Introduction to Fluid Machines, and Compressible Flow

Prof. S. K. Som
Department of Mechanical Engineering
Indian Institute of Technology, Kharagpur

Lecture - 20
Reciprocating Pump Part II

Good morning, I welcome you to this session of fluid machines. In a last class we discussed the basic principle of operation for a reciprocating pump, and we have also discussed that how the acceleration heads during suction, and delivery strokes are developed due to non uniform motion of the piston that during the suction stroke acceleration, and deceleration takes place for the piston similarly the acceleration, and deceleration takes place in the delivery strokes, because of which the piston or the pump as a whole as to develop additional heads over, and above that of the theoretical head you can say determined by the static lift of the pump.

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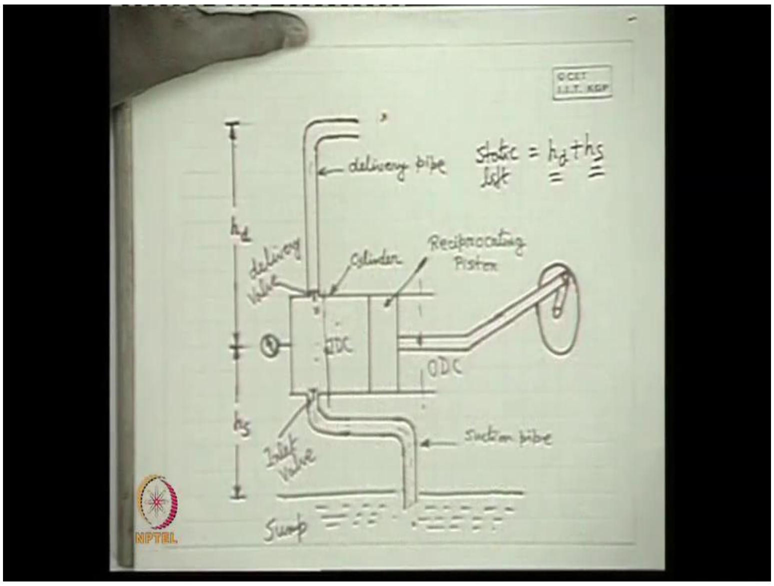

So, today we will discuss the rate of delivery. Now if you see a pump reciprocating pump in its simplest form you see that during the suction stroke when the piston or the plunger moves from I d c to o d c in this direction the pressure falls below that in the sumps. So, the liquid comes through this inlet or suction pipe to the cylinder. So, therefore, during this stroke when the crank moves one eighty degree there is no flow in the delivery line; that means, the delivery is zero; that means, the flow in the delivery is zero when the piston starts the delivery stroke or starts this motion from o d c to I d c in that direction. So, it pushes the liquid the pressure is immediately sensed at this point considering the liquid to be incompressible that we have recognized earlier, and then the delivery valve opens, and the delivery takes place. So, this type of pump is known as a single acting single cylinder; obviously, there is a one cylinder single cylinder single acting pump.

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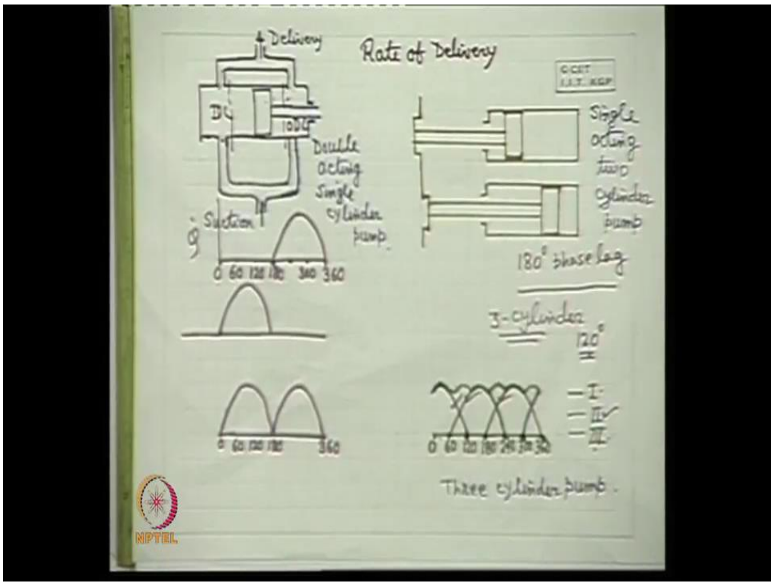

So, therefore, if we plot the rate of delivery versus crank angle; that means, this is the delivery axis the rate of delivery will see that first one eighty degree revolution; that means, if we plot it with respect to crank angle on x axis. So, zero degree is the angle that crank measured from the inner dead centre position. So, zero to one eighty this represent the suction stroke there is zero delivery.

So, delivery takes place only in the delivery stroke from one eighty to three sixty, and as you have noticed the velocity in the delivery pipe varies periodically, because of the acceleration, and deceleration head where it is zero, and then it is goes on increasing attains the maximum they meet of this stroke considering a simple harmonic motion of the piston, and simultaneously of the liquid column in the delivery pipe.

So, therefore, the velocity follows this sinusoidal distribution, and similarly the delivery that is the flow rate; that means, here we can write the flow rate q dot. So, they therefore, we see the delivery occurs only from one eighty degree to three sixty degree angle of rotation for the crank, and that is also a non uniform delivery now this can be eliminated;

that means, to make a continuous delivery this is not a continuous delivery. So, it is intermittent delivery; that means, again another three sixty to five forty there will be a suction, and again there will be a delivery. So, this delivery will be intermittent. So, to make a continuous delivery a type is used known as double acting single cylinder pump; that means, what happens here this cylinder is single, but the delivery, and suction takes place in both the sides the connection is like that which means that if we consider this as the I d c I d c, and let this as the o d c; that means, when the piston moves from I d c to o d c this side the suction takes place where as this side the liquid for the liquid in this side of the piston the delivery takes place; that means, when the piston moves from I d c to o d c the suction valve here or the inlet valve opens at the same time the delivery valve opens here; that means, this is suction for the liquid in this side of the piston, and delivery for the liquid in this side; that means, the right side of the piston this phase.

So, therefore, delivery takes place in both these strokes while this is the suction stroke for the liquid in this side the delivery takes place through this line similarly when the piston moves from o d c to I d c the delivery valves here opens, and the liquid here flows through the delivery. So, it is simultaneously executing both the delivery, and the suction strokes in both zero to one eighty degree rotations of the crank. So, therefore, you see in a double acting machine we can just get a diagram of this type; that means, from zero to one eighty there is a delivery with sinusoidal variation, because of non uniformity in the flow, because of the acceleration, and deceleration of the piston, and similarly this is there from one eighty to three sixty.

Therefore we can improve the delivery from an intermittent one to a continuous one, but still the delivery is non uniform now the non uniformity in the delivery can be eliminated if we use multi cylinder pumps, but multi cylinder pumps if we use two cylinder pumps two cylinder here where the reciprocating motion of the piston is executed by one eighty degree phase lag here one eighty degree phase lag a two cylinder with one eighty degree phase lag unfortunately this does not remove the non uniformity why this gives the same diagram why this is, because when suction for one cylinder will be the delivery for other cylinder, and vice versa.

So, a superimposition of these two gives the similar thing, but if we use three cylinder if we use three cylinder pump let us consider equally spaced; that means, one twenty degree within the crank angle; that means, one twenty degree apart from one another three cylinders are we can get relatively a uniform discharge if you follows this let this cylinder one two three. Now if you the draw the diagram with respect to the angle made by the piston of the first cylinder with respect to its inner dead centre position, then you see from zero to one eighty is the suction.

So, therefore, this is a superimposition. So, rate one is the first cylinder. So, rate on gives the discharge for the first cylinder from one eighty to three sixty well the second cylinder they it starts its suction at one twenty degree with respect to the first cylinder. So, from one twenty to three hundred that is one eighty degree of crank rotation there will be suction for the second cylinder while from three hundred to one twenty this side; that means, it is three hundred plus one eighty. So, it will be the discharge; that means, first sixty degree three hundred to three sixty this will be the part of the discharge curve sixty degree, then for another one twenty degree this is the discharge curve. So, this will be maximum here which is thirty degree.

So, this two curve it represents this part, and this part is the discharge curve for second cylinder, and similarly it one twenty to three hundred is the suction for the second cylinder is very simple for the third cylinder which is one twenty degree apart phase lag from the second one. So, that will be zero one twenty plus one twenty two forty. So, this suction starts from two forty, and it will go upto this point sixty degree here the two forty plus one eighty well. So, one twenty this side, and sixty again it comes back sixty. So, from sixty its starts its delivery stroke. So, this one is the delivery of the third cylinder.

So, if you now superimpose this delivery curve this one this one, and this one, and we show it from zero to three sixty degree of crank revolution with respect to the first cylinder, then we get a continuous curve like that a more than less continuous curve; that means, discharge becomes more or less uniform, if we use more number of cylinder if we you if we large number of cylinders this non uniformity will go down almost we will get a straight curve.

So, therefore, we conclude that the rate of delivery may be made uniform inspite of the deceleration an acceleration of the pistons provided we use number of cylinders in line with some phase lag of their reciprocating motion execution of their reciprocating motion all right next next is very important phenomena that air vessel.

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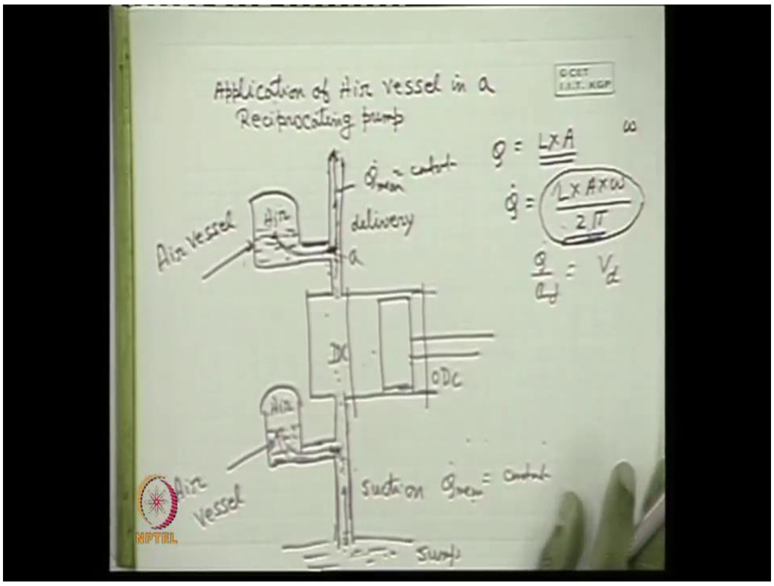

Application of air vessel what is an air vessel application of air vessel in a reciprocating pump procating pump now we have seen that until, and unless we use multi cylinder in the pumps we have for a single cylinder what we have we have an intermittent discharge, and discharge is non uniform. So, to make the discharge uniform for a single cylinder air vessels are used in delivery, and suction side what is this let me draw that diagram first for a air vessel, these are air vessel is very simple now what is done what is an air vessel.

Now, to make the basic purpose is to make the discharge uniform in the delivery line air vessels are used of course, it has multi functions that I will come ultimately we will arrive at that conclusion. So, air vessels are large vessels or large container closed that one end with compressed air inside it with air inside it which is attached to both delivery, and suction lines very close to this cylinder. So, it should not be attach somewhere here as close as possible to the cylinder. So, that these lengths of the delivery, and suction pipes from the cylinder to the air vessels are as small as possible now what happens it is very simple these air vessels work as a fly wheel similar to that of a fly wheel in a machine. So, it takes the extra air from the mean discharge a sorry extra work water from the mean discharge when it is more that the mean discharge, and it gives water when the mean when the water flowing to the delivery or suction pipe is less than the mean discharge let us understand the…

Now, first of all we have to find out we have to we have to understand that the delivery in the first delivery side you consider that delivery side the flow is not uniform it is sometimes more sometime less, if we find out a uniform flow rate uniform flow rate can be found out by finding out the volume swept. Now let the stroke length is l which is is equal to two times the crank radius, and the cross sectional area of the piston is a. So, this is the volume swept per unit per one cycle.

So, if I know the omega the crank revolutionary is p we can tell the rate of volume flow is l a into omega by two pie this is the volume served by the piston this an average volume flow rate. So, if this volume flow rate divide we divided it by the cross sectional area of the delivery pipe let a d, then we get the average velocity of flow, but this velocity of flow varies in the delivery, because of the acceleration, and deceleration show that the flow rate through the delivery pipe, and simultaneously to the suction pipe varies what happens what is the principle of operation for air vessel.

Now, let us consider the delivery side when the flow is very high; that means, flow is more than this mean discharge mean flow, then the pressure here is more. So, what happens when the pressure here is more the liquid rushes to the air vessels. So, the pressure of the air is. So, adjusted that its must equate to a pressure at here which corresponds to the mean discharge. So, therefore, whenever the discharge is more than the mean discharge when it happens at the beginning of the delivery stroke that when the piston starts from its o d c. So, pressure air is more. So, that the discharge is more than the mean discharge the discharge rises there is an acceleration; that means, the flow rate increases.

So, for during that period the extra water flows out flows into the air vessel. So, pressure is going down which means that from this part onwards the flow is reduced, and ultimately brought down to this value the reverse happens that during the subsequent deceleration part that is the latter part of the delivery stroke when the flow rate is less than the mean discharge; that means, deceleration takes place the flow rate decreases. So, therefore, the pressure here is reduced the air pressure is. So, adjusted that when the pressure here is reduced the accumulated water in the air vessel rushes, and joins here. So, that the flow becomes more than the reduced flow, and ultimately flows through the delivery pipe.

So, here a constant pressure is maintained to supply a constant flow through the delivery pipe from the air vessel onwards to the over head tank. So, here we get a constant q mean that is the value which is constant; that means, this way the air vessel either supplies water or absorbs water to maintain a uniform flow rate through the delivery pipe from the air vessel connections onwards similar thing happens for the air vessel in the suction side try to understand what happens in the suction side at the initial stage when this piston moves from I d c, then what happens due to the acceleration of the piston the suction pressure falls below that of the ideal of theoretical suction pressure determined by the height of the pump from the sump level this height.

So, therefore, what happens more liquid the pressure here falls. So, liquid from the sump comes at a rate which is more than the mean discharge, but what happens when the pressure here falls to a value lower than that of the theoretical suction pressure, then the water from this air vessel also comes, because the flow takes place in this direction. So, which increases the pressure at this point. So, that from the sump it takes the flow rate which is q mean; that means, a reduced value not a high value.

Similarly, at the subsequent part of the or the latter part of the suction stroke when the pressure here increases, then the flow rate decreases through this suction pipe, but what happens when there is an air vessel the pressure rises here. So, therefore, water again goes to the air vessel. So, that the same amount of flow is taken from the sump by the suction pipe. So, therefore, this part of through part of the suction pipe always a uniform flow comes from the sump similarly this part of the delivery pipe always a uniform flow comes through the delivery pipe.

So, therefore, if you look as a whole to the pump you see that the incorporation of these two air vessels makes the flow through this part of the delivery pipe, and through this part of the suction pipe almost constant, and this is equal to the mean discharge the discharge or flow rate varies only in this part of the delivery, and suction pipe that is from the air vessel to the cylinder since this part is very small, because the air vessels are connected very close to the cylinder the fluctuations takes place only in the small part of the tubes that also does not create any serious danger from the stress consideration.

So, therefore, we get almost a uniform discharge to the delivery pipe, and a uniform flow rate to the larger part of the suction pipe.

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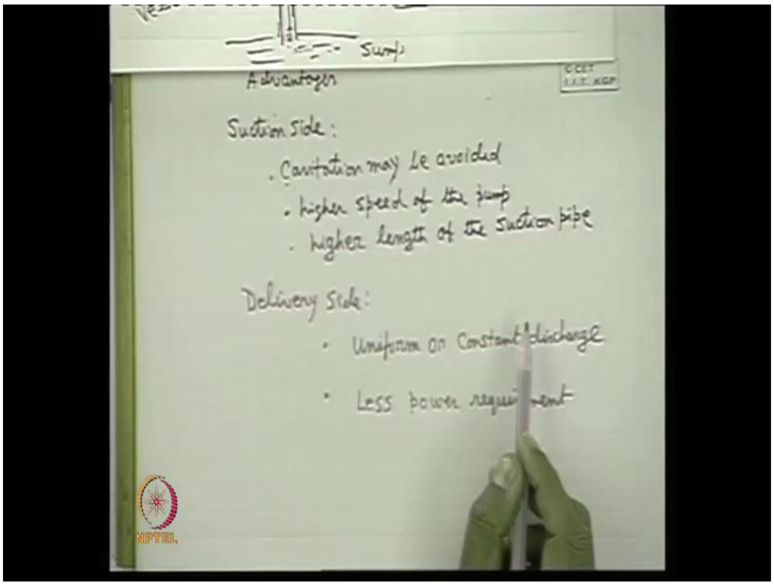

So, what advantages do we get from here first advantage you see let us first write that advantages from suction side suction side what advantage we get advantages. So, distinct advantages suction side we see that now suction side as we have seen earlier in our diagram for head discharge diagram that this pressure e falls below that of a this is h s rho g this is the ideal or theoretical suction pressure which is determined by this height of the pump above the sump level now, because of the acceleration if there was no acceleration the pressure minimum pressure in the pump was this.

So, therefore, it is only the height of the pump which should be the criteria to determine the cavitation you understand this any, but, because of this acceleration at the beginning of the suction stroke that we explained in the last class I explained the pressure falls here e. So, therefore, the speed of the pump I told in the last class is restricted, because of the cavitation, because if the speed is more the acceleration will be more at the beginning of the suction stroke. So, therefore, pressure e that point e will goes still below; that means, the minimum pressure in the pump will go down that should not go below the vapour pressure of the working fluid at the existing temperature.

So, therefore, here we see when the acceleration, and deceleration is coming into picture, then the minimum pressure point goes down. So, that the cavitation there is likelihood for the cavitation to occur. So, here we see when we put the air vessel very close to the cylinder. So, his pressure this point goes very close to that. So, this minimum point pressure is boosted high which is which is corresponds to the mean discharge pressure. So, therefore, the likelihood of cavitation is avoided.

So, the first advantage is the cavitation may be avoided cavitation may be avoided. So, cavitation may be avoided is related to what cavitation may b avoided means we can go for a higher speed of the pump higher speed of the pump; that means, even at the higher speed these are interrelated the cavitation may not be there if we use an air vessel in the suction side similarly higher length higher length higher length of the suction pipe we can use these are the important things from the practical point of view.

So, we can use a higher length of the suction pipe we can go for a higher speed of the pump. So, that the head developed will be more without cavitation without the likelihood of cavitation to occur similarly in the delivery side what we get advantage delivery side the first the advantage is what first advantage uniform discharge uniform or constant discharge uniform or constant discharge almost uniform or constant discharge, because whatever is the variation of discharge in this part of the pipe it is smoothen out by the flow of water in either direction from air vessel to delivery pipe or delivery pipe to air vessel to make the flow in the latter part to be almost constant.

And anther very important thing is that less power, because a large amount of power is eliminated which was consume to accelerate the liquid mass here the acceleration of liquid take place for this amount of liquid mass. So, larger length of the delivery pipe the liquid is not accelerated. So, a large amount of power is saved which was earlier consume to provide the acceleration head to a large amount of liquid mass; that means, it is the liquid mass in the entire delivery tube.

So, therefore, less power requirement less power requirement. So, these are the advantages for incorporation of or for incorporating the air vessels in a reciprocating pump we mainly get the uniform discharge we can increase the speed of the pump with avoiding cavitation we can use the higher length of the suction pipe which means that we can place the pump at a higher height from the sump. So, we can location of the pump made may be made at a higher height from the sump, and at the delivery side a uniform discharge, and less power requirement.

Now, let us find out very simple analytical expressions for the flow of water from air vessels now you see what is the mean discharge mean discharge?

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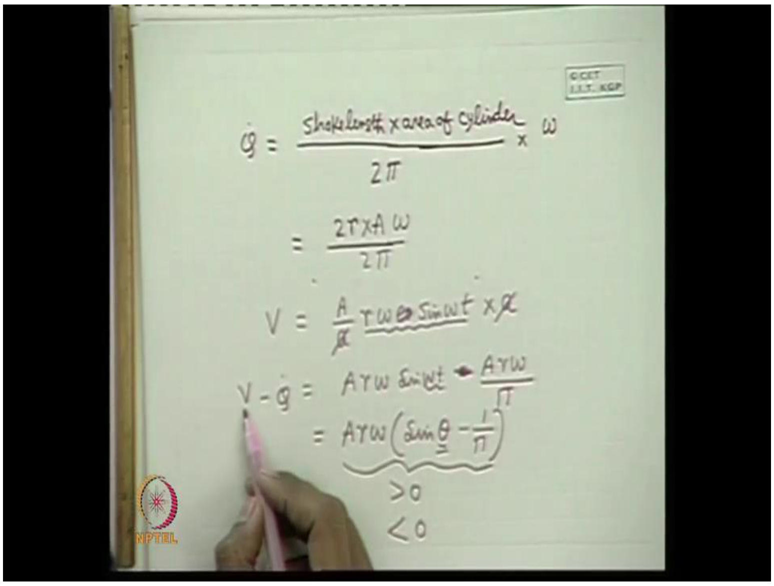

If we write I have said that the length at the stroke length stroke length I earlier also; that means, the same thing that is this is the mean discharge stroke length into area of the piston area of cylinder or same thing area of cylinder this is the swept volume volume swap by the piston in one revolution. So, in terms of time; that means, the flow rate per unit time we multiply with omega by two now stroke length in terms of the crank radius is two r obvious, because it two radius movement of the crank this executes once stroke; that means, this stroke is the distance between I d c to o d c this is two r; that means, half revolution of the crank. So, this is the crank radius well.

So, therefore, two r into a let a is the area of the cylinder into omega by two pi. So, this is the mean discharge based on the swiped volume of the cylinder, but what is the instantaneous discharge if you remember the instantaneous velocity in cylinder or in delivery pipe what was the instantaneous velocity in the delivery pipe v by a by a into r.

Cos omega square.

What is that r omega.

Cos omega.

Cos cos of sine sine omega t ok.

Yes.

R omega sine omega t all right. So, this is the instantaneous discharge. So, therefore, the difference between the instantaneous discharge, and this is the instantaneous velocity not the discharge, then it will be multiplied with the area this is the instantaneous velocity. So, the instantaneous discharge is a r omega sine . So, therefore, v minus q dot will be a r omega sine omega t minus a sorry minus a r omega by pi clear this was the velocity of the this piston r omega sine omega t this we developed just we recapitulate this see this that there is any mistake x is equal to r minus r cos theta this is the displacement of the piston from the inner dead center position after a time t from when the piston moves by an angle theta from its inner dead center position.

So, d x d t is the displacement of the piston r omega sine omega t, and we have assumed that this is the velocity with which the liquid in the piston also moves. So, therefore, the velocity in the delivery pipe will be from the continuity principle a by a again you multiply with a we get the flow rate now simply we can find out the rate of flow as this which will be same for both in the cylinder, and the piton. So, this value only we have written here. So, this can be written as a r omega let us put theta as the omega t which is the instantaneous crank angle.

Now, you see an interesting thing. So, the sine of this quantity will depend upon the value of theta it may be greater than zero it may be less than zero well it is greater than zero means the mean velocity or the instantaneous oh sorry this is not the instantaneous velocity, then it is the instantaneous flow rate. So, I have written v, and again I have made it q there is some problem. So, it it is instantaneous q. So, this part is the instantaneous v ok.

So, when it is greater than zero means the instantaneous flow is more than the mean flow; that means, the liquid goes to the air vessel when it is less than zero means the mean flow is less than the actual flow sorry when it is greater than zero means the actual flow is; that means, q is greater than q dot; that means, the actual flow is more than the mean flow; that means, the water flows to the air vessel when it is less than zero the mean flow is less than the the instantaneous flow is less than the mean flow q dot mean rather you write this is mean otherwise difficult.

So, when it is greater than zero, then q dot is greater than q dot mean; that means, the water flows to the air vessel when it is less than zero q dot is less than q dot mean; that means, the air water comes from the air vessel the most interesting part is that when sine theta is one by pi when sine theta is equal to one by pi, then this these gives two angle theta is as a some sixteen degree.

Eighteen point three.

No theta is some eighteen degree or some minute thirty four minute or like that, and another is one sixty one degree twenty six minute like that I will verify it it is a approximately this angle this gives; that means, sine theta is one pi gives two angles of theta between zero to three sixty degree at those two crank angles the instantaneous value coincides with the mean value there is no flow of water either to the air vessel or from the air vessel well there is no flow. So, corresponding to these equations sine theta is one by pi it is almost equal to eighteen degree another is equal to one sixty one degree that you can see from the trigonometric trouble is approximate values like that.

So, this is the mathematical part for the air vessel. So, you can very well understand what air vessel does it just supplies the surplus air when it is needed; that means, the instantaneous flow rate is less than the mean flow are it absorbs or takes the excess surplus air when the instantaneous flow is more than the mean flow well any question please any question.

Student: Sir using it power requirement will be less in this case.

Power requirement will be less…

Student: We are using power extra power to compress the air in the air vessel also.

No the compressed air in the air vessel we do not require. So, initially the air correct initially the air was compressed, and put into the air vessel by making a pressure equal to that. So, that is equalizes the design characteristics of this air vessel is that the air vessel is very large compared to the cross sectional area of the delivery pipe, and the cylinder. So, that expansion, and compression of the air does not change its pressure the pressure remains almost constant.

So, initially we have to fill with the compressed air, and that pressure remains almost constant it is very large ten times larger in area than the area of the delivery pipes or the suction pipes the air vessel is a large area. So, that initially you fill it with some compressed air to determine pressure. So, expansion little expansion, and contraction of the pressure by the movement of the liquid column that the height of the liquid it increases or decreases does not change the pressure mass that is one of the very important characteristics feature for the design of air vessel it will be large like a surge tank in a compressor as you seen the surge tank in a compressor you have seen is very big air compressor also does the same thing.

So, the discharge becomes uniform when it comes from a surge tank never air is taken directly from delivery line of a compressor it is taken from the surge, and surge tank volume is much more than the volume of the cylinder of the reciprocating compressors same principle here. Next I just like to tell you just straight forward application no doubt straight forward application of this principles just one problem you see example how to solve this problem a single acting.

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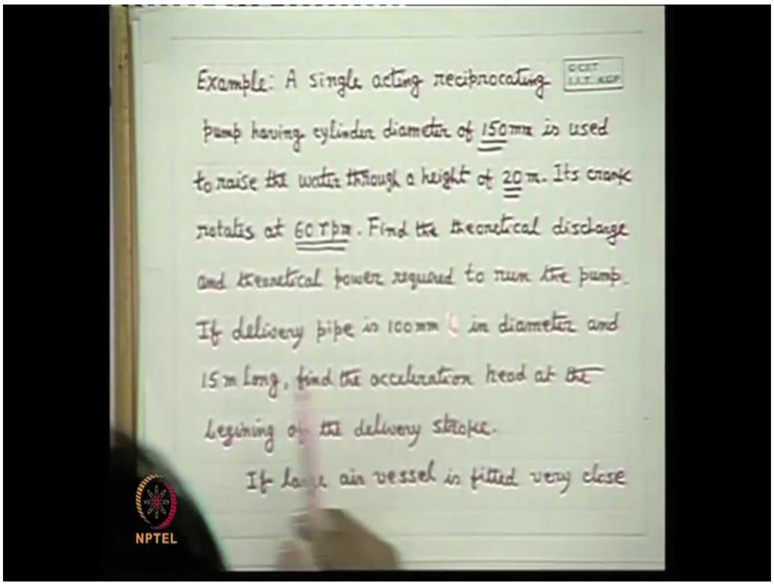

You write example a single acting reciprocating pump a single acting reciprocating pump having cylinder diameter of one fifty millimeter is used to raise the water through a height of twenty meter.

So, diameter of cylinder is one fifty millimeter, and is used to raise the water through a height of twenty millimeter. So, twenty millimeter is the total height, that is the static lift that is h s plus h d from the sump to the overhead reservoir, this is the total height these are the important dimension cylinder diameter its crank rotates at sixty r p m that is the revolutionary speed is sixty r p m find the theoretical discharge, and theoretical power required to run the pump first is the theoretical discharge, and theoretical power theoretical discharge, and theoretical power is related to the power, and discharge which neglects the acceleration, and decelerations of the piston, next part is if delivery piper is hundred millimeter in diameter that is the diameter of the delivery pipe, and fifteen meter long; that means, length, and diameter of the delivery pipe is given.

Find the acceleration head at the beginning of the delivery stroke straight forward application of the equation. So, we know the r p m we know the length, and diameter we can find out the acceleration head at the beginning of the delivery stroke which is maximum which is maximum at the beginning of the stroke; that means, the power developed has to be much more than that of the twenty meter for pumping. If you take care of the acceleration head next part it tells if large air vessel the word large is very important; that means, the pressure in of the air in the air vessel remains constant substantially air vessel in fitted very close if it is not large in this context title this is an approximation that is why there will be a little fluctuations in the discharge if it is theoretically constant; that means, it is always maintained a constant pressure at that point where the air vessel was connected to the delivery pipe. So, it does not maintains. So, because of the fluctuation in the air pressure that is why there is the little fluctuation in the discharge in the delivery pipe from the air vessel connections onwards ok.

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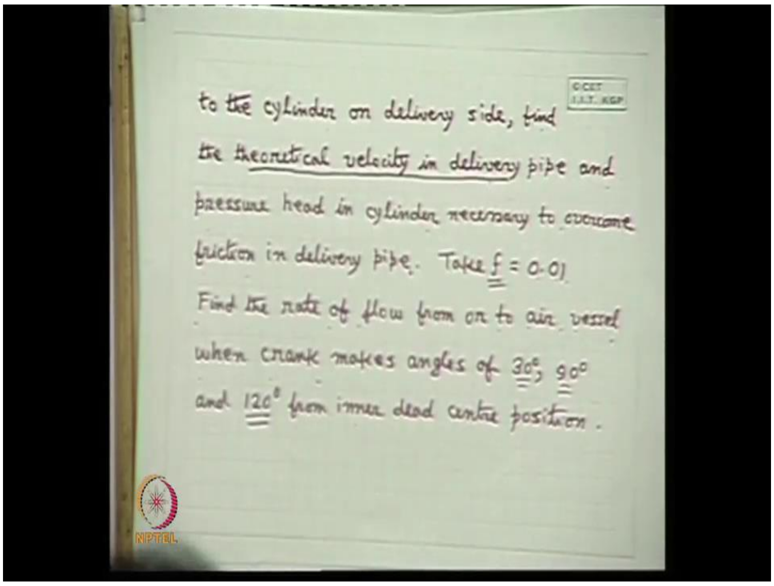

If large air vessel is fitted very close to the cylinder on delivery side very simple find the theoretical velocity in delivery pipe this theoretical velocity is no way connected with this large air vessel this is already know from the flow head volume most important is the, and the pressure head in cylinder necessary to overcome friction in delivery pipe take f is equal to zero point zero, and this is typical darcy's friction coefficient find the rate of flow next part from or to air vessel when crank makes angles of thirty ninety one twenty that is the straight forward application of the equations just we have described from inner dead center position I think all of you can solve this problem there is no need of discussing this problem theoretical discharge is simply the swipe volume per revolution you convert it in terms of time all right.

So, I think you can solve the problem well find the rate of flow from or to air vessel when crank makes angles of thirty degree ninety degree, and one twenty degree from inner dead center position all right now.

Student: Sir.

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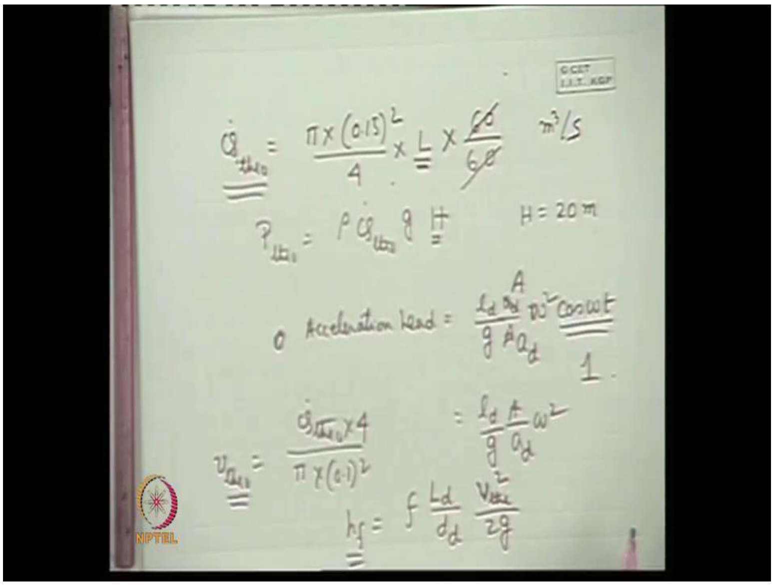

Now, theoretical discharge q dot theoretical, what will be is what is the area of the cylinder pi d square pi into one fifty millimeter meter square d square by four into this stroke stroke what is the stroke length stroke length is giving what is the stroke length stroke length is not given.

Student: Not sir.

Given sir two r.

For r is given what is there pump having cylinder diameter of one fifty is used to raise the water through a height of twenty meter its crank rotates at sixty r p m find the theoretical discharge, and theoretical power required you just say to run the pump if delivery pipe is hundred millimeter in diameter, and fifteen meter long find the. So, stroke length is not given. So, stroke length has to be given I am sorry the stroke length is omitted. So, stroke length has to be given otherwise you cannot find it.

Sir we get ten, and thirty.

What is…

Fifteen length of the cylinder.

No no length of the cylinder cannot be the stroke length there will be a clearance volume inner dead outer dead length of the cylinder, where is the length of the cylinder where is the length of the cylinder.

Not given.

Not given length of cylinder is not the stroke length I am sorry should not tell like that. So, stroke length has to be given this is missing in the problem this data well just you see the procedure, then you can find out here sixty r p m; that means, sixty by sixty; that means, one revolution per second. So, this will be q dot theoretical meter cube per second power theoretical is what rho q dot theoretical g into h what is this h this is twenty h is equal to twenty meter I am sorry that stroke length is missing is data; however, if stroke length is given you can find out. So, delivery pipe the acceleration head as you know what is the expression of acceleration head what is the expression of acceleration head please l d by g next is…

A d by a

A d by capital a, and then r.

Omega square.

Omega square.

Omega square.

Cos omega t.

Cos omega t.

That is d e by a d sir.

capital a in the numerator.

Yes sir.

And small a in the denominator. So, at the beginning means delivery stroke. So, this will be one one eighty cos theta cos zero one. So, this will be l d by g you see that a by a d omega square. So, you can find out well, if large air vessel is fitted very close to the cylinder it is the concept that theoretical velocity will be the theoretical discharge divided by the what is theoretical velocity in delivery pipe is theoretical discharge divided by the cross sectional area of the delivery pipe can it be found delivery pipe diameter is given hundred millimeter; that means, point one meter into point one square into four.

So, if I know q theoretical this is the v theoretical the theoretical velocity, and t find out the pressure head in cylinder necessary to overcome friction in delivery pipe when this air vessel is incorporated, then the theoretical velocity is this, and that will be the velocity in the delivery pipe uniform velocity. So, therefore, h f is f l d by d d diameter of the delivery pipe into v theoretical this v theoretical square by two g. So, this will be the frictional head head required to overcome the friction, because the velocity is uniform, but in other cases you will have to integrate it taking care of the varying heads I am telling this is a very simple problem.

Thank you.