Principle of Hydraulic Machines and System Design
Dr. Pranab K. Mondal
Department of Mechanical Engineering
Indian Institute of Technology, Guwahati

Lecture – 21
Positive displacement pump, indicator diagram - I

We will continue our discussion on principle of hydraulic machines and system design. Today, we will discuss about, Positive Displacement Pump and Indicator Diagram.

So, we have discussed at the beginning of this course that one you know category of pump is positive displacement pump or PD pump we generally call in short. This is very important, because now and I have discussed why it is called positive displacement, because there is a positive displacement of the system boundary as a close mass. And we have discussed that in a positive displacement pump, we can have higher heat developed, but the flow rate that will get that is almost constant.

So, now today we will discuss that the operational principle of the positive displacement pump and what are the several issues, I mean whenever we are installing rather how a PD pumps works. So, there are several pumps I mean which in a first under the category of positive displacement pump may like, a reciprocating pump, screw pump, vane pump, gear pump. So, we will discuss I will take one only reciprocating pump to discuss about the features of positive displacement pump.

What is reciprocating pump, because you have seen that reciprocating pump; a reciprocating the word itself suggest that there will be reciprocating motion of the piston. So that is to and fro motion of the piston and that will be connected with the crank and you know connecting rod mechanism. Now, piston will come from one end to other end, and then it might you know suck some amount of liquid from reservoir. And then whenever it is again going back to the original position, then they will try to discharge that put pressure on the trap liquid within the cylinder and then liquid will be discharged.

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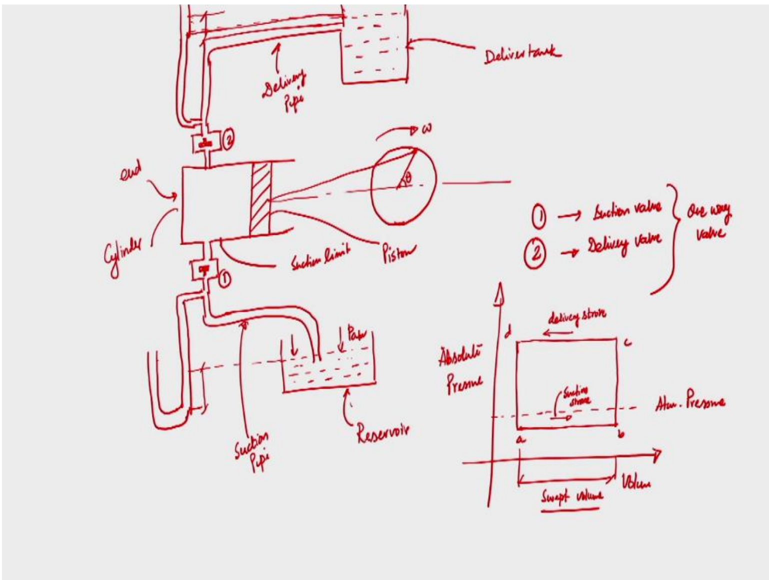

So, if I would have drawn the PD pump, let us say, I need to draw schematic of a PD pump. So, if I draw schematic of a PD pump, it will take some time. So, this is delivery tank, this is reservoir, now we have a few valves; one-way valve, these are valves. So, suppose this is the limit of the suction, this is the suction limit; this is 1, this is 2. So, 1 is the suction valve, number 2 is the delivery valve both the valves are one-way valve, one-way valve. And this is piston, you know which is rotating at an angular velocity. So, we will discuss that now if it is; if I discuss this one, we will discuss that is equal to what it is, so this is atmospheric pressure P atmospheric.

And this is let us say this is piston, and this is delivery pipe, and this one is the suction pipe. So, this is delivery pipe this is suction pipe and so maybe; so if this is the height, so we will discuss this amount and this amount is how much. So, let us now discuss about the how it works; so we are having one cylinder, this is cylinder and we will draw the indicator diagram this is very important. So, if we have absolute pressure, absolute pressure this is volume and say this is the atmospheric pressure.

So, we are having atmospheric pressure, this is absolute pressure and the volume. So, as I said that valve one is suction valve and valve two is delivery valve and both the valves are one-way valve. Now, initially when I piston bring from suction limit to towards outer side that means, from the piston end if I bring this is a piston end, so this is the cylinder end, this is end of the cylinder. So, when I bring piston from end to the front side that open side of the piston. That means, we are creating negative pressure inside the cylinder, and which will fall; which will be below the atmospheric pressure. And that driving pressure difference will allow, because the suction pipeline is connected to the reservoir, where atmospheric pressure is acting on the fluid mass.

Now, when I bringing piston from piston end to the piston open side rather in a front side, then a negative pressure will create inside the piston cylinder; and that will create a pressure difference between the reservoir and the piston inside the piston cylinder; that pressure difference will try to push liquid from reservoir to the cylinder. And in that case, you know valve go up this is one-way valve, valve will allow liquid to go to the cylinder.

So, whenever piston is coming from piston end to the open side, a negative pressure inside the piston cylinder which is below the atmospheric pressure will create a pressure difference or the driving pressure difference, driving force rather that will allow liquid from reservoir liquid in the reservoir to be pushed, rather to be pushed into the supply line suction pipe. And it will go to the reservoir by you know lifting the delivery lifting the suction valve, because suction valve is one-way valve.

Now, when piston has raised to the you know that you know outer limit point, whenever piston has reached to the front you know open side of the cylinder at the at the limiting condition, then cylinder will be filled up with the liquid. And valve try to remain seated over the suction side. And, since it is a one way valve, so when force acting on the valve will be less, because of the less driving potential. So, gradually water will be filled up in the cylinder and a situation will come when the pressure difference between cylinder and the reservoir will be 0; and at that time no liquid will be enter, no liquid will be entering to the cylinder and no force will be acting on the valve and valve will try to remain seated over the valve seat and it will closed.

Now, what will happen the next successive stroke when piston will come from the open side, and towards it will move toward the when and it will move towards the end of the piston. Then since it will create a pressure on the suction valves, so suction valve will trail will try to remain seated over there, rather it will remain closed. On the other hand, a driving force that is acting, so it will create pressure on the fluid mass and that will try to lift the delivery valve. And, it will go to the delivery tank by lifting the delivery valve, because a certain amount of force is required to lift the delivery valves. So, whenever that crosses then liquid will go to the delivery tank through delivery pipe.

So, now if I draw the indicator diagram of this particular pump; so this is the operation principle and of course, how much amount of liquid will get and that essentially depends upon the frequency of the operation frequency of the you know piston movement, since it is connected to the crank and connecting are mechanism.

Now, if suppose I am telling this angle is let us say theta. So, if I draw the indicator diagram, absolute pressure versus atmospheric pressure. So, what is happening; so at the end say let us say point a, piston whenever piston pressure at the cylinder inside the cylinder is less than atmospheric pressure. So, whenever I am bringing piston from piston end to the piston front side. That means, at a constant pressure rather I assume constant pressure, but I am increasing the volume; so it will be like this, say it this is a, this is b.

So, I am bringing piston from piston end to the piston front side, rather I am creating I am allowing volume to be increased and which is known as swept volume. So, this is known as this is called suction stroke, this is suction stroke and this volume is known as swept volume. So, this is swept volume, and this is suction stroke. So, it will be as the entire process is occurring at the constant pressure.

Now, after coming at point b the pressure inside the cylinder after coming at point b, pressure you know and whenever I am bringing piston whenever bringing piston from piston end to the front side, delivery valve is remaining closed. Because, it is again one way valve, there is no sufficient pressure to lift up the delivery valve and to go or to allow the liquid to go out to the delivery tank by a delivery pipe. So, it will remain seated over there.

When you know piston is coming at the point b, let us say at the end of the suction stroke then pressure increases abruptly, pressure increases abruptly let us say up to this point I am calling c, before it start for the delivery stroke. So, at the end of the suction stroke entire cylinder is filled up with liquid and pressure increases suddenly; volume remain constant pressure increases suddenly, because at that time both the valves are closed; suction valve is closed, and delivery valve is already closed. Since, both the valves are closed, so pressure increases abruptly to a point c while volume remaining constant.

Now, again when I am bringing piston from piston right side, rather piston of front side to the piston end side, cylinder front side to the cylinder end side; so what will happen volume will reduce and I am assuming as I have, we are assuming that the volume reduces at a constant pressure process.

So, assume process is constant pressure process and volume decreases to the up to the point d. And then that time suction valve is remaining closed, delivery valve is opened, liquid is moving liquid is going to the delivery tank by delivery pipe. And whenever piston reaches at the end side, then pressure again suddenly falls, because now delivery valve is closed, suction valve is also closed, pressure falls you know to at point a, volume remain constant. So, this is known as this is known as delivery stroke. So, this is delivery stroke.

So, this is suction stroke, this is delivery stroke and this is atmospheric pressure. So, I can see that the entire suction is happening at below the atmospheric pressure, and that that is what is the driving force, driving pressure difference to have a liquid to be entered into the engines as so it will entered into the cylinder. So, this a b always lies below the atmospheric pressure.

So, this is indicator diagram of a positive displacement pump and I think it is clear now that during suction stroke pressure in the cylinder is below atmospheric pressure. So, during the suction pressure inside the cylinder is below atmospheric pressure that is indicated by line a b. While pressure during the delivery stroke is always above the atmospheric pressure, because delivery tank is open. So, of course, we have to have higher than atmospheric pressure, otherwise there will be a driving force to have a flow of fluid from to the delivery pipe to the delivery tank and that is represented by c d.

Now, you are seen that at the end of suction stroke and beginning of delivery stroke pressure rises abruptly along the line b c. So, we have seen that at the end of the suction stroke, and when it so suction stroke is end, suction valve is closed. And when the piston is try to move just putting pressure on the liquid element till now delivery valve is closed, until or unless we are crossing that you know weight of the piston by overcoming the you know; I can increase the pressure which will overcome the piston resistance that sorry valve resistance of the valve weight that time piston valve two will remain closed.

So, the moment at which suction you know piston tries to move towards the end during the beginning of the delivery stroke, suction valve is closed; delivery valve will remain closed, because we need to overcome the resistance of the valve and for that we need to build up a sufficient amount of pressure. And since then pressure rises abruptly at line b c.

Similarly, when piston reaches at the end both the valve closed and piston falls inversely adopt you know point a, because at the end of again suction stroke.

So, this is what is indicator diagram, but here I would like to point out I will keep this schematic same, because two more again I have to discuss so many things. Now, I will discuss that whatever indicator diagram we have draw this is again ideal one, because while we are while we have plotted this indicator diagram we have indicated suction stroke, delivery stroke, and we have discussed about the movement of the delivery valve and suction valve. We did not take into account two different aspects.

One is of course, frictional losses in the suction pipe and delivery pipe that is there, because fluid whenever it is flowing though a closed conduit, then of course frictional losses we cannot eliminate, we cannot ignore that is there; on the top of that what will be there, because whenever liquid is there in the you know suction pipe or delivery pipe, we cannot ignore the inertia. So, because liquid inertia that in the pipes which will try to oppose, the changes in velocity. So of course, we are having own velocity otherwise how we can have flow of liquid.

So, liquid inertia in the suction you know pipelines that will try to oppose the velocity to be developed or a velocity that will be changed. And the in a in frictional effect that is there in the pipeline, suction pipe delivery pipe that we did not take into account while we have plotted this indicator diagram. So, we need to take all this into account while we are providing the indicator diagram ok. So, now if I, a modify this indicator diagram, we have to modify, because we need to take those effects into account; how we can take. So, suppose I am now drawing this indicator diagram in next slides and if I draw it.

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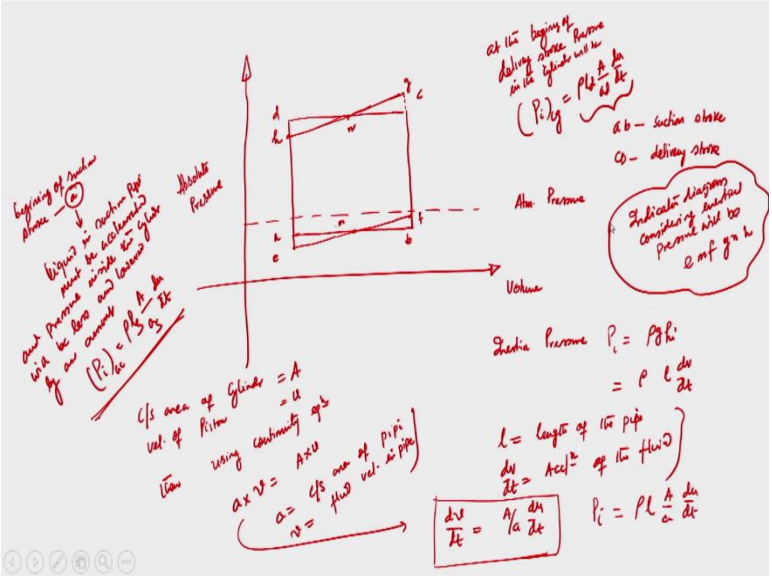

So, if I draw that absolute pressure versus volume. So, this is volume and this is absolute pressure; and we know this is the atmospheric pressure. So this is atmospheric pressure. So, if I draw the ideal indicator diagram that is what we have obtained that is line a b, this is then sudden rise in or abrupt rise in pressure, because the delivery valve you know is remaining closed, suction try to push on the liquid and there will be a sudden rise in pressure. Then the process is assumed to be constant volume process pressure, you know constant pressure process, volume reduces that is delivery valve opens and liquid goes to the delivery tank through delivery pipes.

And when at the piston reaches at the end of the cylinder then a delivery valve will be closed, suction valve will be closed rather it will try to open and again piston will try to come towards the front side of the cylinder. And it will create and pressure, it will create a negative pressure gradient and the pressure will falls abruptly again to the point a. So, this is what is called suction stroke, this is a, this is b, this is C, this is D. So, we have given a b is the suction stroke and b C D, C D is the delivery stroke that you have identified.

So, in this indicator diagram we have to modify it, this indicator diagram we have to modify it by taking the effect of frictional losses in the pipelines, as well as the inertial effect in the pipelines into account. Because whenever pipeline will be always filled up by the liquid, liquid will have inertia and that inertia will change will oppose the change in velocities and frictional losses; how can I, this is very important; so note that the inertia pressure, I mean whenever liquid will have you know that let me discuss a few things at the end of the stroke. So, fluid mass we brought into rest; that means, fluid will be decelerated.

So, maybe at the end of the suction stroke or at the end of the delivery stroke fluid mass will not be brought to the rest and it is deceleration. So, when it is decelerated, pressure will increase, similarly you know so at the end of the suction stroke or beginning of the suction delivery stroke fluid is brought to the rest and it will I mean it will be decelerated. Similarly, you know whenever it is piston is moving towards rather at the beginning of the delivery stroke and a fluid will have acceleration, so accelerated; so, whenever it is accelerated, pressure will fall; whenever it is decelerated, pressure will increase so this is very important.

So, at the end of the stroke of the liquid in the cylinder and element pipe must be brought to the rest. So, at the end each stroke, I mean it is suction stroke or the delivery stroke. Fluid in the cylinder as well as the pipeline must be brought to the rest, so that means I mean that is decelerated. So, whenever it is decelerated, I mean pressure will increase, because and whenever it is accelerated pressure will fall.

So, now that is so what is the pressure because of the inertial effect? So, this inertia pressure, inertia pressure. So, what I am telling at the end of each stroke that is at the end of suction stroke and at the end of delivery stroke, liquid in the cylinder as well as the as well as in the pipeline must be brought to the rest that is decelerated.

So, similarly in next in the consecutive stroke, fluid must be accelerated. So, whenever piston is coming from its beginning, fluid must be accelerated. And similarly, whenever liquid is during the delivery stroke, when piston is moving then fluid must be accelerated. So, in that time because of acceleration pressure will fall. So, decelerate pressure; fall of pressure because of deceleration, fall or rise in pressure because of deceleration acceleration that end clip essentially, you got the inertial effect.

So, inertia pressure that is given Pi = $\rho\ g\ h_i$ that is given. So, I can write for this particular case that is $\rho\ g\ l\ \frac{dv}{dt}$ right., where l is equal to length of the pipe, length of the pipe right. And dv dt is the acceleration of the fluid, and dv dt is the acceleration of the fluid.

so whenever fluid is brought to the rest at the end of the each and every stroke then there will be a brought to the rest that is deceleration, pressure will increase. And at the beginning when whenever delivery stroke is started, so fluid must be accelerated. So, at the end there will be high deceleration; so high acceleration, so pressure will fall.

So, what I told that at each and every stroke at the end of each and every at end of each stroke in the liquid, the liquid in the cylinder and as well as the pipeline must will be brought to the rest, must be brought to the rest that is decelerated, and immediately afterwards at the beginning of the following stroke, the fluid in the cylinder and the associated pipe must be accelerated.

So, whenever at the end of each stroke the fluid in the cylinder, as well as the pipeline must be brought to the rest that is decelerated and immediately afterwards at the beginning of the following stroke, beginning of the following stroke fluid must be accelerated. Fluid in the cylinder, as well as a pipeline must be accelerated. So, we need to know because of this deceleration, acceleration what will be the inertial effect, inertia pressure; there will be rise in pressure or fall in pressure. So, we have calculated inertial pressure Pi = $\rho\ g\ h_i$

Now, if I assume that you know assume cross section, cross sectional area of cylinder, because velocity in the pipeline, velocity of velocity of the fluid in the pipe and velocity of the fluid in the cylinder are different. Cross sectional area of the cylinder is capital A and velocity of piston is equal to u, then from continuity equation then using continuity equation, what I can write. Then using continuity equation, I can write a into b is equal to a into capital U, where a is the cross-sectional area of the pipe, of pipe and v of the fluid velocity in pipe.

a x $v = A\ x\ u$

a = c/s area of pipe

v = vel of fluid in pipe

A= c/s area of cylinder

u = velocity of piston

$$\frac{dv}{dt} = \frac{A}{a}\frac{du}{dt}$$

see du/dt is important; because this du/dt the it depends upon the frequency I mean, frequency of the you know cylinder by which it is now having to and from motion.

So, what I can see that from this expression, what I can see at the beginning of suction stroke that is point a. So, I am writing here beginning of suction stroke that is point a, what is happening at this point a; liquid in the suction line, liquid in the suction pipe must be accelerated. So, beginning of the point a; liquid in the suction pipe must be accelerated, because piston is trying to come from end to the front.

So, pipeline liquid will be accelerated, it was initially at rest now it will be accelerated. So, the pressure in the cylinder must be lowered, so it is accelerated. So, pressure in the cylinder must be lowered by an amount. So, pressure in the cylinder must be lowered. So, beginning of the suction stroke that is point a, liquid-liquid in suction pipe must be accelerated and pressure inside the cylinder will be less.

So, at the beginning of suction stroke liquid in the suction pipeline will be accelerated, pressure will be lowered, pressure will be lesser in the cylinder and that will be lowered by an amount that is calculated from inertial pressure Pi = $\rho\, l\, \frac{A}{a}\frac{du}{dt}$. And if I plot it, from this diagram from the point a, let us say this is point a. So, this will be lowered by an amount up to this or so pressure in the pressure inside the cylinder must be lowered by this amount, let us say a e.

And similarly, at the end of the suction stroke pressure liquid in the suction pipeline will be decelerated of course, because there will be no suction valve will be closed decelerated. And pressure inside the cylinder must be increased and that will be increased by an amount Pi = $\rho\, ls\, \frac{A}{as}\frac{du}{dt}$. So, now that will be increased. So, if it is so this is let us say, I am calling it this; is I am calling it f so f. So, if I plot it, so this will be the new diagram.

Let us say this is crossing at point m. So, now pressure will be actual indicator diagram will be e into f, similarly at the end of rather at the beginning of delivery stroke; at the beginning of delivery stroke what will happen. So, at the beginning of the delivery stroke, pressure in the cylinder must be high, because that will try to put you know you know that that will try to put pressure on the fluid, and that will be equal to similarly at the beginning of delivery stroke pressure in the cylinder, pressure in the suction pipeline. You know pressure in the cylinder will be high; pressure in the cylinder will be high and will be P I, you know that is you know (Pi)cg = $\rho\ l_d\ \frac{A}{a_d}\ \frac{du}{dt}$.

So, by this amount so that will increase of course, pressure will increase, because at the beginning of the delivery stroke piston is trying the moment, momentarily piston is trying to put force on the fluid. So pressure will increase and that increment is because of the inertial effect; so that is I mean and delivery valve will try to open. So, it will be you know, the exact amount will be (Pi)cg = $\rho\ l_d\ \frac{A}{a_d}\ \frac{du}{dt}$. So, pressure will increase.

Similarly, at the end of the delivery stroke again fluid in the at the end of the delivery stroke, the pressure falls pressure will fall definitely, because delivery valve pressure in the cylinder will fall and that fall will be equal to minus of (Pi)cg. So, equal amount, but pressure will fall. So, if I connect this line; so this is let us say c g, c g and this is equal to d h. So, this h g is the new. So now the actual indicator diagram will be let us say this is n, I am calling at n. So, now actual indicator diagram considering the inertial affect, the indicator diagram considering inertial effect will be e; you know that e, m, f, g and h.

So, indicator diagram indicator diagram, considering inertial pressure will be e, m, f, g n h, so this is clear. So, at the beginning of the delivery stroke pressure in the cylinder will be high, of course piston will try to move the trying to move towards the end, it will create force on, it will create, it will try to create pressure rise the liquid that is being there in the cylinder. So, pressure will increase by amount that is inertial pressure. And at the end of the beginning stroke again, I mean pressure in the cylinder will be will fall, and that is will be equal to the rise in pressure during the beginning stroke and that is given by dh.

So, this is the indicator diagram considering inertial effect we have obtained, we need to again superimpose, because we till now we did not take into effect frictional losses, because frictional losses will be there in the pipeline whatever it is pipes suction pipeline and delivery pipeline that we need to take into account. And considering frictional effect, what we need to modify and what would be the modified indicator diagram that we will discuss in the next lecture.

So, I stop here today.

Thank you very much.