Momentum Transfer in Fluids
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I welcome you to this lecture on Momentum Transfer in Fluids. We are going to discuss in today's lecture about flow metering and associated problems. However, I want to very briefly touch upon one issue of cavitation in the associated problems of fluid machineries that we discussed in the last class. I just briefly discuss that for a few minutes before we get into the details of flow metering. What we saw at the end of last class is that Bernoulli's equation when we apply across pump with a pump that is delivering obtaining fluid from a reservoir and then we said that the suction pressure here at the suction end of the pump has to be above the vapor pressure by certain margin to avoid cavitation. So, here in case we are trying to find out what is this NPSH available from the system.

$$p_1 + \frac{1}{2}\rho\vec{V}_1^2 + \rho g z_1 = p_s + \frac{1}{2}\rho\vec{V}_s^2 + \rho g z_s$$

So, we said there are two things one is NPSH available from the system itself. The system itself, the height, etc, was chosen in such a way that the suction pressure is above the vapor pressure by a certain margin, and the other is the pump manufacturer wants the margin to be this much. So, that after entering into the pump still there would be some reduction in pressure. So, that has to be accounted.

So, now what we saw is that the suction pressure if we apply Bernoulli's equation the suction pressure can be written as this.

$$p_s = p_1 + \rho g(z_1 - z_s) - \frac{1}{2}\rho\vec{V}_s^2$$

So, this is what is the suction pressure. Now on top of that you have another round of head losses possible because of friction, contraction, expansion due to flow through valves and fittings. So, this is essentially the frictional loss $f\frac{L}{D}\frac{1}{2}\rho\vec{V}_s^2$ and this is for various fittings we have and then expansion contraction etc you have this. So, there is this net frictional losses possible.

So, if this P is converted to the head P is pressure. Now pressure is always written as the head H into ρ of the fluid and g. So, any pressure P_S we can have corresponding H_S. H_S is in head the unit would be in meter instead of Pascal. So, that represents if I open a hole small hole and let the fluid to rise it will after some time and that is that tube that I connected that is open to atmosphere after some height that will stop.

So, that height would be the head at that point. So, you can find out what is this H. So, PS corresponds to HS, P1 corresponds to H1 that way it will go. You have already I have written these are the losses. So, these are the losses and they include in some way or if they do not include we have to put half rho VS square as well half rho VS square this term also will feature there and if you include this somehow within this then it does not need an extra term.

$$h_{NPSH} = \left(\sum K + \sum f\frac{L_e}{D} + f\frac{L}{D}\right)\frac{1}{2}\rho\vec{V}_s^2$$

$$H_s = H_1 + z_1 - z_s - \frac{1}{2}\rho\vec{V}_s^2 - \left(\sum K + \sum f\frac{L_e}{D} + f\frac{L}{D}\right)\frac{1}{2}\rho\vec{V}_s^2$$

So, this is what is the suction head nets this is the suction head and how do you find how will you find this out what would be these what would be the value of F what would be this what would be F for example, F is a function of F you have friction factor chart. So, you can even refer to the friction factor chart friction factor versus Reynolds number. You find out what velocity you are looking at and then correspondingly you find out the Reynolds number and from there you find out what is the friction factor. And at in some case suppose we do not know what velocity we are operating then in that case there would be some some other implicit method one has to apply. But essentially this you can as long as you know the velocity VS you find out what is the corresponding friction factor and that has to be applied.

$$f = f\left(Re, {}^{e}/_{D}\right);\ Re = \frac{\rho VD}{\mu} = \frac{VD}{\upsilon}$$

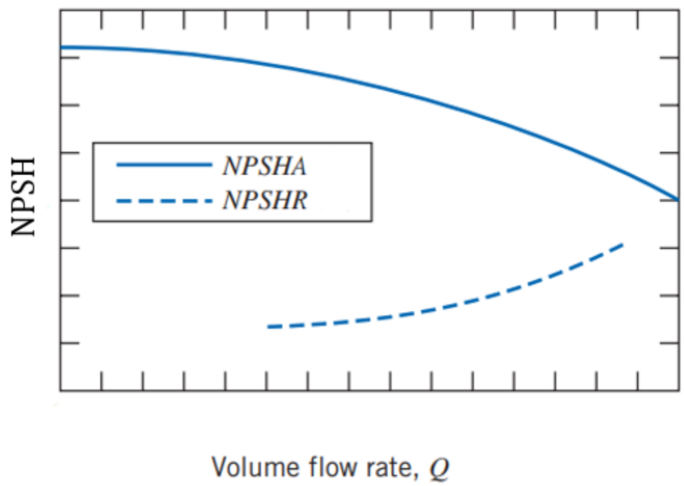
$$\bar{V} = \frac{Q}{A};\ A = \frac{\pi D^2}{4}$$

Then what you do is we write the NPSH available the system provides you the this net positive suction head which is Hs the Hs that we have calculated here the suction head available. Then we have additionally the velocity head. So, when the fluid enters into the pump casing that time it has that much of head possible the head is there that head is the pressure head. So, I have when it comes to the fluid entering the casing I have two forms of energy there. One is in the form of pressure head another is in the form of velocity head that referred as kinetic head.

$$NPSHA = H_s + \frac{\bar{V}_s^2}{2g} - H_v$$

So, both these heads with these heads the fluid is entering into the casing and after entering into the casing then again it is subjected to a little bit of expansion etc. But we note that this is the net pressure head plus kinetic head that is present in the fluid as it enters into the casing and that has to be greater than the vapor head corresponding to the vapor pressure by some margin and what I see is that system provides the difference system provides this much of margin. So, then what you see here is that if the flow rate changes as the flow rate through the pump changes I have a setting I can change the impeller rotation rate I can change the flow rate for a centrifugal pump. So, as the flow rate changes you have the Reynolds number changing. So, Reynolds number changing one thing you have this Vs changing the velocity and the Vs is also changing.

So, correspondingly the Hs is also changing. So, Hs is changing, Vs is changing. So, that means the system NPSH that the system provides that NPSH has changed. So, NPSH of the system that is a function of flow rate itself. That means as I change the pump flow rate my system NPSH that the system provides that is going to change.



So, that is why I can see the suction head H itself sorry this it is essentially NPSH. So, NPSH this is the y axis is NPSH. So, net positive suction head I have two types of lines possible one is known as NPSH available. So, this is the line that comes from here from the system the other line is NPSH required. NPSH required means you have this line is provided by the pump manufacturer.

So, this line is provided by the pump manufacturer and these two lines they will cut at a point. So, you have to ensure that your NPSH available has to be always greater than NPSH required because pump manufacturer said that you have to provide that much of NPSH for this particular flow rate. For this flow rate this much of NPSH has to be provided because that NPSH would be lost as the pump enters into the casing. Now, your system is providing that much of NPSH. So, that is why you are safe, but if your NPSH available goes below this NPSH required then invariably there will be cavitation.

So, one or so immediately one will say what are the ways we can do what are the what are the immediate measures we can do? One thing is we cannot lift fluid by that extent Z_1

- Zs, we cannot lift fluid by that extent. So, we have to reduce this height. So, beyond some height it would be it will not be possible for the pump to suck the fluid. So, this height has to be reduced, or you have to we have to leave out some of the bends and some of the valves because those are also the potential areas where pressure drop takes place. So, these are some of the measures one has to take and make sure that NPSH available is more than NPSH required and then you would be safe.

That is all I wanted to again re-emphasize. I have already mentioned this in the previous class in connection with the cavitation and cavitation. However, this I wanted to emphasize before I proceed with the flow metering problems. Flow metering is we needs to do flow metering if come to many different applications, be it process, be it in a process flow, be it in a pollution environmental setting, or in pollution control issues. There, we need to capture the data, we need to have a real time, or we need to have a log of what flow rate is taking place through a pipe, through a channel, through a conduit of any type.

So, flow metering is extremely important and one has to also note that once you meter the flow you can take the corrective action. For example, I have A plus B forming C and I have a process going in there a continuous process is taking place from one line fluid A is delivered another line fluid B is delivered to a big industrial scale reactor and the reaction is taking place to form product C. There is certain stoichiometry, the reaction has a stoichiometry A of this amount will react only with B of that amount and so exactly that amount of A and B in exact ratio that has to be delivered. If for some reason there is some fluctuations, there is some issue with the pump the flow stop daily flow is delivering maybe at a 90 percent rate 90 percent of the rate that you thought it should deliver. So, then immediately there are corrective actions to be taken because B has to be reduced so that the stoichiometric ratio is maintained.

Secondly, the reactor might have been there is a heating arrangement around the reactor. Some steam is fed to the reactor, or steam is fed to the enclosure such that the reactor is maintained to a certain temperature, but those are based on a certain flow rate, and now the flow rates got changed. So, that flow rate of steam also had to be changed has to be changed. So, at all times the flow rates have to be precisely measured and any control action required at any time that is based on what flow at what flow rate the fluid is flowing through the flowing into a reactor. It could be a reactor, it could be any other process, it could be a digester, it could be in an industrial problem, it could be some other system altogether, but wherever you have to measure the flow at a real-time and there are controllers placed which will apply control action based on the input from these flow meters. So, how the flow metering is done? There are many different ways a flow metering is performed.

There are you might have seen that there are these flow meters possible. One is this type of flow meters this is referred as rotameter. This type of flow meter you might have seen already. This is known as rotameter in many places in a steam generation unit and in many places you will find this type of a unit present that is known as rotameter and there are other several types of flow meters possible. So, we will start with there is this one class of meters which goes by the name Venturi meter.

Then a variant of that is sorry variant of that is orifice meter. So, these are some class of meters that is possible. The another class is rotameter. There is another class of meter which works on a similar principle as Venturi or orifice meter. However, these Venturi and orifice meters they are more well defined more you have the you have you have essential theories discussed and all, but you will find that there are certain meters that are that are using some form of obstruction to cause pressure drop and they are monitoring that pressure drop.

This is very similar principle as Venturi meter or orifice meter, but these are highly proprietary in the sense you cannot they know if you get this much of pressure drop across that obstruction then the flow rate would be that much. So, that type of proprietary information is there. So, this type of meters are also in place. There is another possibility of so to say turbine meter. Turbine meter would be you on the flow line you have a turbine placed and the number of times the turbine is rotating.

So, when there is a fluid flow is taking place at a very high flow rate you will find the turbine is rotating at a very high speed and that we is tracked somehow what is the rpm of the turbine and from there you can get a quick information of what flow rate is what is the flow rate. Whereas, when the flow is taking place at a very slow rate turbine is rotating very slowly. So, using a turbine you can get and particularly if it is a open channel flow turbine meter works very well. So, this turbine meter that is very much possible. There is another type which goes by the name mass flow, but it is typically used as a mass flow controller.

There is also some amount of metering involved and then based on that they do they apply control action as well in the same place. Mass flow controller this is little it has little more sophistication and it is little more expensive. Mass flow controller here the mechanism is that you have a fluid flow taking place through two parallel channels and then there is a heating coil. I mean the essential principle I am talking about there are many variants possible with the proprietary changes. Now, you have a heating coil present and then you have the flow taking place in through this channel and let us say no flow is taking place through this channel it is just stagnant.

And you have to maintain certain temperature on the heating coil you have to provide some amount of current or you have to provide some energy to make because fluid will be carrying the heat out from that heating coil as the fluid flows. Whereas, here there will be less energy to be put because fluid is not carrying the heat. So, what is the difference? And of course, when you have a greater flow rate more heat would be carried when you have a very small flow rate less heat would be carried. So, using this information one can come up with what is the exact flow rate. And so, these types of devices are there, and they give quick digital information.

Here turbine meter can give digital information that is very much there. And these other devices are also very much. I mean, one can go for further transformation to digital systems, but typically, the venturimeter and orifice meter are there. We just measured the pressure. And for rotameter it gives you a good visual and people generally because rotameters these rotameters these are very inexpensive. So, you do not you put the rotameter just to get a visual of what flow rate what is the flow rate at what flow rate fluid is flowing. So, that visual itself where the where let us say we have a pointer here of float this is called float.

So, these float what is the location of the float that gives me the that gives me the idea what the flow rate is. So, there is a marking on this tube and from the marking we immediately see float is located here. So, the flow rate is this much. So, now, it is with this background and of course, there is another type of meter which is known as pitot tube. So, this is a little different the this type of device it measures the velocity at a point within the conduit.

So, this all these all these measurements that I am talking about here all these measurements are going to give you the average flow rate of average flow rate as far as the flow through a conduit is concerned, but pitot tube gives you the local velocity within that within that conduit not the average velocity. So, this is another unique device which is used. Now, coming to the operation of the Venturi meter, essentially, this is the structure. You can see that there is a contraction, and then there is an expansion in the conduit, and you see that here, this is here in this location a lot of times. This is called throat. So, here you can see that it is there is a velocity that is increasing.

So, the pressure is decreasing. So, there is there would be a change in pressure and that pressure is measured that that difference in pressure is measured and from that we find out what is the flow rate. So, what we do first of all we see that the velocity here is v_1 and the pressure is let us say pressure is P_1 at this location and here the velocity here the pressure is P_2 and velocity is v_2 area here is A_1 and area here is A_2 and the flow that takes place is Q. So, we note that

$$v_1 = \frac{Q}{A_1}$$

$$v_2 = \frac{Q}{A_2}$$

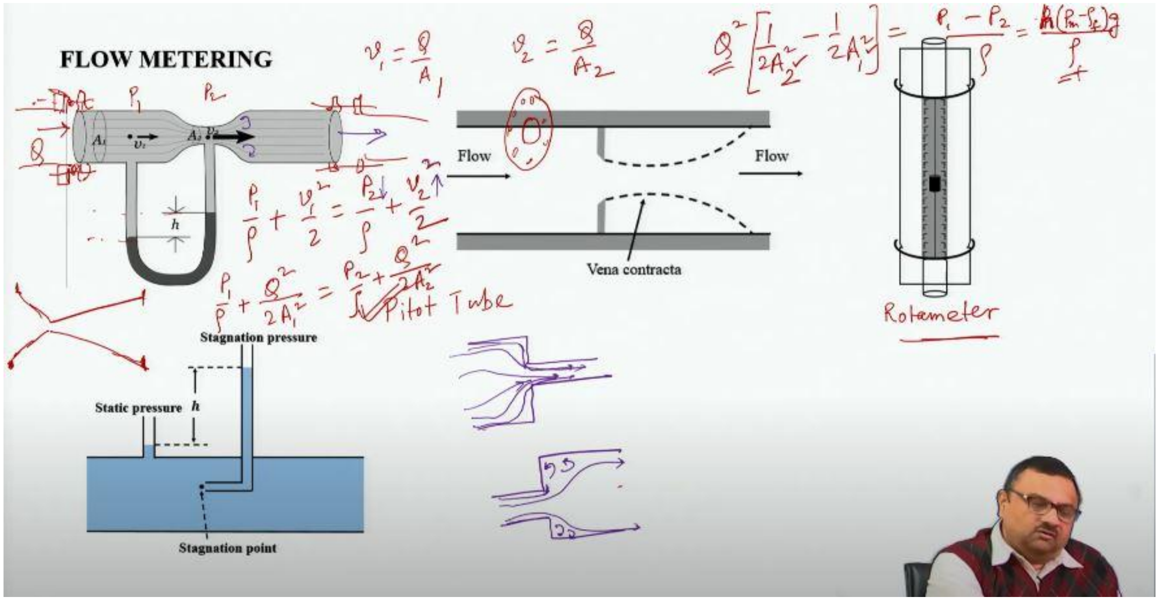
$$\frac{P_1}{\rho} + \frac{v^2{}_1}{2} = \frac{P_2}{\rho} + \frac{v^2{}_2}{2}$$

$$\frac{P_1}{\rho} + \frac{Q^2}{2{A_1}^2} = \frac{P_2}{\rho} + \frac{Q^2}{2{A_2}^2}$$

So, what we see here is if we take this q square term together q square into 1 by 2 a 2 square minus 1 by 2 a 1 square that is equal to p 1 minus p 2 by rho and p 1 minus p 2 by rho is essentially this difference if you ignore the density of the fluid here compared to the manometer manometric fluid density then p 1 minus p 2 is essentially h rho manometer into g. So, this is the h or let us remain. So, p 1 minus p 2 we can always find out what is this h ideally you write rho m minus rho f no problem rho m minus rho f into g divided by rho you can. So, this h you can measure. So, you have a q flow going in now you insert this device you insert this device in the form of this is venturi meter.

So, insert this device how will you insert you have pipe going in here you have a flange you have to place first. So, that flange and then on the venturi meter there would be another flange placed at this point and then these two flanges there has to be you have bolts placed within these there would be gasket. So, make sure there is no leakage and tighten the bolt similarly on this end the pipe will continue again the pipe will have a flange venturi meter will have another flange and then these two would be again I mean on if you take the cross sectional view it would be a circle it would be a circle this is the flange there would be several bolts present all over the flange and this is the pipe. So, this is how you are going to put these venturi meter connect it to another to the part to the other end of the pipe. So, if the flow continues and by measuring this pressure drop by measuring this height difference you immediately find out what is the by measuring this height difference h you find out what is q because you know for this device what is your A_2 you know what is A_1 you have measured h from the manometer you know what manometric fluid you have and what fluid you are flowing rho m minus rho f g and you know what is let us say this is this is rho f.

So, this you will get this you can get what is the value of q that is the idea. So, using this venturi meter you can obtain this information. There are couple of things which I must point out before I proceed that is the venturi meter though it is drawn this way it is not the venturi meter actually appears a little different the venturi meter will appear something of this sort here on this corner. This is what we see that means, the contraction part is much smaller compared to the expansion part. Expansion happens very slowly at a smaller angle it slowly expands to the same diameter it is the same diameter it is expanding from wherever it contracted the same diameter to which it expands to, but it expands much slowly than the or the gradient is much is less steep compared to the contraction part.



That is one thing this is done keeping something in mind one is that you have when there is a sudden expansion and sudden contraction you will eventually have when there is certain expansion and certain contraction there are certain ad formations that are quite common in the sense you have let us say let us say you have a sudden contraction I have one case and you have certain expansion I have another case. So, you will find here if you look at the streamlines they would be taking this shape going like this whereas, sudden expansion means this is how the streamlines are going there. You will eventually find that this in the compression part the streamlines will follow the wall very closely. The streamlines will follow the wall very closely as far as this contraction part is concerned. Whereas, when it comes to expansion part the fluid is I mean giving the fluid more liberty you will find that here there would be what is is generating.

Here there would be boundary layer separation in here around the wall there would be a boundary layer and you will find that this boundary layer cannot continue to travel this way further when there is a sudden expansion. So, there would be a boundary layer separation at this location. So, such issues will come up. So, because of these you will find that there are some recirculation zones forming on the expansion when it comes to expansion, but not in the case of contraction. So, this moment there is expansion then that will lead to loss of pressure loss of energy.

I mean moment there is a recirculation that means that is that is taking away some amount of energy and which you cannot afford because you have a venturi meter here you if there is a major pressure loss you are you are expecting whatever delta p that you have caused here that entire delta p again it will regain it will regain here you want this just to be just there should be an interplay. Kinetic head got convert pressure head got converted to kinetic head when it reached the throat that is what it is because your v2 is v2 has increased significantly. So, the pressure has pressure p2 has to come down to maintain to satisfy the Bernoulli's equation. This term is going up v2 square is going up. So, p2 by rho that term has to come down or essentially you were what we are saying is that the kinetic pressure head is getting converted to kinetic head and then when it again it goes through this expansion part I mean if you had put a manometer from this point to the downstream point instead of upstream to the throat you could have put a manometer that way then you would have expected that this it would be just the reverse I mean that means over this part of the venturi meter the kinetic head gets converted to pressure head.

So, when it comes out it comes out at the same velocity and pressure that means same q by a1 because this is again a1. So, the velocity would be again q by a1 and the pressure again would be p1 that is what your expectation is just kinetic head plus pressure head has to be conserved as it travels through the venturi meter at the throat the one got converted to the other, but the total energy is conserved and when it you go into the downstream when you go into the outlet again the reconversion takes place and you are back to square one that is the idea. But if in this in the middle of all these you start forming vortices here then that will eat away some energy and if that will eat away some energy means you lose some pressure. So, both you total head is lost I mean total energy is lost and you cannot afford energy is extremely important you cannot afford to have loss of energy. So, that is why you try to find out where these such boundary layer separation such for recirculation some such energy loss takes place.

So, you know that the compression side is safe we do not have such problem. In the downstream on the downstream of the throat there could be a possibility how you can avoid it you increase the cross section very slowly you heard of streamlining a body. So, that you follow the exactly follow the streamlines will follow the contour. So, so it is it is you are you are trying to grow very slowly you are not going for a sudden expansion you are just completely opposite of sudden expansion that you have here you are completely opposite of that and so you reduce the energy loss to a minimum. But still there would be some amount of energy loss and that energy loss typically the venturimeter manufacturer they will give you they will provide you this information that how much of energy loss you can expect not I mean energy loss it will it will not be just the energy loss it will be some kind of coefficient because of course, the energy loss would be a function of flow rate.

So, energy loss will not be a single term it has to be a function of flow rate. So, the manufacturer will provide you some kind of coefficient, but that coefficient they said that ok we are 99 percent efficient or 98 percent efficient maybe 1 percent or 2 percent loss will take place. So, they will provide they will provide that information of at what flow rate what would be the loss. So, we so that is so we had introduced the venturimeter there are other aspects to it and the other meters that I talked about I will continue this discussion. So, I will I will continue this discussion on flow metering in my next lecture as well.

So, till that time thank you very much for your attention for this lecture.