Fundamentals of Industrial Oil Hydraulics and Pneumatics
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Module 4
Lecture 15
Proportional Solenoid Pilot Operated Two Stage Pressure Relief Valve

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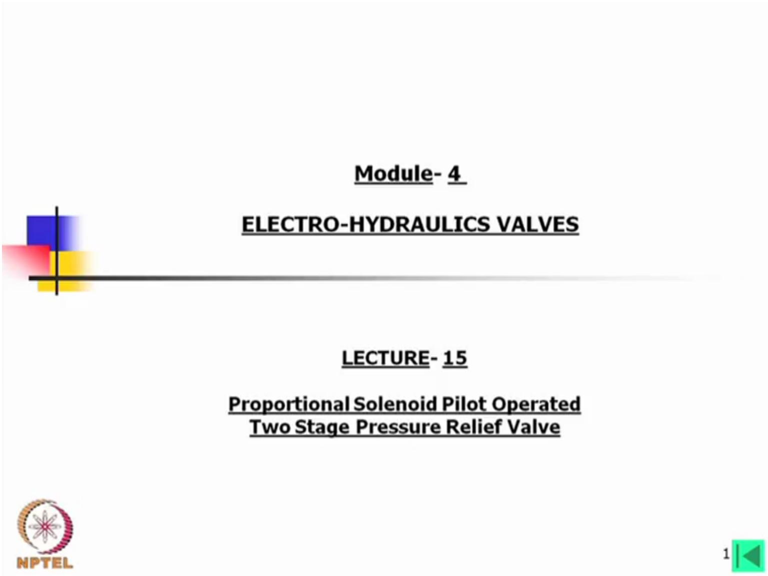

Welcome to today's lecture on Proportional Solenoid Pilot Operated Two Stage Pressure Relief Valve this lecture is the first part of this topic. Now we know about the pressure relief valve then two stage means there is main stage and pilot stage, pilot stage can be compared with direct pressure relief valve and when that stage is associated with main stage then this must be operated by something and it is called pilot operated and in this case operation of that pilot stage is done by proportional solenoid.

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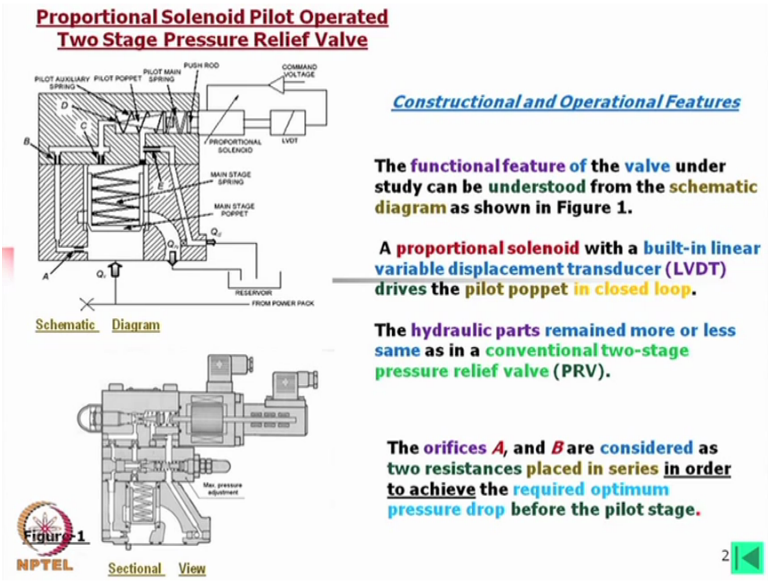

Now Proportional Solenoid is in comparison to the ordinary solenoid is that in this case the input to the solenoid is either current or voltage and then due to that it is input is in such a way the output will be linear to the current or voltage what is the input. Now let us look into the constructional feature of this valve. In this diagram what I have shown one sectional view of the valve in this case in this view this is the main stage and this is the input side flow input side, if we look into the figure at the top which is schematic diagram the main system line is here and this is connected, this valve is connected to the main system.

Now this is the drain to the tank so oil on relief it will come out from this path and will go to the tank. Now the upper part here this is the pilot stage in pilot stage what we find we find a poppet this conical poppet and this is sitting on a hole so this must be a variable orifice and then the operation can be described like this. Now this spool is being driven by the proportional solenoid and this drive force is being transmitted through a spring not directly this poppet is not directly connected to the solenoid spool, it is connected through a spring.

Now this is the input for the current or voltage whatever it might be this is input to the proportional solenoid so this will move this movement may not be linear although output will be linear but this will move the right and left depending on the input here and this is the LVDT to record the position of this spool. So for this portion it is a closed loop we can say that one current is there then the signal is going over there and then again this is being corrected, this portion is closed loop, the other portion is may be closed loop through a computer or microprocessor we can make it closed loop.

Now how it is being operated if we look into this view then we should compare the main portion the main stage portion is the bottom portion here, whereas the pilot stage is the top portion here. Now in between that there is another portion which is maximum pressure adjustment setting this means that this valve depending on the solenoid input this can be operated for a range, say it can be operated from 0 to 20 Mega Pascal but due to the over precaution or for more safety what we can do? Knowing the system pressure requirement we can set the pressure here, say this is 10 Mega Pascal or 12 Mega Pascal then at 12 Mega Pascal this all flow will go through this.

So although this can be operated upto 20 Mega Pascal but due to setting maximum pressure adjustment over here for the 12 Mega Pascal this oil will be relieved through this valve it will not come to this stage. However, in many cases this part is not there first thing, second thing this is again we can say the another pressure relief valve so for studying the pressure solenoid operated solenoid pilot operated pressure relief valve we shall not consider this part. So we have consider only the bottom the main stage and top the solenoid part.

Now what we will look here that this is the main flow, then the flow is coming over here say it is we will operate at 10 Mega Pascal upto maximum that means upto 10 Mega Pascal pressure will be there but this will not open. So then this oil will be connected to this, okay it will be connected to this part. Now when this oil is going through this path if this does not open how it will be open how it will open? When the pressure here sufficient to open this poppet only then it will open.

Now unless the pressure is not increased to that level there will be no flow. So there will be no flow through this passage although this will be filled in with the pressurized oil, this means that whatever pressure here the same pressure will be here also you can see this path it will be here also, here everywhere the pressure will be same and this will not open. Now this is we are operating at 10 Mega Pascal range say after 10 Mega Pascal this will be there.

So what we can do we can set this current for 10 Mega Pascal in fact this proportional solenoid is there that this pressure relief valve can be operated within that range for any pressure, that signal instead of in ordinary system where we set the pressure by adjusting the norm and we leave the system like this, in this case through the current signal we can or voltage signal we can operate any time or any pressure within that limit, okay. It might be computerized, it might be manual also or may be through an microprocessor, okay.

Now let us consider this signal what we have given in such a way that it should open at 10 Mega Pascal this means that at 10 Mega Pascal this will open. Now once this opens the flow will start, this flow will go like this and then through this, this is block so through this passage it will go to the drain. Now this passage is also blocked, okay. Now as flow begins then definitely there are so many orifices, so there will be pressure drop.

So upto pilot stage how many orifice we find? One orifice A, another orifice B and then here there is the variable orifice these are the fixed orifice A and B are the fixed orifice and D is the variable orifice here. And after this pilot stage also there is another orifice in this direction and the oil is being transmitted through this main spool chamber also through an orifice C. Now when flow begins then there will be pressure drop, now as there is a pressure drop the same pressure will come over here, so if we think of the force balance this side the full pressure, this side the reduced pressure plus the spring force so depending on the flow at one point these two force will be less than this force then this will open and oil will go out and that will depend on how much setting we are doing through this proportional solenoid.

And as you know due to this differential pressure this will remain stable for a longer time to bypass the oil that means no chattering, otherwise normal case you will find that here there will be pressure drop and if it opens too much pressure here and pressure well here will be same that means it will be almost zero pressure and but this side is the pressure is automatically there if it is zero pressure, try to be zero pressure then again it will be closed like that.

But due to this balance there will be a an orifice effect a small orifice will open so maintaining the pressure here up to the system pressure say it is 10 Mega Pascal the oil will pass until this pressure reduce to close this valve, okay so this is the basic operations. Now here again I would tell that we have seen one orifice A here, another orifice B before this pilot stage that means if I think the same oil is flowing through this pilot stage atleast there are two orifices.

Now apart from that what we find that there is also some I mean fixed resistances, fixed orifices is also there. These orifices can be replaced, whereas this cannot be replaced. Now here I shall discuss later but here what we find that there we find a spring I have already mentioned the force is being transmitted through the spring not directly through a solid steam, whereas this spring is very soft spring and this is just to keep this poppet in positions, it has a role as there is a spring definitely it is having a stiffness so we have to consider this stiffness also for the functioning.

But the stiffness of this spring is much less in comparison to stiffness of this spring and but this is required otherwise this poppet may not be in proper position it may start malfunctioning, okay. The functional feature already I have described. Now this solenoid already mentioned it has a built in linear variable displacement transducer which is called LVDT, this LVDT transducer is there it monitors the position of this spool and for this it is a closed loop, this valve whether it is closed loop or open loop depends on how we connect this, this control over there, the driving current which we are supplying. However, the position transducing is closed loop, okay.

Now another important point the hydraulic parts remained more or less same as in conventional two stage pressure relief valve which is normally called as PRV. Actually there is some confusion in this terminology, normally we call pilot operated pressure relief valve PoPRV, o is small all other capital the next lecture I will describe that also. So here again it is solenoid operated so for that no this abbreviation term is there normal course we call proportional PRV, simply call it but once it is a proportional PRV means it will be PoPRV proportional pilot operated pressure relief valve that we should remember.

Now another important aspect I would like to mention in comparison to the servo valve, the solenoid valve the proportional solenoid valve the accuracy of the all components is not that important what we require for the servo valve. In case of servo valve it is completely closed loop and there if it starts malfunctioning then whole valve is to be rejected, whereas in this case it can be made closed loop through the main drive that is it might be a there is card of course here is a card is there and then it might be a microprocessor, it might be manual, it might be a computer. But there we can set a program so that it can correct all those error of course it should be within a limit.

So therefore these valves are less expensive in comparison to the servo valves but we should look into the purpose say for example if we think of operating a missile we have to perhaps still go for a servo valve but it is also possible we can put a proportional valve there very accurate proportional valve there and it will also can perform the same thing but as you know in both the cases everything will be destroyed everything will be destroyed this is just for single applications.

Now if we look into the accuracy servo valves perhaps if say missile if you have targeted a point then it might be within say 1 meter circle the missile will hit there if it functions properly. In case of proportional valve probably that area will be more that does not mean it will not that point, it might be instead of that it may hit the point whereas say same thing is using a proportional valve it may hit the target whereas servo valve may be half meter away but still for more accuracy we are going to we use the servo valves.

Now proportional valve so where is the function of this proportional valve, where we need a longer life by compensating the accuracy a little bit we should go for proportional control valve. In that way I would say the in between the servo valve and ordinary valve the proportional valve is may be the optimum from application point of view and in many cases where we can go for a higher cost a little higher cost then even the ordinary valves are being replaced by the proportional valve for better performance say in where we use the automation like that, okay.

Now the orifice A and B are considered as two resistances placed in the series in order to achieve the required optimum pressure drop before the pilot stage. I would say for the same valve if you change these two orifice then the range of this operation will change suppose you have used A and B orifice with a particular diameter then you find for 0 to 10 voltage or may be current irrotated in current it is not in the mille ampere, it is not in the range of ampere, within that range suppose it is working for 0 to 10 Mega Pascals but if you change this orifice you may find that this will depending on the restriction here it may change say 0 to 5 or may be for higher it is like that.

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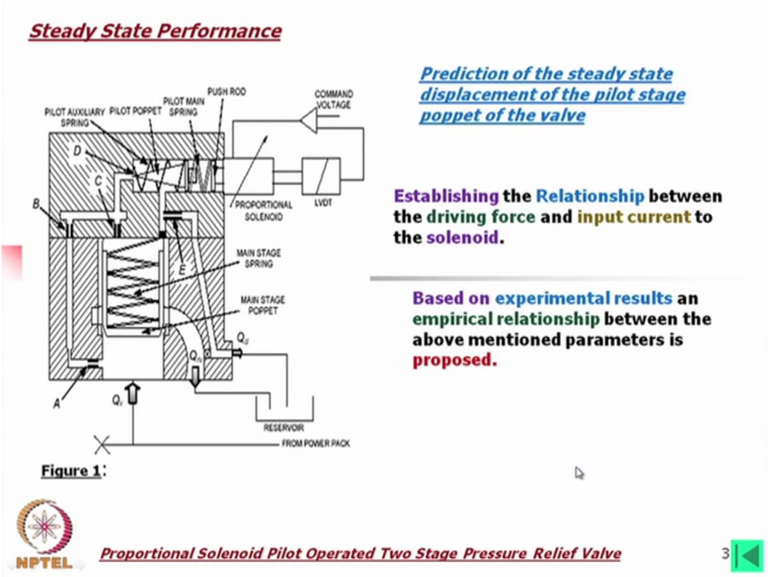

Now we will predict we will try to predict the theoretically what will be the steady state displacement of the pilot stage poppet of this valve. Now establishing the relationship between the driving force and input current to the solenoid in this case we have consider the current is the input input current to the solenoid. Based on experimental results an empirical relationship between the above mentioned parameter is proposed.

Now I would like to say this in the control what we will try to do suppose we are using a computer then what we will try to do? We will try to estimate how much current is required to achieve the desired pressure setting then if we can have some linear function or may be empirical relations it is linear so that empirical relations we can use and very fast we can calculate how much current will be required and then that can be again given as a input.

So what we did I mean this was an real study was conducted here in IIT Kharagpur then what was done we wanted to establish we tried to establish that relations, this will make us understanding how this valve can be analysed both for the design as well for the performances.

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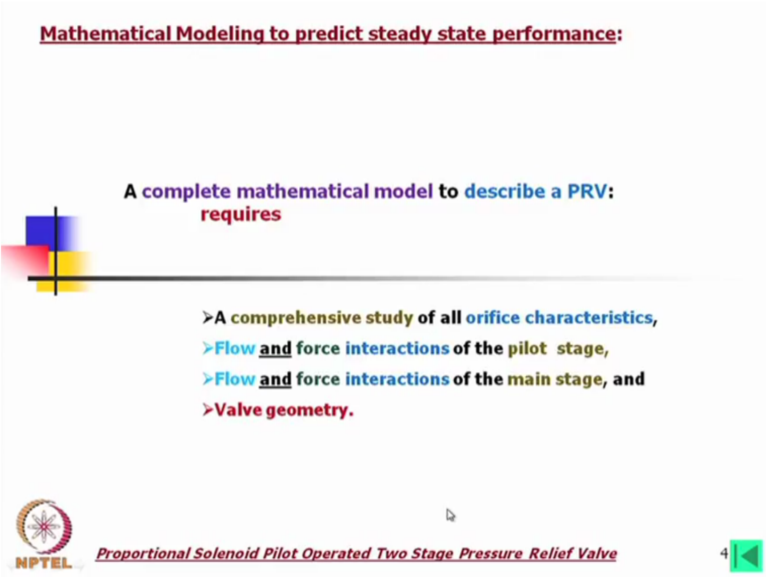

Now a complete mathematical model to describe a PRV requires first of all a comprehensive study of all orifice characteristics, flow and force interactions of the pilot stage, flow and force interactions of the main stage and valve geometry that we should know. Now I would like to say that if you go to the market you will be able to buy one proportional solenoid valve, the characteristic is given and there is it is available that what should be the current input for the pressure output pressure range.

So this curve what is the curve is given that either you can program or you can fit on in the in a computer on the databases you can make a data table and that can be used for the control and usually the supplier they have their own control features so that you directly you can use and nowadays you will find there are many many controller is available which can be given say we need say 1 micro mille ampere to 10 mille ampere so you can have a programmer that you can fit and as you know that what will be the outputs so you can program that easily and you can use this. But once you are thinking of designing such a valve then in that case you have to know all such characteristics and we have studied this so we shall explain how it is really functioning.

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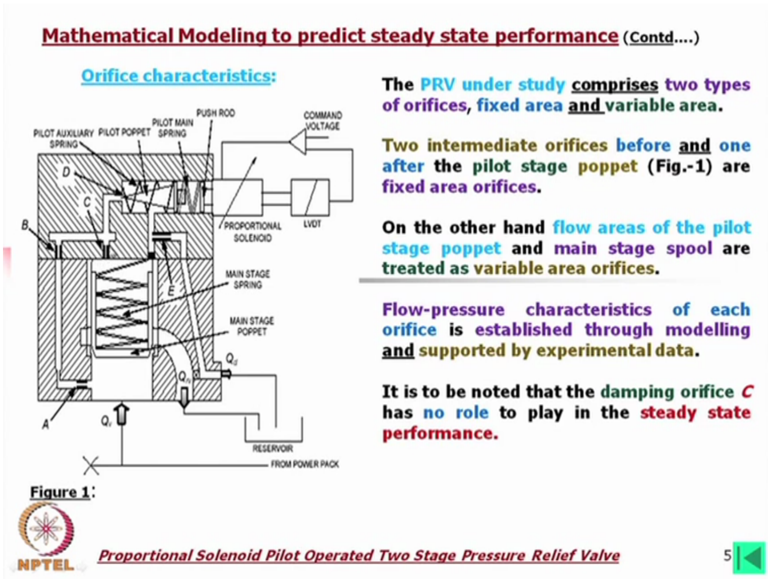

Now first of all we shall look into the orifice characteristics. Now again coming back to the this valve then A, B, C, E these four orifices apparently it is we should call the short tube orifices. Now in broadly we should say this comprises this valve will comprises of two type orifice one is that fixed area 1, 2, 3, 4 the fixed area orifice and the other is variable area this is one variable area here, another variable area is there.

Two intermediate orifices before and one after the pilot stage poppet are fixed area orifices, say 1, 2 and this 3, this 2 before the pilot stage and 3 after the pilot stage are the fixed area orifices. On the other hand flow areas of the pilot stage poppet and main stage spool are treated as variable area orifices, which I have explained already.

Flow pressure characteristics of each orifices is established through modelling we can establish this through mathematical modelling and then it can be supported by the experiment. Now damping orifice this orifice is called damping orifice, orifice C has no role to play on steady state performance. This orifice only when there is the transient conditions, the dynamic conditions comes here then this oil flow through this orifice it is in reversible flow occurs and that helps in damping the motion of this main poppet, we if we remove this then you will find it will take much more time to stabilize however, this has no role on steady state performance. So we have not studied here in this analysis.

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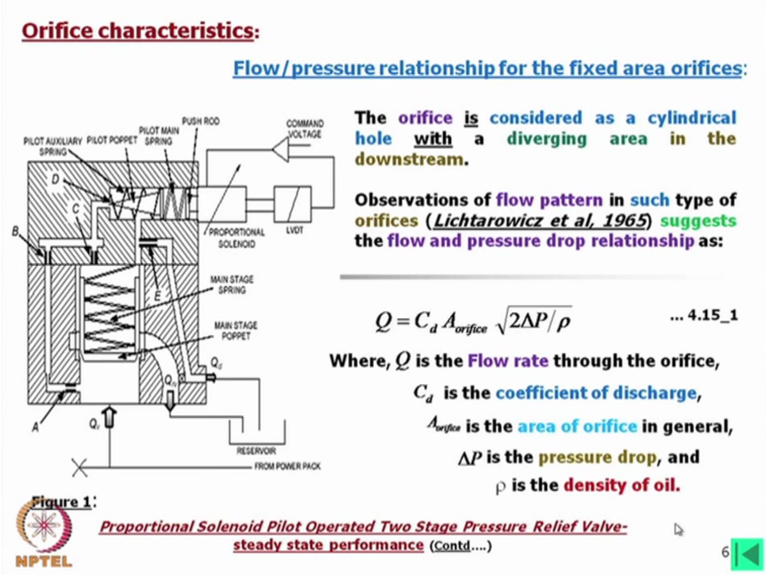

Now flow pressure relationship for the fixed area orifices again we consider A and B, the orifice is considered as a cylindrical hole with a diverging area in the downstream. Actually these orifices are like that almost straight hole is there but at this side I mean in towards the downstream side this is upstream if the flow is going like this this is upstream, this is downstream slight divergent is there.

Now the flow pattern in such type of orifices suggest the flow and pressure drop relationship as follows. This is the general equations however, the these are known already we know A is the orifice of this, del P is the pressure drop and C d is the coefficient of discharge so these equations is already known to us so we can use these equations for this orifice analysis also.

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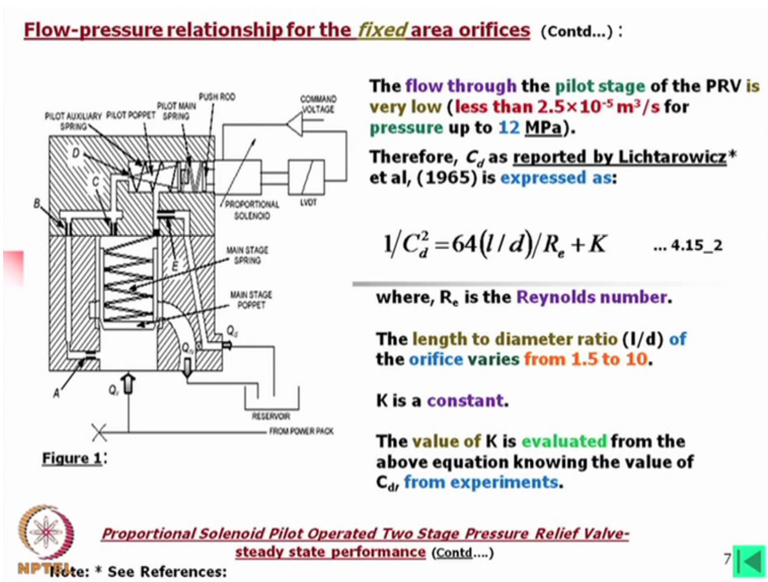

Now the flow through the pilot stage of the pressure relief valve is very low it is 2.5 into 10 to the power minus 5 meter cube per second for pressure upto 12 Mega Pascal, okay. Therefore, C d as reported by Lichtarowicz is expressed as 1 by C d square 64 into l by d divided by R e plus a factor K. Now here I would like to say that we have already studied that how to find out the C d and there are also Von Mises proposal that how we can calculate and as I told in most of the cases we may consider that it can be taken as 0.6 close to that 0.611 preciously we can take those. But it has been found that in this type of valve if we consider that exactly that one that will not fit rather we should follow some more refined formula to estimate the C d.

Now in 1965, long back this is about 45 to 50 years back about 50 years back Lichtarowicz he proposed that this is more suitable but this he established using the experiments through some experiments he proposed this one and we have also examined and we found that this is really suitable for finding out the orifice characteristics. Here l is the length of the orifice this length and d is the diameter of the orifice this is in the range of 0.5 millimetre or even less.

R e is the Reynolds number we have already known, l by d of the orifice varies from 1.5 to 10. Say this is 0.5 millimetre then l will be maximum 5 millimetre, if it is 0.5 then it will be for the maximum value 5 millimetre, whereas as well this might be 1.5 this means how much 0.5 into 1.5 it will be 7.75, so 0.75 is the length of this orifice it might be like this of this range.

Now again I have not specified the what is the capacity of this pressure relief valve what is the physical size may be next lecture I will give physical size of that but this is we have considered only particular valve it is about 30, 40 litres per minute maximum flow. Now K is a constant, the value of K is evaluated from the above equation knowing the value of C d from experiments. So what we have done here we have found out the C d value from the experiments and then we find out the evaluated the value of K.

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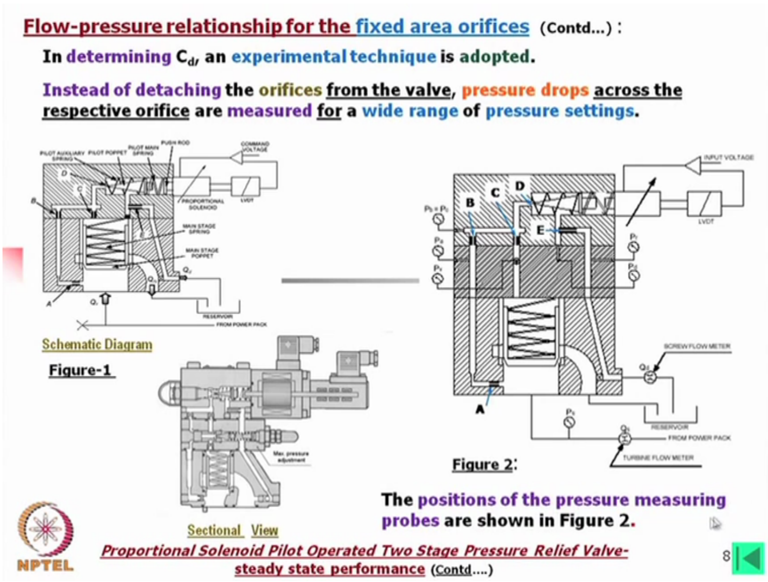

Now in determining C d an experimental technique is adopted. Instead of detaching the orifices from the valve, pressure drop across the respective orifice are measure for a wide range of pressure setting. You see if we use this orifice separately we can it is possible that (())(32:01) can be made and there the orifice can be put and we can find out its C d but instead of that we have used all the orifices in their positions and then we have measured pressure, how?

If you remember it is here in this figure that there is a place for maximum pressure setting, we have removed this instead of that we have put a simple a block here with these holes and here is the pressure tapping. So we put several pressure transducer to record the pressure here and for the flow measurement here if we at steady state condition no flow is here so flow path is only one path it is going over there so a flow transducer was there, okay.

So this means that what we did we measure the pressure drop over each and every orifices and we measure the total flow through all these orifices. So the position of the pressure measuring probes are shown in this figure.

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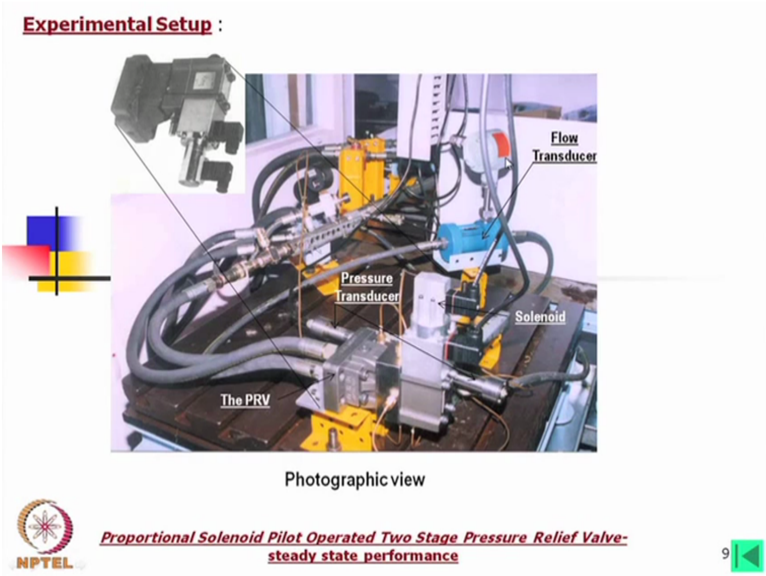

Now this experimental set up was like that this is the valve what we used here, this is the Denison valve I will give the specification next day. Now here are the pressure transducer this is the solenoid we have shown LVDT and solenoid is here and pressure transducer one is here, one what we can see one is here, another is here probably another is here so everywhere we put pressure transducer, okay and here on the (detail line) drain line we put a float transducer this is a turbine type flow transducer this is a turbine type flow transducer as far I remember.

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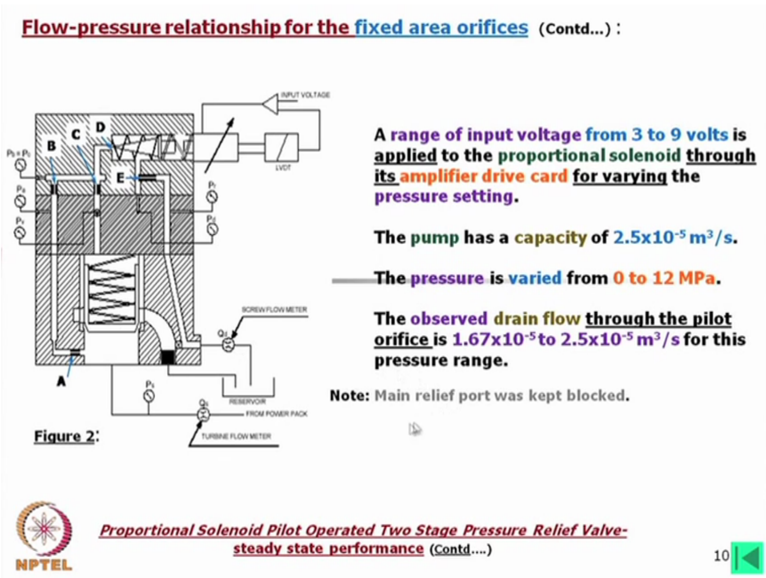

Now so what we find these are the orifice this we want and these are the pressure transducer and then a range of input voltage from 3 to 9 volts is applied to the proportional solenoid through its amplifier drive card. Now here I would like to say that in our case 3 to 9 volt was the input but through a drive card the output of the drive card was the current and then that current was driving these solenoids, okay.

The pump has a capacity of 2.5 into 10 to the power minus 3 meter cube per second, this is also not very high because we ultimately we block this one and through this we just measure the flow through this path no flow through this path, okay. The pressure is varied from 0 to 12 Mega Pascal and the observed drain flow through the pilot orifice here it was 1.67 to 10 to the power minus 5 to 2.5 to 10 to the power minus 5 meter cube per second for this pressure range.

Now I would like to say at zero pressure there was no flow definitely but we varied from 0 to 12 Mega Pascals then definitely at certain pressure this opened and for this range it is it was 1.67 to 2.5 into 10 to the power minus 5 the flow. Now here again I would like to mention if you voltage we have seen the 3 to 9 that means upto 3 voltage almost no response is there, again from 3 to 9 voltage you may find only may be from 4 to 8 voltage the output is linear, so that is the application range of this valve that is specified the manufacturer will specify we will specify also experimentally we have found the similar results.

The main relief port was kept blocked if you look into this, this was kept blocked so that all the flow goes through this. Now keep in mind if we keep this is blocked then this will not function so that means this flow will come it will try to open but this will not function so all the oil will go through this and our purpose of finding the C d will be achieved.

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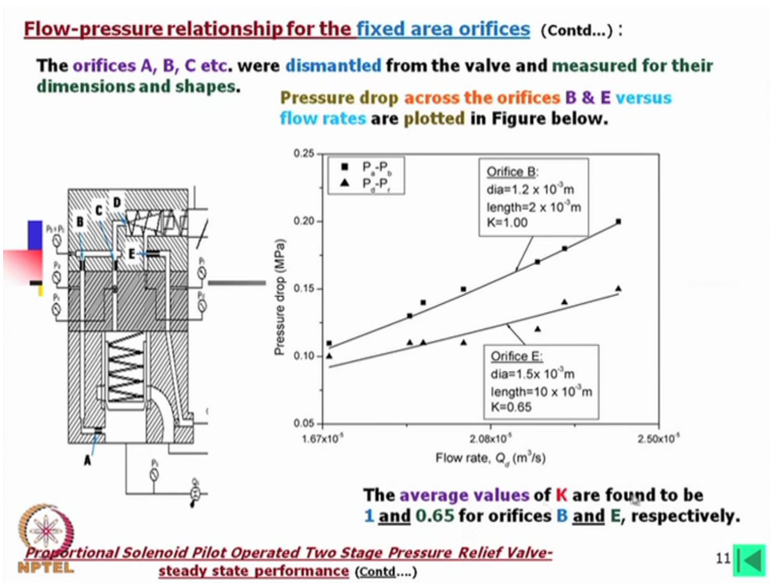

Now A, B, C etc were dismantled from the valve and measured their dimensions everything were measured. Pressure drop across the orifice B and E you see that across the B and E flow rates are plotted in this figure, if we look into this, this is the orifice E and this is the orifice B, okay. Now here one interesting point is that we found that E is having a different dimensions then B however, A was having the same dimension what in B.

However, A zone at the A zone not A orifice we are measuring pressure here say this is the pressure gauge and we have a pressure gauge here that means pressure here and pressure you can say here these two pressure we are measuring but for that it show different characteristics although the dimension of A and B is same. So definitely we have to find out the characteristics of this zone separately.

Now for that it was calculated that K is coming that equation if you remember the equation that K is coming 1, whereas in that case K was coming 0.65. Now once the K is found out then this equation can be used and using this K and that formula these are experimental data you can see this line was coming like this, if you plot that formula what we used then the line will be like this. Now next here I have given this what I have the values of K.

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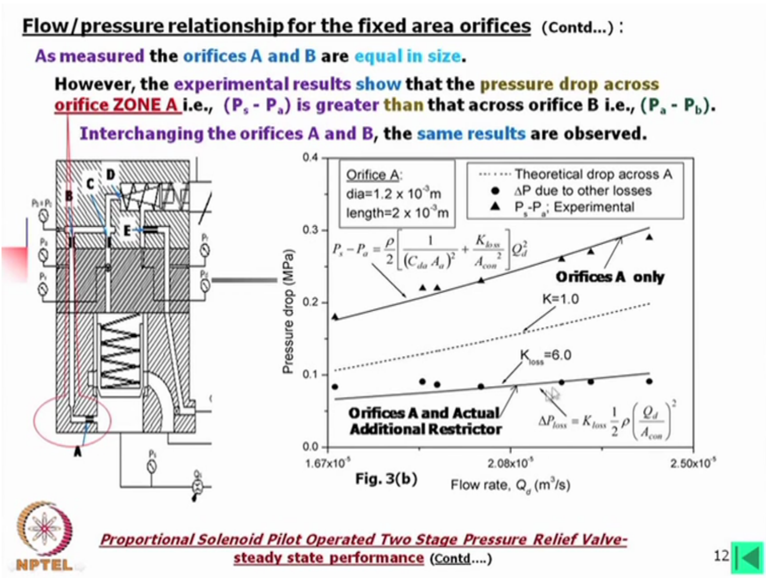

Here I have mentioned that as measured that A and B orifices are equal in size. However, the experimental results show the pressure drop across orifice zone A here is greater than that across orifice B that means here it was more pressure drop this means that there are more restrictions I would like to mention there is no way to verify what is there although you see this construction wise here there was a hole but that hole was blocked and neither we removed that block but we could not remove this one we could not really find what is there inside but definitely there was an restriction so this portion was characterized together considering A and whatever restrictions B is there.

Now if we look into the orifice A then this is the characteristics of the orifice A or rather we should say orifice A zone, whereas if we put K which for K is equal to 1 which is for orifice B its characteristics was something like this, okay. Now if we put orifice A only then this will be same as like this whereas orifice A and actual additional restrictor this was showing like this, this characteristics was showing like this and from where we again calculated that K loss came to 6.0.

Now the question is that say for example here we are getting 0.65 whereas here we are getting the 6 then why we did not use the same thing, probably reason is that this gives better performance that means one small another variable, variable means we can replace this. With this probably the better performance can be achieved and more over if you look into this, this is very flat type characteristics of when we combined these two together although the K factor becoming the same.

Now for that again this equation is like this and for this one we can have this equation like this, okay. So interchanging the orifice A and B what we did to confirm that the this is a this zone the losses will be more or less same and as we have measured these two orifices are same, what we did we replace this orifice but again conducted the experiment and we found that the results are same.

So this confirms two things one is that orifice A and B are same, second thing is that even after interchanging the performance is same so this confirms that what we have derived estimated these are expectable for this valve analysis.

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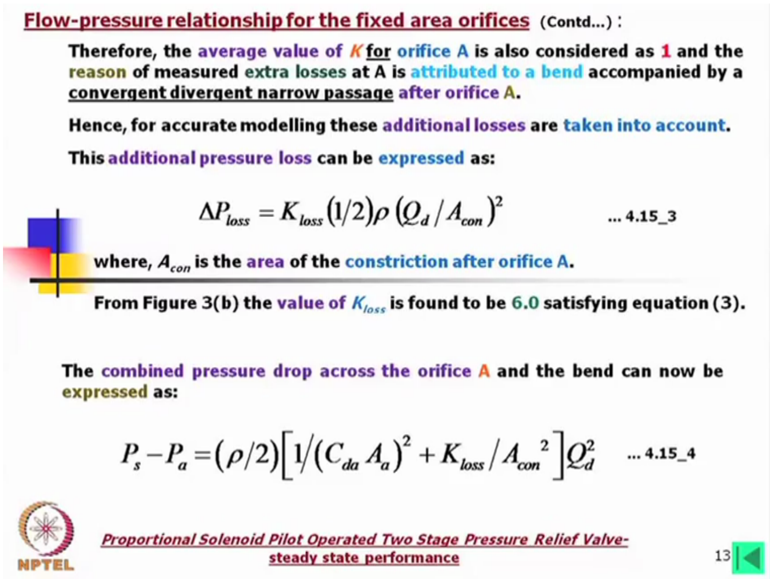

Now average value of K for orifice A is also considered as 1 and the reason of measured extra losses at A is attributed to bend accompanied by the convergent divergent narrow passage after orifice A. Hence, for accurate modelling these additional losses are taken into account. This additional pressure loss can be expressed as with this formula K loss half Rho Q d A con that area of that restriction to the power square.

What we could do? We measure the area by putting a wire cage different size wire was put there only the diameter was measured and we found that if we use this formula this is we have developed numerical formula then with this loss factor pressure loss can be calculated estimated this is not exactly experimentally but this can be also calculated. Now here again I would like to mention in all such cases normally through these theoretical formulation we can arrive into a value very close to the actual value and therefore transducer and controller their job is that getting this value close to that further requirement is done by the controller itself, this I have described.

And then K loss already we have shown that we can take this value 6 and the combined pressure drop across orifice A and bend can now be expressed as with these equations. So we can use these equations for the estimation of the pressure drop. Now as I told this we measured in that way but this probably manufacturers they can have better dimensions so may be this formula further can be modified to have these results.

Now I would like to say it is not easy to remember all such formula this is empirical relations. So in this case so suppose if you like to use this valve and you would like to estimate what are the values and etc in that case you should have in your hand to calculate all these values.

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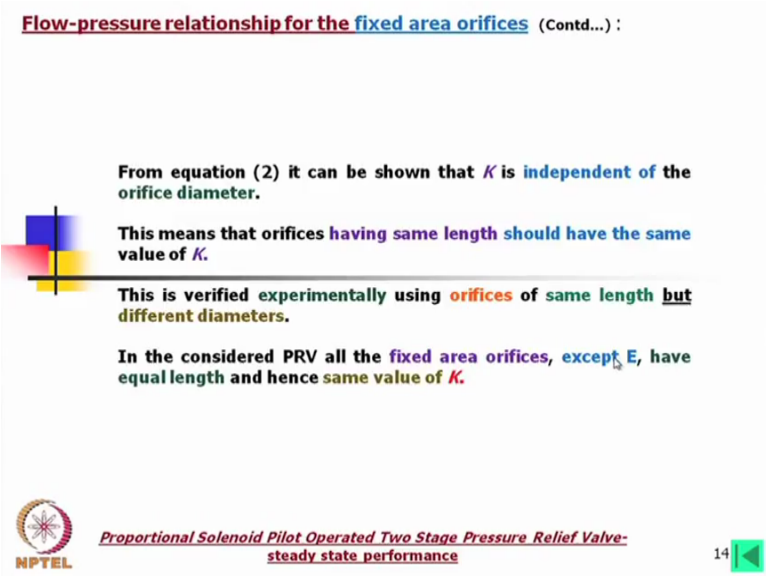

Now from equation 2 it can be shown that K is independent of the orifice diameter, this is another thing that K is not dependent on diameter it is dependent on the length this means that orifices having same length should have the same value of K. This is verified experimentally orifices of same length but different diameters, we further conducted the experiment by using those orifice changing the diameter of the hole keeping the length same and we found this K value is coming same.

So that again proved this for the formula we have derived that can be used for estimating the orifice characteristics. In the considered PRV all the fixed area orifices, except E, have equal length and hence same value of K, E means which is after the pilot stage to the drain.

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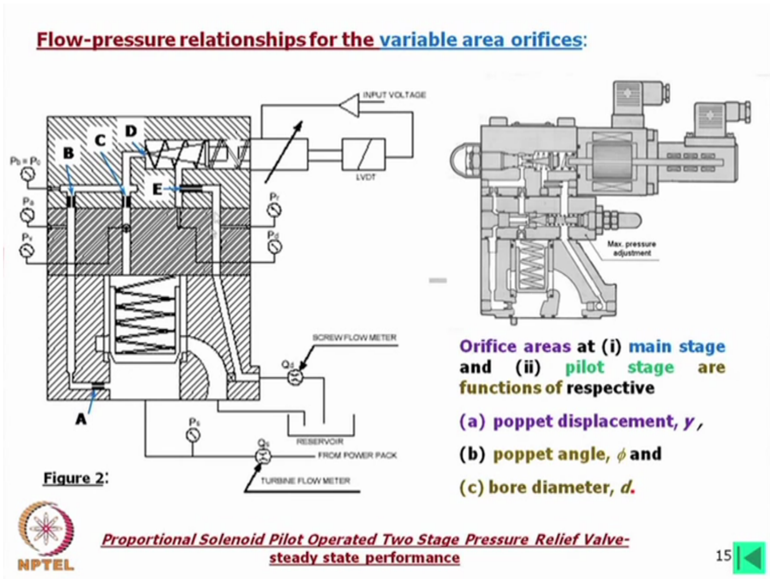

Now we shall consider the variable area orifices. Now in this I again I am showing this value, so variable area means here D and the main spool, okay. So D is the pilot stage and this is the main stage, but if you look into this construction of this here this angle is much more higher than this angle so definitely with small displacements the area increase, increase in the area will be much higher than this. So definitely this will have this C d particular if the coefficient of discharge will have different values we look into this.

Orifice areas at one main stage that is variable and pilot stage are functions of respective poppet displacements. So we have to develop this formula knowing how much is the poppet is displaced, poppet angle this angle is called Phi and then the bore diameter d, what is the this bore diameter here and what is the bore diameter there.

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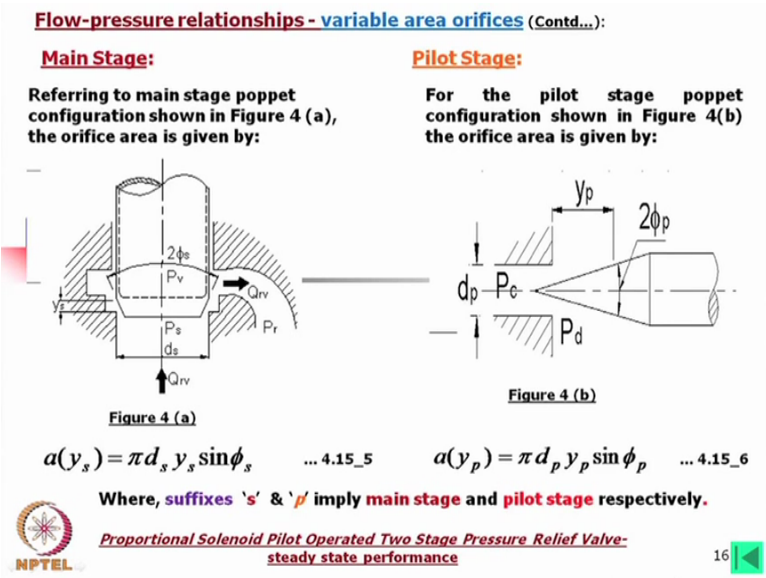

Then main stage you can see this I have mentioned this all this angle this is the main stage for which we can write down this formula and similarly for pilot stage we can write down this formula, this formula is same only this subscripts that s is for the main stage and p is this for pilot stage but you should remember these two angles are different so definitely nature of variation of this area with this stroke definitely or stroke or displacement will be different.

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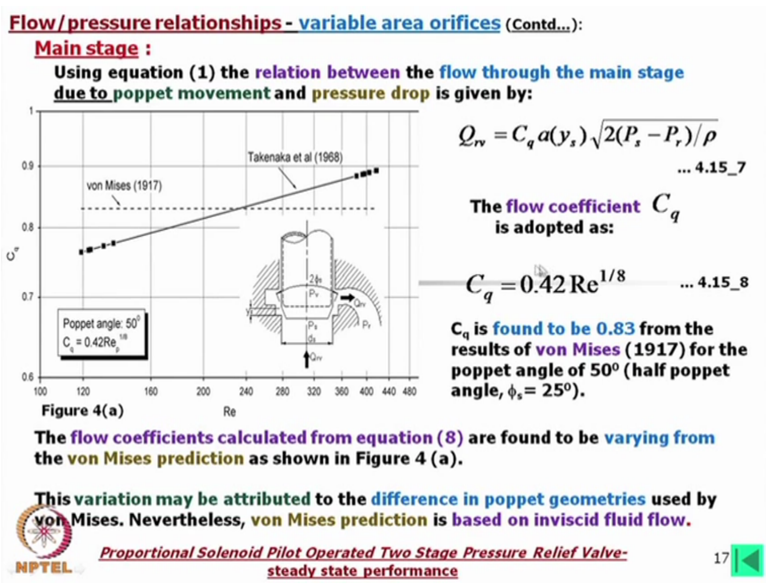

Now flow pressure relationship variably orifice, main stage it can be written in this form. The C q is the flow coefficient, now here instead of coefficient of discharge we call it flow coefficients and C q can be written in this form, where Re is the Reynolds number 0.42 like this. Now this is also established experimentally but if we now compare with the Von Mises model then C q is found to be 0.83 from the result of Von Mises because the angle here is less 0.83 about 0.83 and this you can calculate this will be close to this but not exactly same.

Then what we find that Von Mises he proposed in 1917 according to him this would be the coefficient of discharge what we have given is the flow coefficient, whereas in such type of valve normally we find a result like this. So Takenaka a Japanese scientist in 1968 he proposed this formula and so flow coefficient this value can be calculated using this formula, okay.

Now this variation may be attributed to the difference in poppet geometries used by Von Mises this is one point and second point he did it for inviscid fluids and whereas this in this case all the fluids will be viscous. So what we did, so the experiment we found that this formula holds good for this type of valve, this type of puppet the mains puppet but this is again I would say this is an empirical relations this depends on what the geometry we are using. So for a particular valve this formula will be a particular formula, okay may be if you change this angle this might be some this coefficient will be something different.

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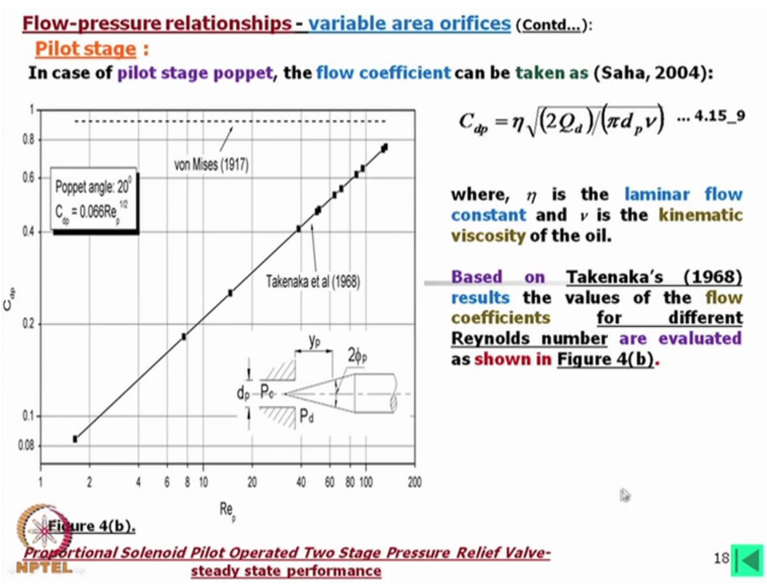

Now for the pilot stage similarly this formula can be used and it is called laminar flow constant and this is the kinematic (kinetic) kinematic viscosity sorry not kinetic, kinematic viscosity of the oil. Now in this case I think I have made mistake here 1 by 8 this relation will be more or less same and he also proposed this formula for this one this formula but in this case as you see for the pilot stage this curve is different from the main stage. In this case this angle is very low.

However, this also experimentally found is suitable for this proportional valve. So this definitely dependent on the Reynolds number and this angle, okay but one thing is sure that these two types of puppets are used in proportional solenoid valve and if we would like to design a valve like this then we can use this formula and directly we can arrive into this say we can develop the control feature also using this formula.

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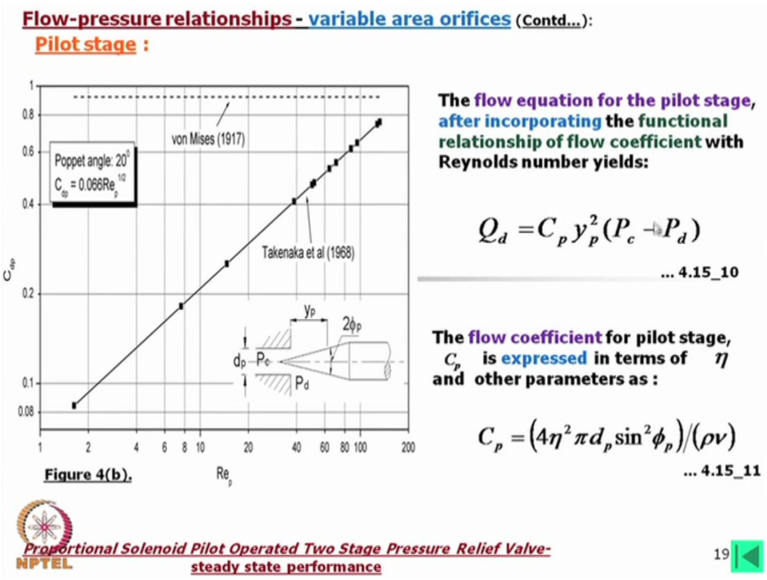

Now the flow equation for the pilot stage, after incorporating the functional relationship of the flow coefficient with Reynolds number yields if we use all such formula then we can put in this form and the flow coefficient of the pilot say C p is expressed in terms of Eta and other parameters as this we can use this formula there, okay so now we can use this formula to flow through this.

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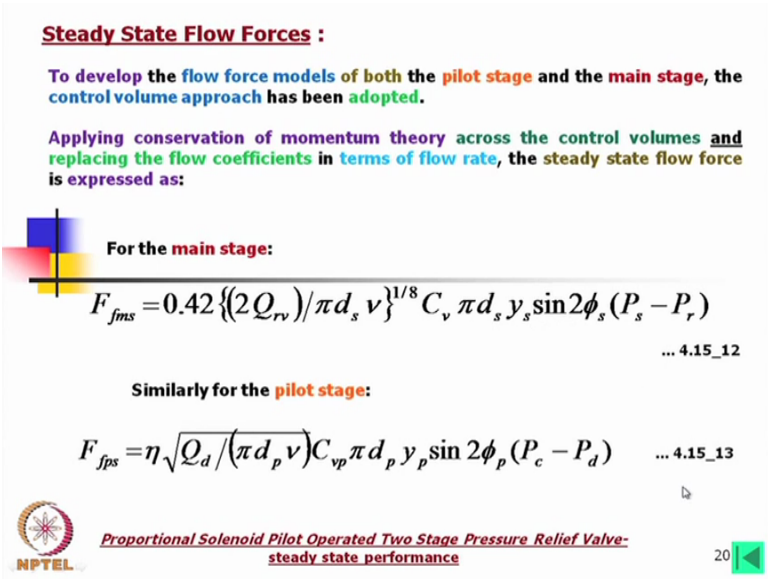

Steady state flow forces model for both pilot stage and main stage the control volume approach is adopted. Now we have to find out the flow forces. So main stage flow forces can be expressed like this, this is again using the flow force equation we have arrived into that but I think we need to explain this in a little better way so maybe we shall continue in the next day.

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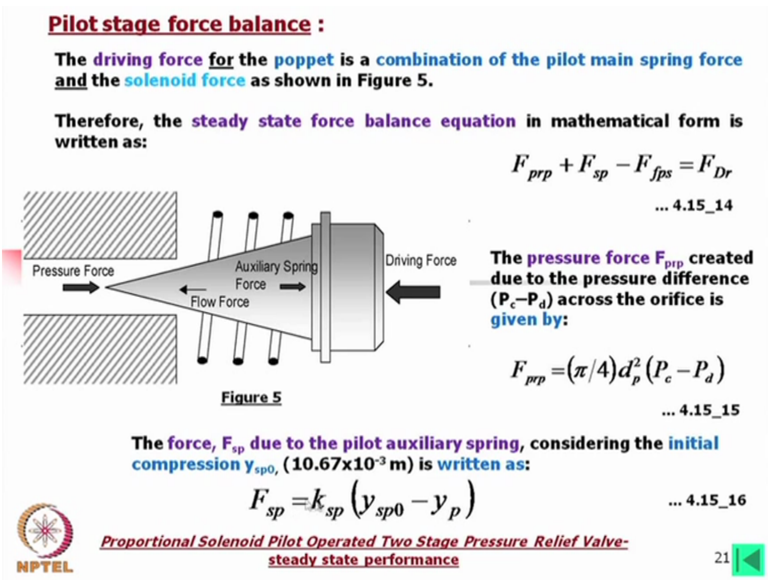

Now pilot stage force balance can be achieved by this, this is the pressure force and this is the driving force and this equation can be written in this form, this F Dr is the driving force, here what we find the auxiliary spring force and then flow force and this pressure force these three forces are flow force, spring force and the pressure force, okay. Now the pressure force is created due to the pressure difference so if we know the pressure difference we can estimate what will be the force and then knowing this area we can calculate also the flow force, so this force directly given by this formula.

And then spring force this was experimentally measured that considering the initial compression is this much this formula can be written as like this at this is the displacement at zero positions and this is the actual displacement and from there we can find out what will be the spring force there.

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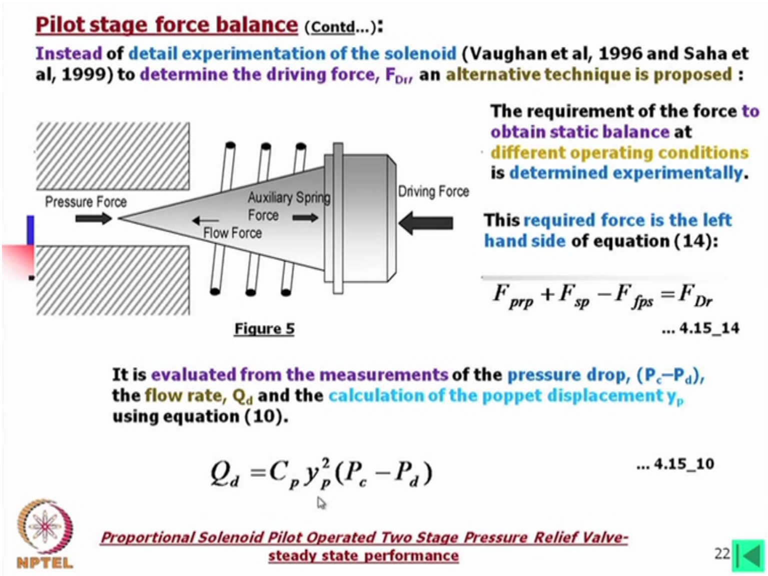

Then to find out this force also what was usually for a valve what is done say calculating all such meticulous things you may not find exactly what will be the force best thing we can go for experiment and we can see this how much really force is there. So what we did that the required forces in the left hand side of the equations can directly found by the driving force how much we are putting here, okay.

It is equivalent from the measurements of the pressure drop P c and P d and the flow rate is Q d the calculation of the puppet displacement Y p using this equation 10 now can be achieved so this we experimentally find out flow was measured this pressure was also measured. So what could be established that is the what will be the displacement for various pressure drop may be with the pressure drop this is related so once the flow is known and this data which we have examined earlier from there we could have make a estimate what will be the Y p there displacement there.

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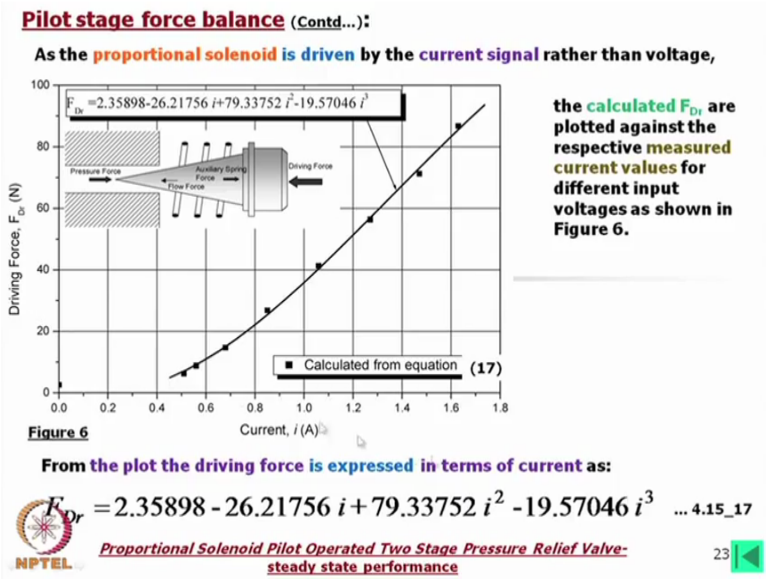

Ultimately this formula was developed, this is an empirical relations but this is in terms of the i input current, once you just directly substitute the input current then you can calculate what will be the driving force there. Now from the plot the driving force is expressed in terms of current as the same formula I have written here. So this means that if this formula is given for a current we can find out what will be the force, once the force is known then we can find out that pressure drop and from there we can estimate at what pressure it is working.

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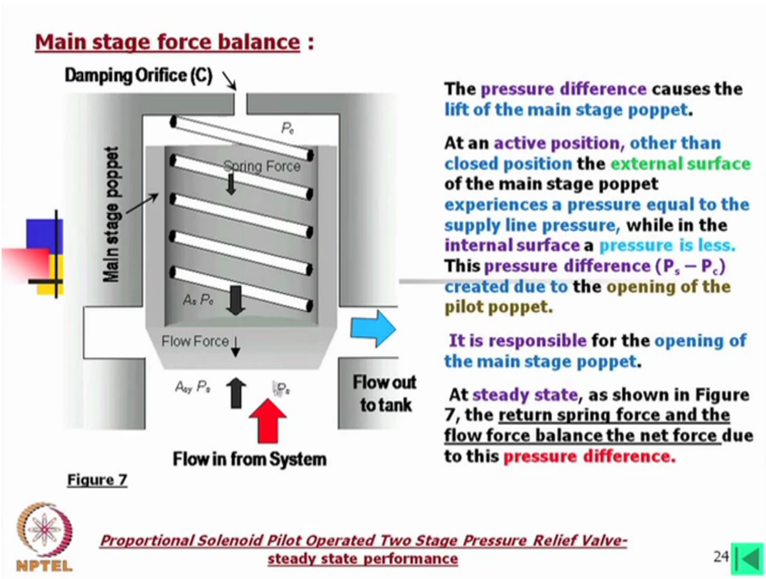

Now main stage force balance will be like this here the oil is coming in, now only there is a flow then there will be pressure drop so we can calculate what will be the pressure drop here, very quickly I am showing this, return spring force and the flow force balance the net force due to the pressure difference, what is there? This P c is less than P s, so P c into this area the area is same because the thrust area is same this puppet area and here the puppet area but there will be definitely some difference that is balance by this spring.

So when at point when the P c reduces then definitely force here will be more than this and then this will open but while it is opening this spring is being constant and at one point it will balance the force.

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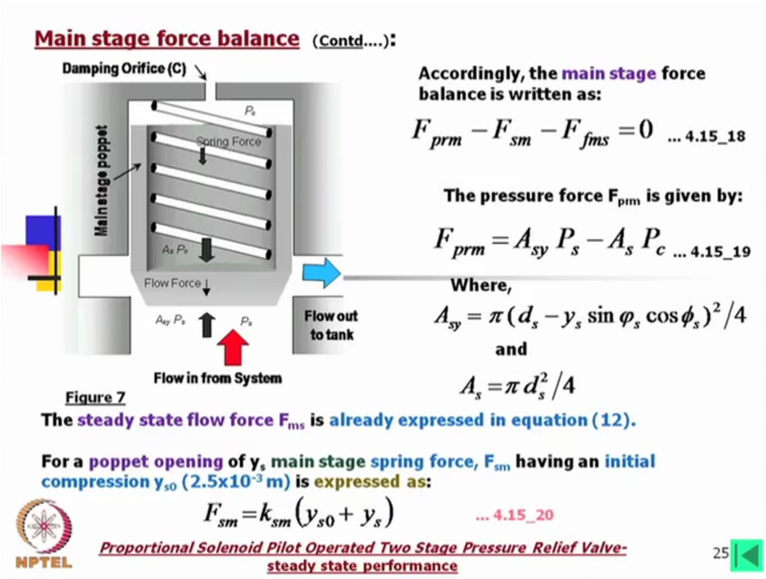

So according to the main stage force we can write down these equations and we can the pressure force F prm is given by this, this is the area and this is the pressure here and this is the area there and the P c is the pressure here this pressure is actually this A s although it is written like this but A s is the full pressure here over the whole area, it is not only acting over here it also acting over there, so A s and A sy it might be same but this we have kept separately because if there is any differences because when it is closed it might be this area is less than this, we can use this formula.

And steady state flow force is already expressed in equation 12 earlier and the puppet opening Y s main stage spring force F sm having an initial compression of Y s0 is 2.5 into 10 to the power minus 3 is expressed as. Now this is for a specific value of course, we have used this formula. So in that way we can estimate what is the force balance everything we can calculate.

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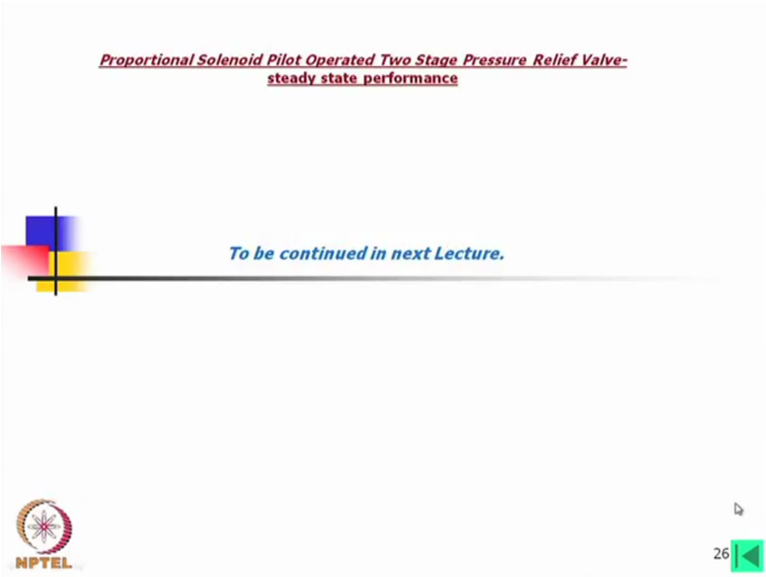

Now this is only we have how we can estimate the orifice characteristics, force balance equation all such things, flow force everything we have calculated, next day we will continue that how the performance is achieved or this the purpose of this analysis is that not only to understand the performance but also to understand the design of such valves.

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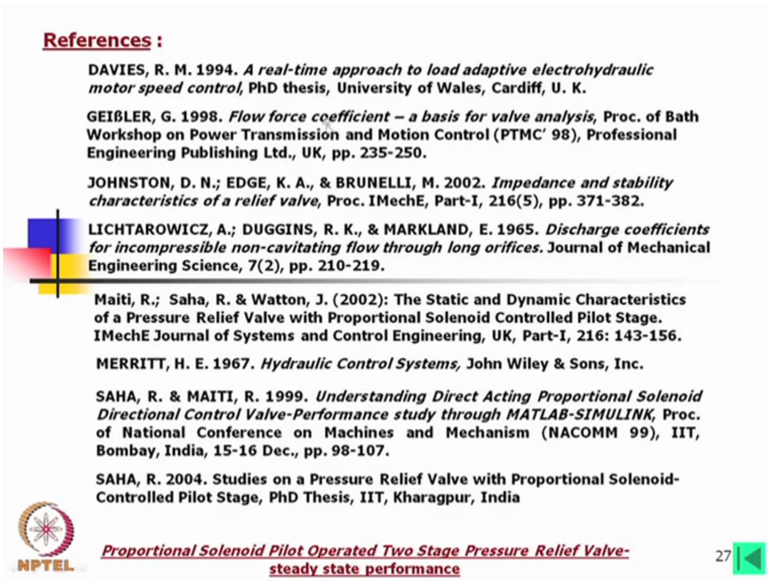

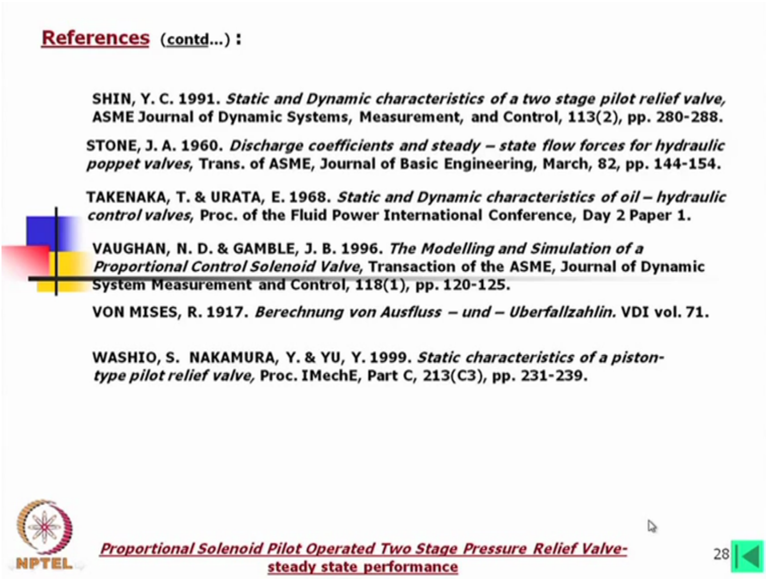

Now this is definitely in the note you will find or this so many references if you are interested you have to go through few of such references, thank you.