**Fundamentals of Industrial Oil Hydraulics and Pneumatics**
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**Module 5**
**Lecture 17**
**Introduction to Positive Displacement Hydrostatic Units (Hydraulic Pumps & Motors)**

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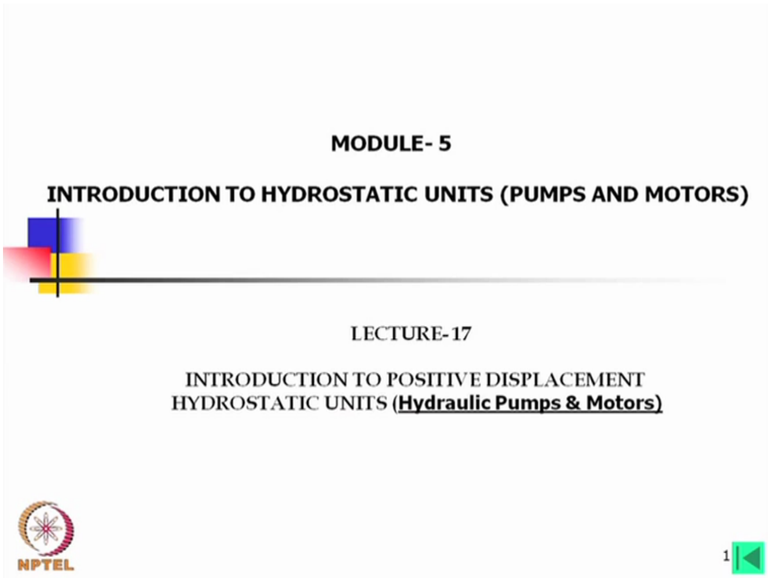


Lecture, tittle is introduction to positive displacement hydrostatic units, hydrostatic units means hydraulic pumps and motors.

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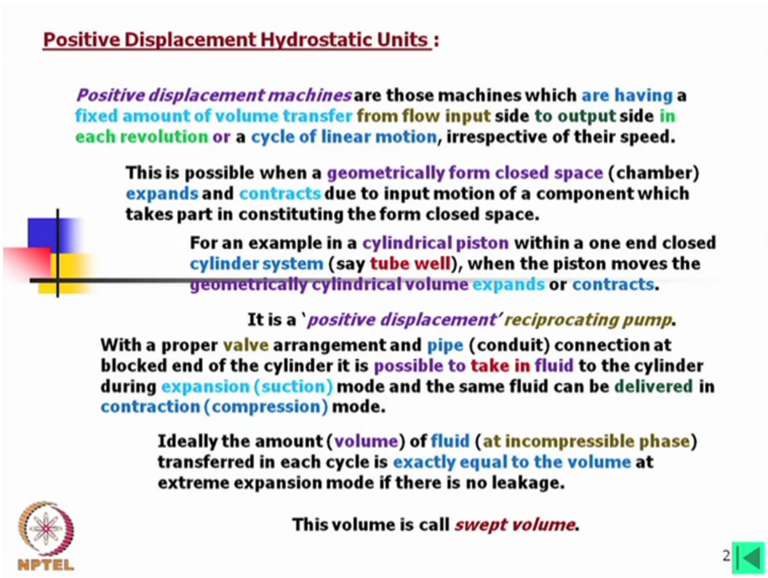

Positive displacement machines are those machines which are having a fixed amount of volume transfer from flow input side to output side in each revolution or a cycle of linear motion, irrespective of their speed. This means that whatever will be the geometric displacement the same amount will be transferred from input side to the output side let it be a rotary machines or a linear actuator this is of course there is no leakage we are considering there is no leakage.

This is possible when a geometrically formed closed space chamber expands and contracts due to input motion of a component which takes part in constituting the form closed space. For an example let us consider a cylindrical piston within a one end closed cylinder system say tube well, when the piston moves the geometrically cylindrical volume expands or contracts, we know this.

It is called positive displacement reciprocating pump. With a proper valve arrangement and pipe conduit connection at blocked end of the cylinder it is possible to take in fluid to the cylinder during expansion which is suction mode and the same fluid can be delivered in contraction or compression mode.

Ideally the amount that is volume of fluid at incompressible phase transferred in each cycle is exactly equal to the volume at extreme expansion mode if there is no leakage. This volume is called swept volume. Now here I would like to mention contrary to this if we consider hydrokinetic machines which I have already discussed say for example centrifugal pump there is physical connection between the input and output and the medium is being pumped say for example a centrifugal pump is pumping water, you will find the water coming in suction side and being discharged they have physical connection, only we are adding kinetic energy to the fluid to generate the pressure at output side, okay.

But in case of positive displacement machines the volume is taken in then it is cut off, the whole volume is now posed out in the output side and usually you will find there is no suction head for positive displacement pump. However, depending on the machines it may have low suction head.

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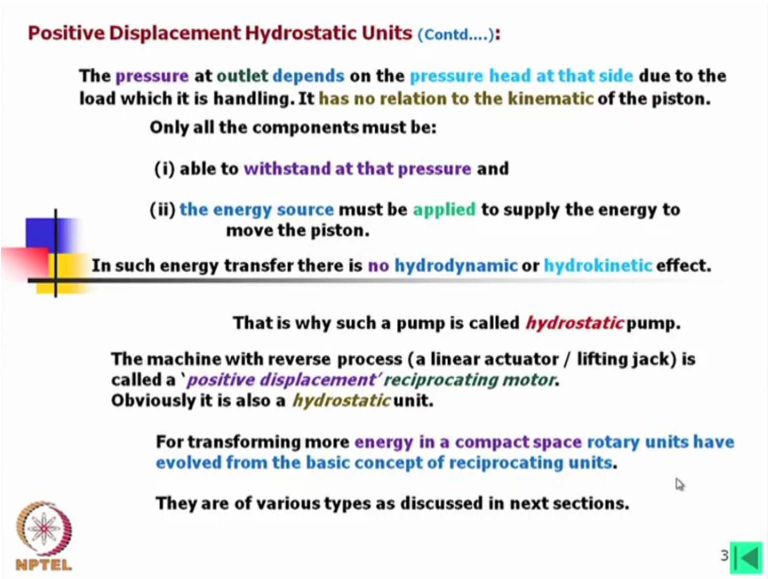


The pressure at outlet depends on the pressure head at that side due to the load which it is handling. It has no relation to the kinematic of the piston, this means that if there is no pressure or if it is not transmitting any load only the pump in the volume you may find there is no pressure on the oil except it has to overcome some resistance so there will be some pressure.

So pressure is experienced, if I consider a pump it is not pumping the pressure, it is pumping the fluid and pressure is being experienced. Now one thing I would like to mention that we are talking about mostly in this lecture incompressible fluid that is mostly the hydraulic units. Now only all the components must be in case of as it is not pumping the pressure, pressure is being experienced at the outlet, so we should have one able to withstand at that pressure the component should withstand at that pressure it should be able to take the loads. And the energy source must be applied to supply the energy to move the pistons this means that if there is a pressure in the outside if it then the energy must be sufficient to generate that much pressure, okay.

In such energy transfer there is no hydrodynamic or hydrokinetic effect. That is why such a pump is called hydrostatic pump, in fact we should call hydrostatic unit it might be pump or it might be motor. The machine with reverse process a linear actuator, lifting jack is called a positive displacement reciprocating motor, we can have either linear or rotary, there is also another term is used which is called rotating in one case rotary means the position of the piston and cylinder fixed only when it is the piston at the it is some (())(7:31) is rotating these pistons are being actuated. But there is also a rotary pistons where the whole piston units itself is rotating we will come to that later.

Obviously it is also a hydrostatic unit that mean linear actuator which is reciprocating motors the hydraulic jacks it is we should call it hydrostatic unit, we should specifically call it it is a linear motor, linear actuator. For transforming more energy in a compact space rotary units have evolved from the basic concept of reciprocating units. This means that say tube well the only one cylinder is there so it is reciprocating.

Now if we put few cylinder together and we actuated with the (())(8:32) with a phase time phase and we have to mix (())(8:37) mix of the output then we can develop a rotary machines, in fact the rotary machines are like that. They are of various types as discussed in the next suctions.

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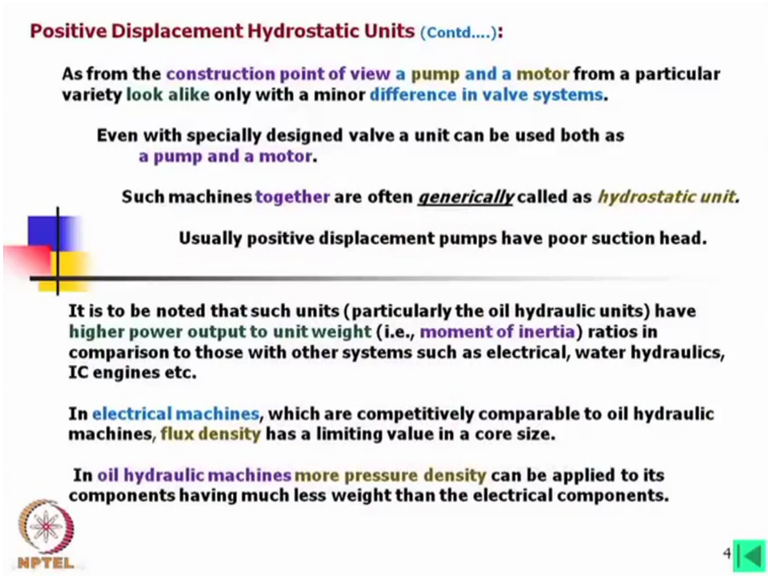


As from the construction point of view a pump and a motor from a particular variety look alike only with a minor difference in valve systems. It is very difficult to identify whether it is a motor or pump, in case of pump we rotate the shaft and oil is taken in in suction stage and it is delivered at compression stage, in case of motor it is reversed the high pressure oil is pumped in and then output is taken through the shaft.

Otherwise there is very difficult to understand which is pump or motor it is indicated there from there we can consider that this is pump and this is motor. If we think of the components there, there is a valve that valve if we change the valve the same unit again can be used as a motor. Even with specially designed valve if we design the valve specially a unit can be used both as a pump and a motor, when we learned about the symbols there is a symbol that a unit which is used as a pump and motor but we should keep in mind if we design the valve to act both as a pump and a motor definitely we have to sacrifice some finer activities of the valve in that way you will find normally such pumps or motors having a lower efficiency but still it can be used.

Such machines together are offend generically called as hydrostatic unit, this term is many people they are not much (())(11:17) with that suppose even if within the mechanical engine if you say this is a hydrostatic unit, these people will always they will ask whether it is a pump or motor, they will never except that is a hydrostatic unit, hydrostatic unit mean this can be used as pump and motor just changing the valve. But if you think of the centrifugal pump of course that can be used as a turbine but it is difficult, it is difficult you have to change so many things there.

Usually positive displacement pumps have more suction head which I have mentioned we do not need even suction head in many cases usually the purpose for which we use the hydrostatic unit we can put the pump even submerged inside the oil. However, the small suction head means in terms of the height may be 1 meter suction head may not be problem. Even for very good performance of hydrostatic units sometimes a charge pump is used we will come later on the hydrostatic systems when we learn about the hydrostatic system.

Now it is to be noted that such units particularly the oil hydraulic units have higher power output to unit weight, this I have explained but still specifically I would like to mention that very high power output to unit weight or you can say that moment of inertia to torque output divided by moment of inertia that ratio is high in comparison to the other system such as electrical water hydraulics, IC engines etc.

In electrical machines, which are competitively comparable to oil hydraulic machines, flux density has a limiting value in a core size. That means the motor core which is if we measure the flux density comparing with its weight we will find it will have some saturations we cannot make it very small to have very high flux density. So that is why we cannot reduce this electrical motor size and I have already perhaps told you but still I would like to mention.

Say for example if we consider a 5 kilowatt electric motor may be it will be around 300 meter length and diameter may be 250 millimetre, whereas if I think of 5 kilowatt an oil hydraulic motor, size will be may be only 150 millimetre length and diameter about 80 millimetre. In oil hydraulic machines more pressure density can be applied to its components having much less weight then the electrical components, this is the advantage that is the fluid inside it is generating pressure equal pressure in all directions, so load is distributed on the body which is usually ferrous components and if the load is distributed in that way it can take much more load, more stress so that is why we can go for small size.

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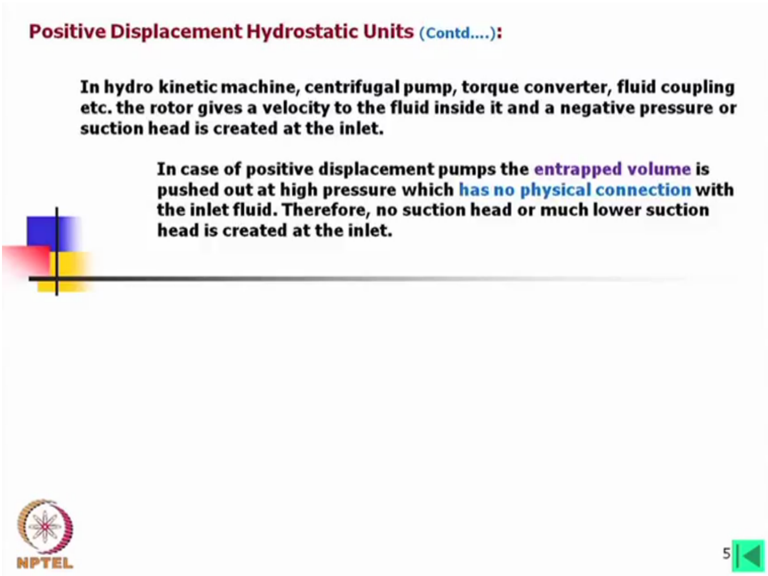


In hydrokinetic machines, centrifugal pump, torque converter, fluid coupling etc. The rotor gives a velocity to the fluid inside inside it and a negative pressure or suction head is created at the inlet, I have explained so this is the difference there. In case of positive displacement pumps the entrapped volume is pushed out at high pressure which has no physical connections already which I have already told you with the inlet fluid. Therefore, no suction head or much lower suction head is created at the inlet. That is actually we can specially arrange the machine to create the suction head but it is of no meaning, it is not required.

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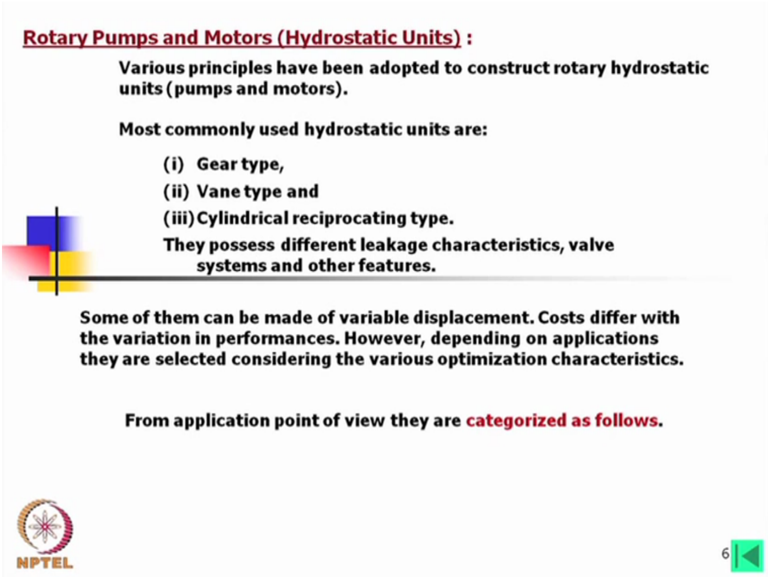


Various principles have been adopted to construct rotary hydrostatic units pumps and motors, we shall in this lecture we shall discuss about the rotary pumps and motors and we will see we will look into that there are various types of such motors and units. Most commonly used hydrostatic units are one is the gear type, then vane type and cylindrical reciprocating type these three are most common and these are rotary machines usually not rotating machines. They possess posses different leakage characteristics, valve system and other features.

Some of them can be made of variable displacement. Costs differ with the variation in performance. However, depending on applications they are selected considering the various optimization characteristics. You understand this because if we would like to optimize some sizes say for example gear pump we have more leakages we cannot optimize that leakage characteristics. In comparison to that best will be the cylindrical reciprocating type, whereas vane type will be in between that. From application point of view they are categorized as follows.

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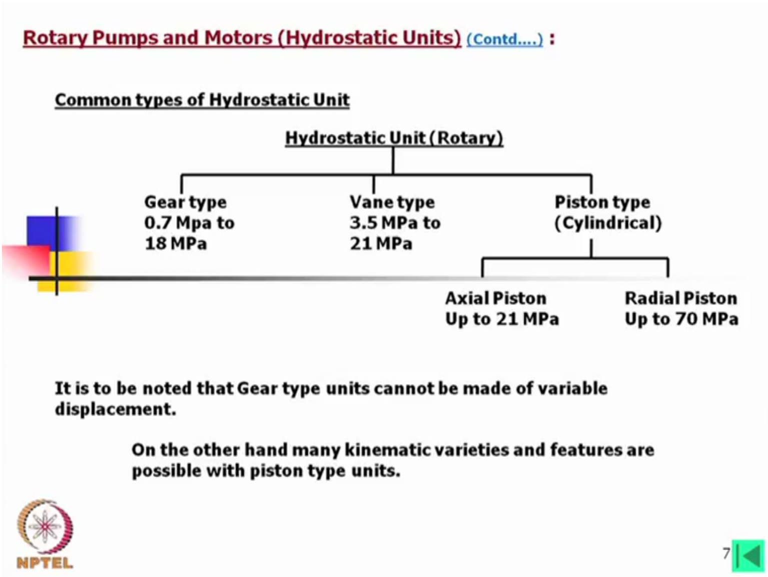


Gear type normally for low pressure 0.7 Mega Pascal to 18 Mega Pascal. Now this 0.7 that is we would say that we do not normally use the hydrostatic units for such low pressures but it can perform at such low pressure also. Now next one is the vane type, where 3.5 Mega Pascal to 21 Mega Pascal then why this 3.5 you may ask a question we this what at 0.7 Mega Pascal or even less the answer is yes obviously but when we would like to have pressure range of this in between 3.5 to 21 Mega Pascal, we would look for vane type.

Now in piston type we have axial piston which can be used upto 21 Mega Pascal and radial piston also which can be used upto 70 Mega Pascal. Now I would say that these are all general purpose, we can have more pressure particularly axial pistons we can go for higher pressure, very carefully designed gear type pump nowadays it can give even 20, 21 Mega Pascal or even more and vane type also can give higher pressure.

It is to be noted that gear type units cannot be made of variable displacement, whereas vane type we can make it variable displacement and obviously piston type we can make axial piston and radial pistons both variable displacement. On the other hand many kinematic varieties and features are possible with piston type units.

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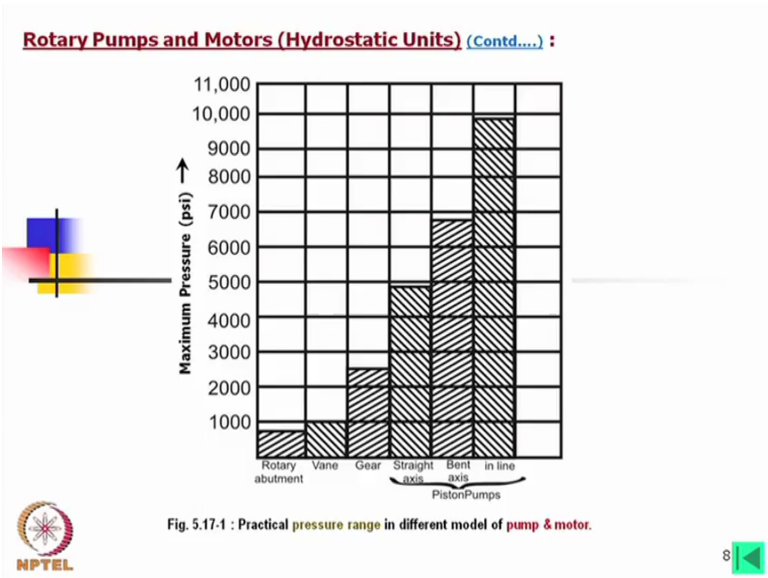


Now if we look into the there the maximum pressure capacity then what we find rotary (()) (20:40) means it is a some sought of rotary not exactly gear and these are usually very low pressure, next comes vane, next comes gear but I think this than vane also nowadays this chart is not very upto date, vane also can be made of I pressure and next is straight axis I have I shall explain what is straight axis and what is bend axis and in line, in line, straight axis that is a lowered pressure bend axis a little better and in line means usually which is like a radial piston it is called in line they can go upto 10000 PSI and this means that about 70 Mega Pascals.

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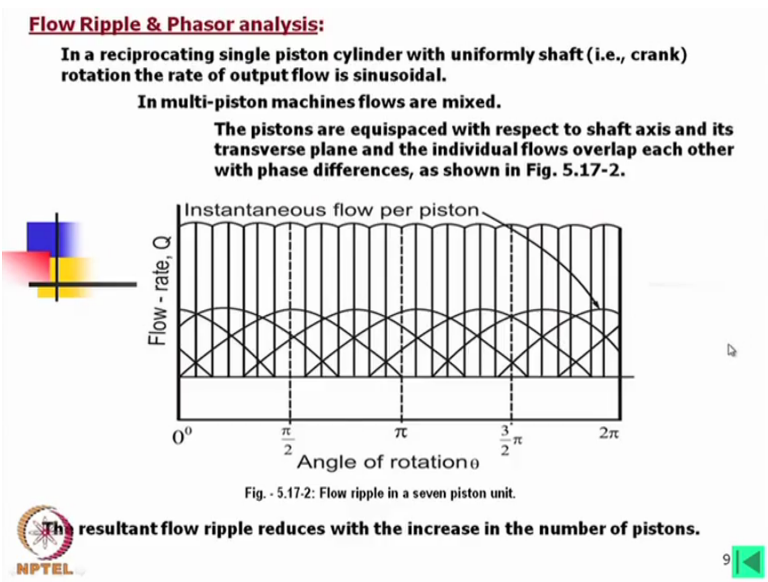

In a reciprocating single piston cylinder with uniformly shaft crank rotation the rate of output flow is sinusoidal. In multi-piston machines flows are mixed that has to be here I would like to mention that as flows are mixed we call it DC direct current we can compare with it is a DC type machines, whereas there is also possible we can make alternative flow hydraulic machines.

However, this is not popular due to the there is a valve in problem and it is not much beneficial if we do not want to separate the fluid or I would say that for the same fluid it is not much benefited that is why we do not go for AC. However, we need not consider at the present moment any alternative flow hydraulics we should call all are direct DC flow machines.

Now we have here we have written that it is a sinusoidal effect but it might have also higher harmonics, this is there. The pistons are equispaced with respect to shaft axis and its transverse plane and the individual flow overlap each other with phase differences, as shown in figure 5.17-2, in this figure if you look into this say this is one piston, okay next piston is this one, next one this one, next one like this depending on how many pistons simply we can divide the 2 Pi divided by the number of pistons and then we can start its cycle from that angle and we will get this sinusoidal curves, this curve ideally it is sinusoidal but with higher depending on kinematics it may have some higher harmonics but nature will be more or less same.

The resultant flow reduces with the increase in number of pistons, what is resultant flow ripple? This one is called resultant flow ripple, as we are mixing the flow for a single piston we are getting a flow like this. Suppose you are rotating in a tank shaft a single pistons, you will find half cycle it is delivering the oil and half cycle it is suction it is not delivering but whenever mixing for each piston although it is half cycle delivery and half cycle suction but for multiple pistons you will find that when one piston is in the suction mode definitely another few pistons in the compression mode and they are delivering oil.

So ultimate flow ripple we will get like this, that means if the shaft is rotating at a constant speed we will find that flow is fluctuating, with the increase in number of pistons that fluctuation reduces. So we cannot go for very small number of pistons and there is another factor interesting factor we will come to that now.

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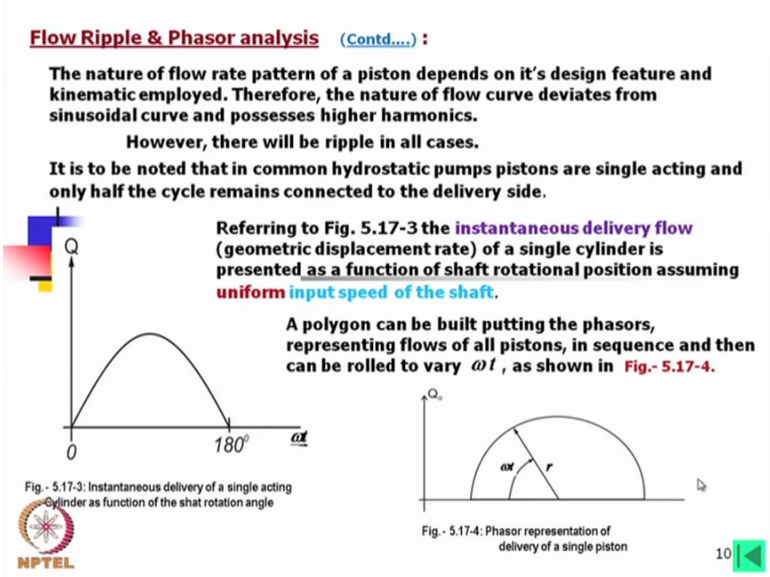


The nature of flow rate pattern of a piston depends on its design features and kinematic employed. Therefore, the nature of flow curve deviates from sinusoidal curve and possesses higher harmonics, which I have explained. However, there will be ripple in all cases whatever may be the harmonics are there, there will be ripple. It is to be noted that in common hydrostatic pumps pistons are single acting and only half the cycle remains connected to the delivery side.

You should know this double acting say for example in many cases you will find that suppose if you take a linear actuator and it is had rod at the both side for equal volume displacement. Now while it is going right side then left side is suction it is accepting oil or allowing oil to take in whereas the right side it is delivering the oil and when it is moving in the left side it is vice versa we can have a special valve in the suction side and we can have a special valve in the delivery sides.

And in that case although there is a single cylinder but that we should call double acting not single acting but whatever rotating machines you will find with the pistons normally they are single acting not double acting only one side. So each piston is having half cycle delivery and half cycle suction, only as they are being mixed then when one is in suction mode, other in the delivery mode ad that is why there is a continuous delivery.

Now we can say this is a cycle say may be for the delivery side we have drawn this cycle, okay. Now referring to this figure instantaneous delivery flow geometric displacement rate of a single piston is presented as a function of shaft rotational position assuming uniform input speed of the shaft, okay.

So this is presented with respect to that uniform speed omega is constant, okay. If we it is not constant this nature will change that is obvious, okay. A polygon can be built putting the phasor, what is phasor you can this is in electrical analysis these are used, you can consider a phase that is say r is the arm, then amplitude you can calculate r of sin theta and at any instant you can say this is the amount of delivery, so this is called phasor. Now for all the pistons if we draw their phasor together will get a polygon.

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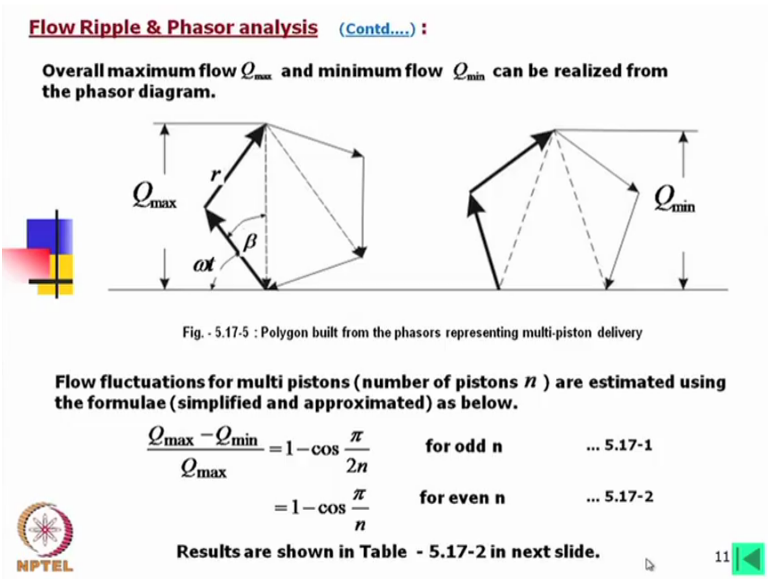


Overall maximum flow Q max and minimum flow Q min can be realized from the phasor diagram, it is like that. Say we have five pistons, so what we can do this phasor say this is with respect to the shaft this is the first piston position, the second piston obviously you will find it will be here because this angle difference will be say if this is 0 plus omega t, then this will be 0 plus 2 Pi divided by 5, we have 5 pistons plus omega t.

So in that way if we put all the phasor together you will find this polygon and this will be the this height is the maximum height which will represent the maximum flow this is analogous to the flow that means in the flow ripple the higher point can be find out this by this one and the lowest point will be this one that means if I rotate this one on this line then it will this point will generate a curve say small curve this one then next this one will generate the other curve.

So in that way we will get a wavy curve which is the flow ripple but this is again ideal we are not considering any harmonics higher harmonics only on the basis of sinusoidal. However, this can be we can formulate this one. Now flow fluctuation for multiple pistons number of pistons say n are estimated using the formula simplified and approximated as below, it is simplified one you will find that even if with this if you calculate then this formula that Q max minus Q min by Q max is not this one there will be some other term which you can neglect.

But you can arrive into this simplified equations neglecting the other parts and 1 minus cos Pi by 2n is for odd number of n and for even number of n it is 1 minus cos Pi by n, where n is the number of pistons. Now this can be plotted for multiple difference cylinders multiple cylinders.

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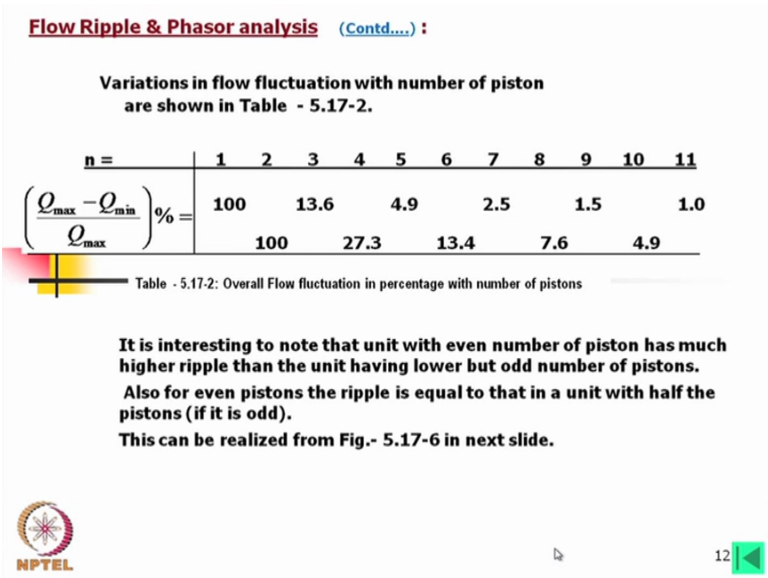


And this we have presented here in this table. Now if I consider 1 pistons then Q min is 0 in the flow ripple that it has will be 0 definitely, okay and so this will be 100 percent, 100 percent fluctuations that means if you consider the sinusoidal curve it will be from the top to bottom at the 0 lying so this is 100 percent and if we look into this formula this is quite interesting that for 2 pistons also it is 100 percent.

Now when we use 3 pistons remember those formula just n is equal to 3, you will find this is 13.6 only 13 percent fluctuations, if you go for 4 cylinder it is again increasing this is you can visualize like that. In case of odd number it is like that they are lagging after one another is in such a way 3 pistons are in delivery when 2 in suction say let us 5, or even if for 3, 2 in delivery 1 in suction or vice versa, in case of 4 pistons there is a there is a situation 2 in delivery, 2 in suction, so that is not advantageous.

For 5 pistons you see this is reduced to 4.9 about 5 percents and for 6 you get again 13.4 which is you find it is for 3 pistons the same fluctuation will have for the odd number 3 pistons and even number 3 into 2, 6 pistons, okay that means if you get any even number you will find that if you divide by 2 you will have a odd number the same fluctuation will be there, if you divide an even number get an another even number then again you have to divide in that way you can find out except if you divide 4 divided by 2, then 2 piston is not having the 27.3 it is having 100 percent fluctuations otherwise you will say for example 8, 8 is having 7.6 this if you divide it is 4, it is having 27.3 so you will find that this is having different but all in the higher side, whereas if you go 10 pistons and 5 pistons they are having same because 10 divided by 2 is 5, okay.

Now in that way if we arrived into 11 pistons you will find that it is only fluctuation is 1, so next if you go for a 13 pistons you will find this is less than 0.5, so this means that if you can use the 13 pistons we would say there is no fluctuation and it is better to use the 13 pistons machines why 5 we should go for 13 but you should always remember with the increase in number of pistons the cost will increase, valving valve porting will be problem second problem.

Thirdly in terms of reliability you would say that when they will start a little error then the dynamics will increase in case more number of pistons. After certain time you will find all the pistons cylinder are not of same size, within the tolerance zone they are different now when they are worn out if there is more number of pistons dynamics will be increased. So in that way what I would say you will normally find the multiple pistons there are not less than 5 pistons, whereas not more than 13 pistons not more than 13 pistons. However, 5, 7 and 9 these three are very common 5, 7 or 9, mostly 7, 7 is a very good number for the number of pistons for which only 2.5 percent fluctuations and considering the leakage it is slightly in higher side.

It is interesting to note that unit with even number of pistons has much higher ripple than the unit having lower but odd number of pistons. I would say that in interview normally it is asked it is a question that why there normally you will find this odd number of pistons in hydraulic pumps and motors, answer is here but I would like to mention in case of gear pump or vane pumps or vane motors this is not followed. Usually vane and gear pump they are having more than easily it can be designed more than 13, so maybe 20 that means there is a 20 pistons in case of gear pump.

And there for the 20 pistons you will find that maybe 2 percents, 3 percents so not much difference so this is only or mostly for a cylindrical piston machines which are used for very high pressure. Also for even pistons the ripple is equal to that in unit half the pistons if it is odd not for the even say as I told 8 divided by 2 is not giving the same fluctuations.

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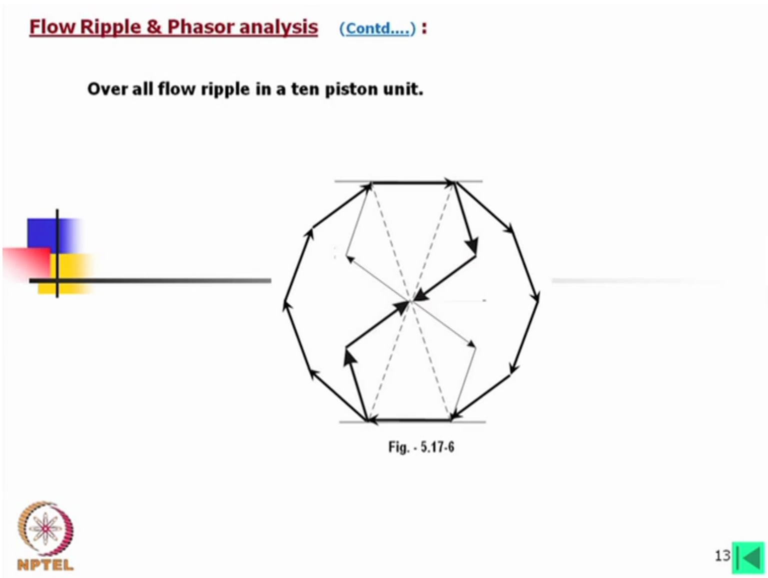


This can be realized from another figure now here I have shown what we have done say this is of 5 pistons, okay this is another 5 pistons. Now obviously if I consider this of same phasor definitely say this means that I have drawn the 10 pistons phasors like this and 5 pistons. Now as the length of this arm are same this means that we have used same pistons and same stroke for constructing 10 members, 10 piston machines obviously for the same rotation the delivery will be double.

Now to make the delivery equal we have to reduce the size upto half stroke and but if you look into the nature you see this is showing the 5 piston minimum flow mixed flow minimum this height and maximum will be this one diagonally so when it will become the straight vertical this line will become vertical but in case of 10 also you were finding just double of that in case of the minimum one it is just double of that, that means we are going to get same nature only it is multiplied by 2 and if we divide by 2 for in case of 10 pistons stroke length then it will give the same nature just with this phasor of diagram we can realize this.

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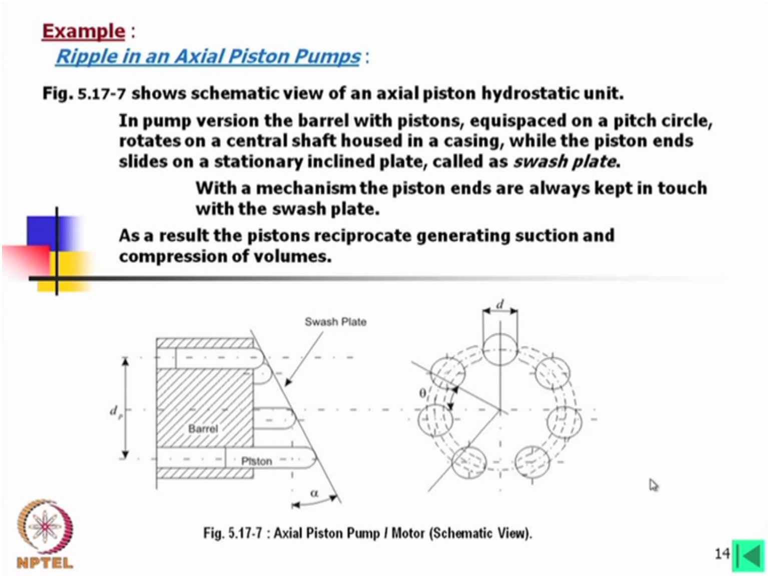


Now we are considering for the ripple we are considering an example now this is what we have shown that is axial piston pump how it works? We will come into detail later but let me explain a little bit this is called a barrel, barrel means it is just a cylindrical body of thickness of this much and then there are holes, how many holes that depends on how many piston we are using, you can see here you have used 7 pistons so there are 7 equispaced holes on which the pistons are placed.

Now this plate is called first plate, this can be made fixed or this can be mixed variable angular displacement that means this alpha can be varied. In case of variable pump or motor this can be varied, in case of fixed this alpha we keep fixed, this is the tilting angle of the first plate. Now let us consider this piston or say the top one here this pistons now this is while it is rotating like this, this coming this side and again it is going up.

So that means while let us consider from this side it is rotating a clock wise, so this point is going beyond this crane and it is rotating like this. So gradually this piston is coming out and the stroke is increasing that means total stroke can be taken from this point to this point if I draw a straight line this is the total stroke. So one side it is a suction another side it is a delivery.

Now in pump version the barrel what I have explained this is written here it is a equispaced on a pitch circle and this is a central housing shaft through this while the piston ends slides on a stationary inclined, plate. Now there is an arrangement so that the piston is always touch this swash plate. It is written here it will always touch the swash plate. As a result the piston reciprocate generating suction and compression volumes.

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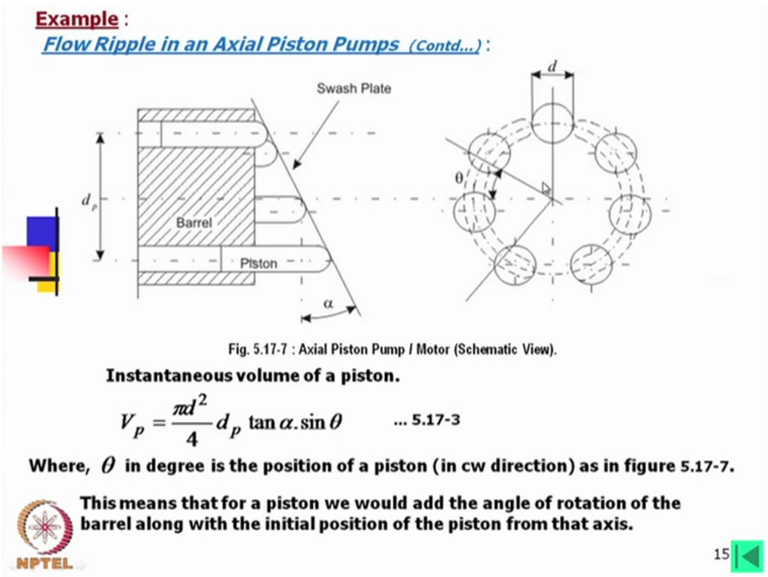


Now instantaneous volume of a piston can be written by you see Pi d square by 4 is the area of this piston one single pistons, okay and then d p is their pitch circle diameter, d p tan alpha is the stroke length. Now this stroke length we can it is varying with the shaft rotations, what we have to do that we have to if I if we imagine this height then this is the sin theta. So that is the displacement volume, okay you can just do this exercise of your own you will find that this is the instantaneous position of this piston.

So if we plot this one we will get the flow curve, so that is why it is called this is a sin curve because this part is fixed for when alpha is fixed and this is also fixed part. Now theta in degree in the position of a piston in clock wise directions we have considered so from 0 position this piston has rotated this much so we have multiplied we have taken sin theta, for this piston how much we should take, theta plus 2 Pi divided by the number of pistons so this is written here.

This means that for a piston we would add the angle of rotation of the barrel along with the initial position of the piston from that axis, okay this is very simple. So if we would like to plot this one we have to add theta plus 2 Pi by number of pistons.

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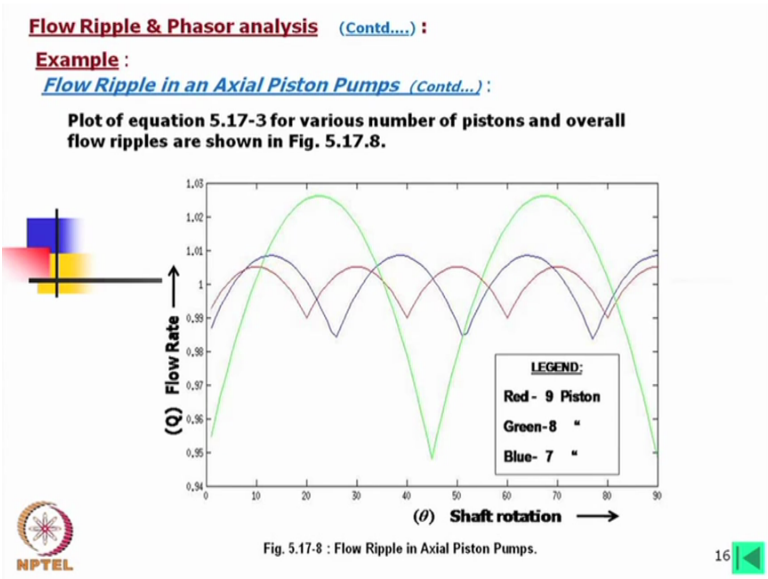


Now this we have plotted here, now what we have consider we have consider the blue one is the 7 piston we have taken 7 pistons and for 7 piston is this one, this is the fluctuation. So we have used the same formula or it might be the exact variation formula this formula what we have developed that we have used to plot this curve. Now this we have not mentioned the unit, it might be meter cube or may be inch cube like that depending on the size. So even if this can be presented in dimensionless form.

Now for 9 piston as you see this ripple is being reduced, whereas in case of 8 pistons this is increasing now if I consider this angle this is around how much this is 18 degree because 360 divided by 9 no sorry 20 degree it will be 180 by because half cycle 180 degree Pi divided by 9 so this is 20 degree, okay.

Now in case of 7 pistons this is 180 divided by 7, how much it is about 2 and (40, 20) 25.5 I think like that so you can see this is the angle. In case of 8 piston so it is how much 180 divided by 8, 22.5 but you can see this curve is like this because (())(48:31) so because 2 pistons, 4 piston suction 4 pistons so you will get this type of cycle for 8 pistons. So if you plot that equations you have to you can do such exercise because usually this is a questions that what will be the pistons showing this was plate angle we do not shown here the offset of this first plate, it is pivoted on the axis of the shaft.

In many cases or not many cases in some special design this is also a offset, once you put that offset you will find that another term will come. So this curve will be slightly different from this sinusoidal curve, okay. So in that way we have what we have understood that by the phasor analysis we can find out the in general form what will be the flow ripple in rotary piston pumps.

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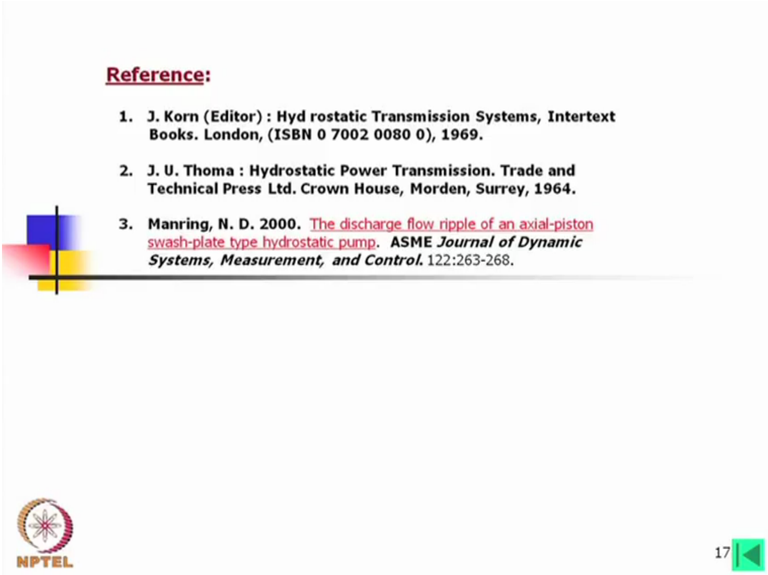


And for that I would say that the references are the same hydrostatic transmission system by Korn, we can follow this and particular if we would like to know more about the phasor diagram because this is I have not seen anywhere except in that books this is by Professor J U Thoma who is also I would like to say he was one of the pioneer who used (())(50:26) in fluid power, he is a man from Switzerland fortunately he came here he came to IIT Kharagpur and we have met him and in his book you will find that phasor analysis.

But the formulation part is not given you can try of your own, you will not arrive into that equations only thing you will get some equation close to that you have to neglect the part which is having less contributions. Now another I suggest that you should read the papers on this pump motor design by Manring there are many other people but Manring he in recent times in last 10 years he has published many papers.

So if you particular if you would like to know more about the in line piston pumps which I have shown in this figure you can follow you can website you can just click on the Manring’s name you will find that this paper is available there, this particular the paper which I have mentioned this is still in online if you click his name you will find a list of papers and then if you click on this paper you will get this paper, you can read it, thank you.