The required N p s h will change with the design whatever be the speed with which the impeller is working and how much of fluid it must pump to a certain level to a certain level that means, h s with a certain with a certain pressure and so, the capacity of the pump is going to be going to dictate the capacity the speed and the design is going to dictate what is going to be the N p s h for the pump. Now, whenever we install a pump, we must first find out what is the available N p s h for the available N p s h is calculated from this equation.

So, I know what is the atmospheric head I know which height the liquid must has to be has to be lifted what are the losses which are going to be there in the pipeline and what is the going to be the vapour pressure head for that specific liquid in question. So, when we combine all these, I would be able to calculate what is the value of the N p s h. So, this is the this is the available N p s h. So, to have cavitation free operation the available N p s h must be greater than the required N p s h. So, the required N p s h gives you at the minimum value which must be provided which must be present for the pump to operate without any cavitation.

So, we first need to calculate how much of N p s h we have in the system based on these 4 quantities such that we can say that my N p s h press of my pump the system that at which my pump operates is more than the required N p s h for the pump. So, I can use that specific pump for my operation for this specific operation without having to worry about the presence of cavitation in its path in the path of the fluid at the suction side. So, it is so, while choosing a pump for a specific operation we need to do 2 things. First find out what is the N p s h of the pump that you are planning to incorporate in the path in the in the pipe pipeline. And second looking at the location of the pump we service the level from where the liquid is going to be sucked liquid is going to be lifted find out what are the 4 different quantities the h a h s h f s and h v.

And then decide whether the N p s h that you have is sufficiently more than the N p s h which has been provided which has been mentioned by the manufacturer. If the difference is positive the more the difference the more confident you will be that the centrifugal pump will work without any cavitation. Because you do not want to have cavitation under any circumstances for the health of the pump for the health of the pipeline and for an efficient operation without any vibration. So, the last point that I would like to mention here is that. So, therefore, it limits the centrifugal pump is limited by these 4 quantities mostly by the vapor pressure.

So, what is going to happen what how are you going to handle the situation where you would where you want pump at a I mean where you want the discharge pressure to be much more than that provided by a centrifugal pump. You want the liquid at the outlet at a higher pressure. So, if that happens a centrifugal pump may not work because the N p s h required for that would not be sufficient for such a case. And one such pump which is commonly used for high pressure delivery of the liquid at the discharge side is known as the reciprocating pump. As the name suggests there is a piston which goes back and forth and when and so, it is attached to a cam when the cam rotates it is going to when it is at this position then it the piston goes back and when it turns another cycle the piston moves forward.



So, when it goes back the liquid is going to enter through this inlet and it will come over here fill up this portion and when the piston is coming back in this inlet check valve gets automatically closed and the liquid is then forced through the outlet at a high pressure. So, you can go to a very high pressure since it is based on the based on compressing the liquid available in this area. So, the so, you can generate very high pressure using a reciprocating pump for your process conditions. So, this in a nutshell is some information about pumps which you would find useful while designing and choosing this a specific pump for your purpose. Thank you.