Fundamentals of Industrial Oil Hydraulics and Pneumatics
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Module 11
Lecture 11
Basic Spool Valve Design Analysis

Good Evening, today's lecture basic spool valve design analysis.

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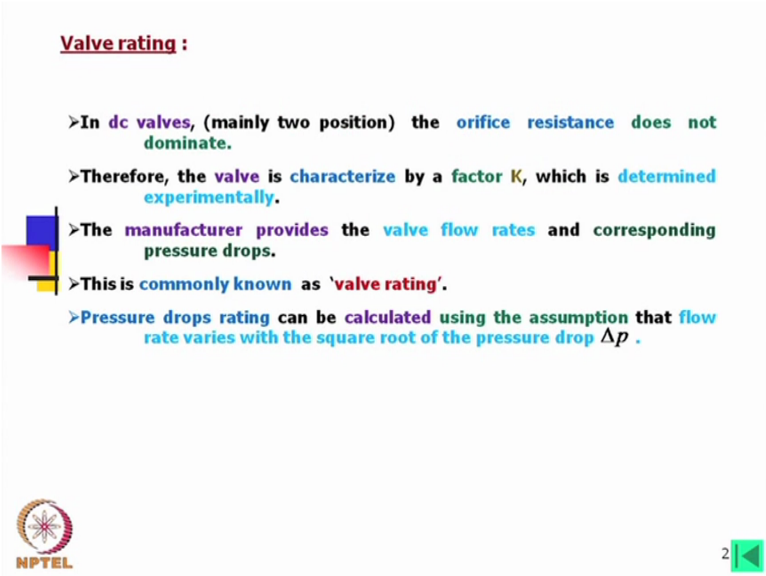

Now first of all we learned about what is valve rating? In dc valves, mainly if we consider two positions the orifice resistance does not dominate. This means that usually for direction control valve which we should consider as a on of valve, the orifices are not so accurately made although it is made close centre or open centre that means overlap, under lap or evenly it is made critical centre but orifice edge finishes or tolerances are not that close.

Therefore the valve is characterized normally by a factor K, which is determined experimentally. But in other words you find that in case of manufacturer catalogues you will find that they will either provide the factor K or they will provide some data from which we can calculate K and by which we can characterized, that means we can find what will be the flow, quantity, pressure drop etc and pressure drop usually point to point I mean for every position of spool valve or intermediate position of spool valve is not that important.

We will look into this how the K is expressed, what the manufacturers normally provide that is valve flow rate and corresponding pressure drop. This is commonly known as valve rating or in other words I would say that once a valve flow rates and corresponding pressure drop graph is available then from there we can find the relation K. Pressure drop rating can be calculated using the assumption that flow rate varies with the square root of pressure drop del p, this is a known formula.

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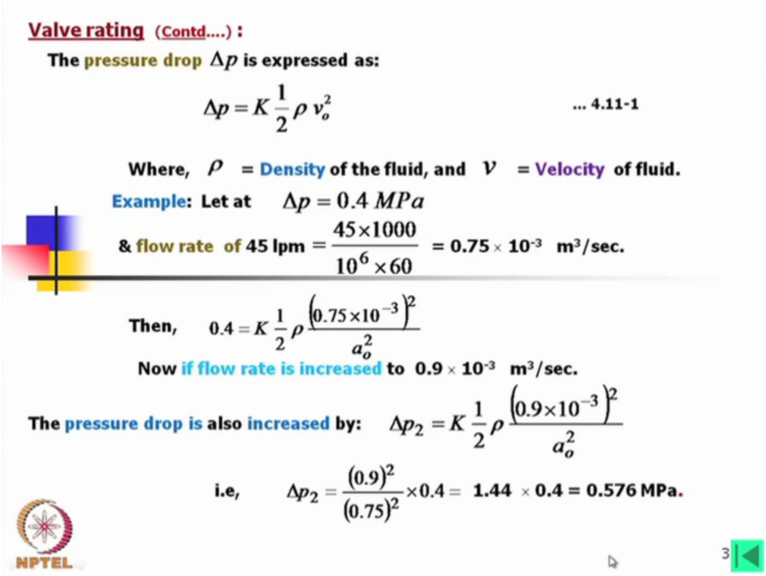

Now the formula is used del p is equal to K into half Rho v 0 square, whereas K is the valve rating what I have mentioned, Rho already we know and v 0 is the velocity. Now Rho is the density of the fluid and v velocity of fluid, v 0 at a particular position it might be at the Vena contracta or it might be at a particular relate to particular area corresponding area may be v 0 is expressed for a 0 position where the valve area is mentioned. So this means that we have to follow this valve rating along with this v 0 corresponding v 0 for which it is given. Now normally v 0 is the original area of the orifice, the geometric if the geometric dimension is given from that from there we can find out what is the area of the orifice.

Now with small example that we have explained how K helps in find out the flow pressure, etc. Now let us consider for a pressure drop is equal to 0.4 Mega Pascals is very low pressure drop as shown and flow rate of 45 litre per minutes, usually the valve rating flow rates still we use the litre per minute litre per minute although we should use in a SI units meter cube per second.

So I have converted here in meter cube per second, you can easily understand that first of all we have converted into the cc and then divided by 10 to the power 6 and divided by the 60 seconds is equal to 1 minute which gives 0.75 into 10 to the power minus 3 meter cube per second. So for that fluid velocity flow rate, okay we can calculate K and here this is the velocity, so this must be divided by area velocity divided by no I would say the flow rate divided by area should be velocity that is why we have taken this area here in the denominator that area square for which the velocity corresponds this is again I will mention a 0 normally we consider the orifice area, the geometric design.

Now if the flow rate is increased to 0.9 into 10 to the power minus 3 meter cube per second, then we can estimate what will be the pressure drop, this will be the same relations we can again write down this equation. In this case say manufacturers they may not provide this data a 0 that what is the exact area and we should consider also the Rho is not varying that means there not too much change in temperature or too much change in pressure, pressure of course it will not be very high for this differences in flow ratio.

But this we have to assume that we are finding out more or less at same temperature and area will not also change. So just to calculate this pressure drop at a new flow rate we can easily calculate what will be the pressure new pressure that is the pressure drop means this is the input, output pressure drop. So we had originally 0.4 Mega Pascal pressure drop and now we find that 0.576 will be the pressure drop, this is due to the increase in flow rate, for the decrease in flow rate also the same way we can calculate.

Now to calculate K obviously we should know the area factors of things. So may be in the valve manufacturer catalogue we have to look into this linearity upto which we can use these equations, say it may be not for all flow rate or not for all pressure drop, there are characteristics curves following that we can easily find out. And we need to calculate this how much will be the pressure drop, so accordingly we have to adjust the system pressure, okay. So these are very fundamental what we need to consider while we are using a valve.

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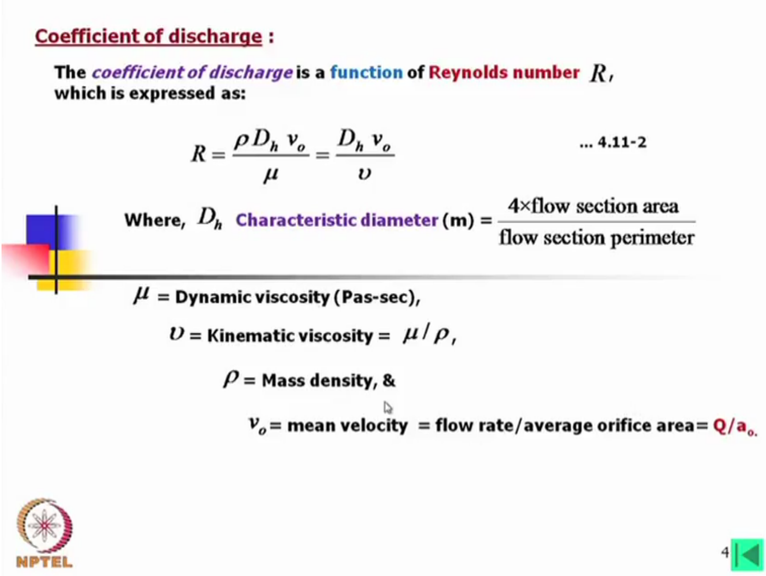

Now the important factor coefficient of discharge again the problem main problem is that in a valve the coefficient of discharge is an important factor to calculate many properties of the valve. Now coefficient of discharge for a valve for whole range may not be given, so we have to look into this how much this coefficient of discharge vary within the range of this valve and some data will be given there from which we can reassess what will be the coefficient of discharge.

However we will look into this how it can be determined experimentally as well as theoretically, experimental determination is normally not done in applications, whereas looking into the valve characteristic and theoretically background we consider what might be the coefficient of discharge for the valve. Now for dc valve or other valves which are used for not much of control I mean time control or online control or feedback, normally we do not care about the coefficient of discharge. However to calculate some characteristics accurately of say servo valve or the proportional valve we need to know how the coefficient of discharge is calculated.

Now the coefficient of discharge is a function of Reynolds number Reynolds number I discussed earlier but we can recapture it here, this is given by R is the Reynolds number, the Rho D h the v 0 divided by Mu or simply it is given by D h Rho 0 by Mu, which is this is the dynamic viscosity, this is the kinematic viscosity and this kinematic viscosity is nothing but Mu by Rho.

And D h is the characteristics diameter it is called characteristics diameter. Now this is although it is called diameter but it is apparently we are comparing the section with a circular pipe what is done we consider D h is equal to 4 into flow section area (flow into flow section area) divided by flow section perimeter. In case of circular pipe it will come as Pi D square by 4, you will find that but in case of rectangular or other area we need to calculate this flow section area.

Now in case of say rectangular or geometry simple or area of simple geometry we can calculate by knowing the geometry of that section and the perimeter also we can calculate easily, in case of which is not circular or which is not easily calculate by in knowing the dimensions we can easily measure this flow section area by some methods or and also we can measure this perimeter, then we can find out D h and from that value we can calculate what will be the Reynolds number. Now these parameters already I have discussed.

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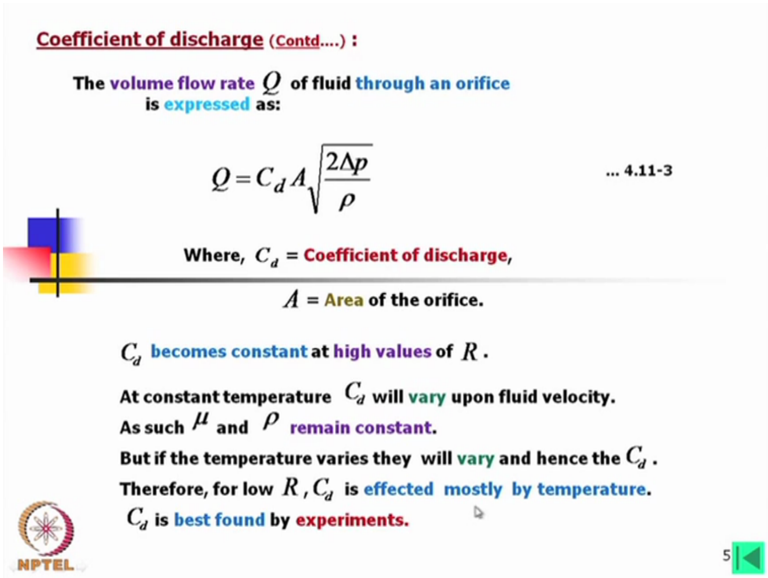

Now again we have written the a 0, a 0 is the normally the geometric area. Now the volume flow rate Q of fluid through an orifice is expressed as Q is equal to C d A (by twice) under root twice pressure drop 2 into pressure drop divided by Rho this is very known formula widely we use but this I have again used to concentrate on the C d the coefficient of discharge factor.

Now here A is the orifice area of the orifice again I would say this is geometrically of the orifice, C d becomes constant at high values of R this has been found experimentally, this means that for a given orifice if the Reynolds number is very high the coefficient of discharge becomes constant and here I would like to mention a very important clue for the design of those valve that while we are designing the valve looking into its flow range and operation and particularly our desired operation, desired output we try to keep the flow should be of high Reynolds number so that we can use the constant C d because you will find these equations the equations what we use for control or I mean fluid power calculations mostly nonlinear in cases of some cases those are very highly nonlinear.

So we should try to give some values as much as possible this would be constants they should not vary. So if we can keep this C d constant then this will be definitely helpful but let us see that how to estimate this C d. At constant temperature C d that is coefficient of discharge will vary upon fluid velocity, okay. As such Mu and Rho remain constant. Now fortunately the hydraulic oil which used the temperature range we cannot go for very high range somehow we have to maintain this temperature, this is due to not only for change in viscosity and other part there are also other hazards.

So looking into that we go for cooling arrangement in case of high temperature, in case of very low temperature we go for the heater. Therefore for a range even say for example 30, 40 degree centigrade what the change in Mu and Rho that may not be very significant in many cases may not be significant in many cases. However for accurate calculation in some cases we have to take those into account.

But as such the C d is considered again the effect of the that C d within the range of 30 degree temperature change very significant. But if the temperature varies they will vary and hence the C d therefore for low Reynolds number for low Reynolds number C d is effected mostly by temperature that means if we have to work in low Reynolds number range we have to very careful about the C d we have to consider all the factors.

However the C d is best found by experiments, in fact I would say that for each and every valve when those are deigned then their C d are tested, I mean experimentally found out whether within a range, I have told in some cases that C d in case of valves normally it is taken 0.6, 0.61, 0.62 but the valve are deigned in such way they keep this C d factor of that range.

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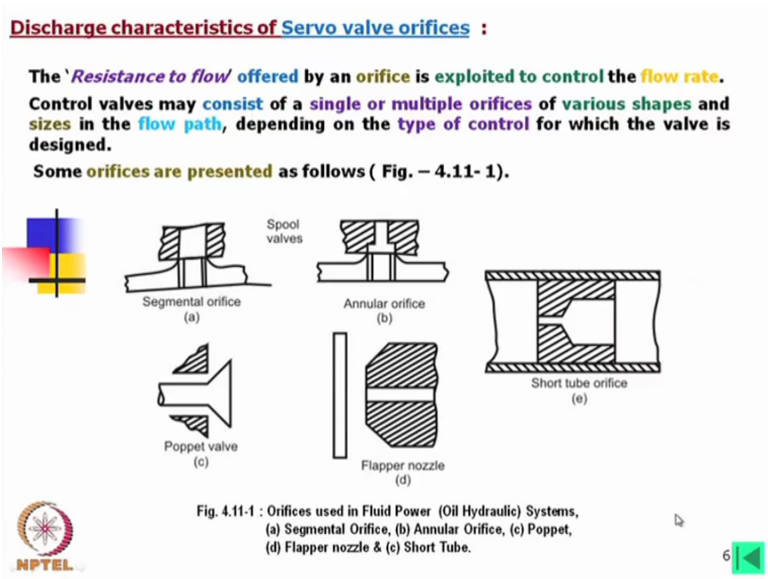

Now the importantly when we come in case of servo valve, the servo valve or if we say its characteristics we should know in details, the resistance to flow offered by an orifice is exploited to control the flow rate in case of servo valve we need to control the flow rate and as well as pressure, this is maintain, this is done by varying the resistance to flow that means we have to vary the orifice, or varying orifice means we are not varying the geometry sorry I mean the shape, shape may be constant I mean say for example in a hole if we use a cone to vary the orifice then the characteristics of the area of the orifice remain more or less same that is not much varying.

Only thing we have to look into that how much the C d is varying there or in case of the spool valve normally the port is rectangular. So in that case also what we doing? We are varying the area but not the shape of the orifice. However there are some orifices say for example in circular hole and let us consider a circular hole is there and the length of the spool is moving then it is first a part of the circle to the half of the circle and then may be at some point full circle.

So definitely there area is varying not linearly, variation of area is not linear. In that case also we have to carefully consider what will be the C d coefficient of discharge. Control valves may consist of a single or multiple orifices of various shapes that I have mentioned and sizes in flow path, different size as well as many. Say for example in a proportional control valve simple which is pressure control valve the most common type with a I mean pilot operated you may find 5, 6 orifices in total flow path, okay.

In some orifices are just a small hole with surfaces, in some cases it is like a short tube and in some cases it is a long tube orifice. Of course in some for some cases we will consider that is a capillary flow but usually in that case also sometimes we consider what will be the coefficient of discharge or those orifice. Some orifices are presented as follows I have shown some orifices you can see this figure.

Now a it is segmental orifice, segmental orifice means in that case it is from the figure it is not clear but it is apparently there are two circular holes on one circular holes and another circular body but they are moving slowly at when the one under the other I mean the in position we can say Null position it is completely closed. But when one moves from the other then as I told it will be spat of the circle, than half of the circle, then full of the circle like that.

The second case annular orifice, this is like a there is a circular hole and there is a cylindrical bar so if you allow this to enter inside then there will be annular passage, if you remove that one that is a full circular passage otherwise there will be annular orifice. Now third one is the poppet valve, poppet type in that case what you find that this will always say if I consider this will remain always an annular but the annular area we decrease and increase also if you look into the jet angel, jet angle normally depending on flow for an annular passage that jet angel takes its own angle say sometimes I discuss that it is it might be 69 to 70 degree.

But providing this shape of the poppet changing this angle of the poppet we can also change the jet angel say that obviously depending on the flow. Suppose in this case also if there is a very high flow then jet then the flow will detach from both this and this and it will take its own angle. But you will find that with the increase and decrease in the area the jet angel will change fortunately we can go for theoretic analysis to find those although those are always to be verified experimentally.

Now in case of d this is flapper nozzle, now in case of flapper nozzle you will find that there is a uniform cylindrical hole and there is a plate but depending on that gap this flow will take it is something like umbrella or in water umbrella but still this will take its own shape. So what will be the area, area actually the annular area here that means flow is coming over here and it is going out through this periphery and we are decreasing this passage. So this will have definitely its own characteristics.

And another is as I told is very offend we go for short tube orifice this portion is the short tube orifice. Normally it will have within taper angle due to the drilling we use a drill and it is also unless otherwise for specific purpose it is better to make some cone here rather than making it a flat step, okay. So these are the basic orifices which are used in control valves.

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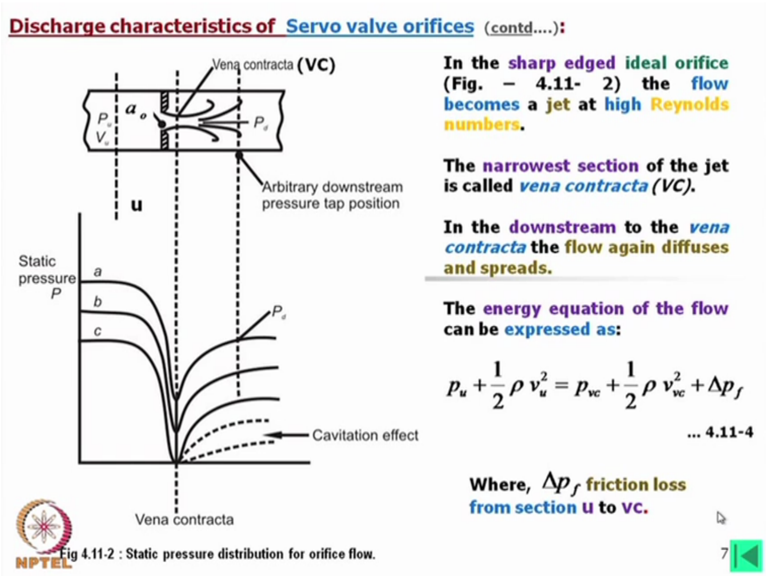

Now to find out a discharge characteristics of a servo valve orifice, you see this look at this orifice in a pipe you must have learned already how to find out this coefficient of discharge Vena contracta in may be in the hydraulics classes, one important thing is that always you will find that orifice usually this orifice is surface. You will find that at the entry point the diameter is the lowest, area is the lowest and a 0 is the area, the a 0 (())(26:08) mentioned.

Suppose if it is a 1 millimetre dia easily we can calculate Pi into 1 square by 4 will be the in millimetre square will be the area. But after that you will find that there is a this is a diverging this is diverging. Now the question is that suppose if I take a very thin plate and if I make a straight hole and if I make slightly diverging will be there any change the answer is yes there will be change.

So to get a good I mean characteristics good characteristics of the orifice it is better to make this surface orifice. So this will give such characteristics which will be reliable for varied flow range, okay. Suppose if I make suppose it is a thin plate and we can make it okay, let us make it as a straight hole for that in a range of oil flow what the characteristics will get that will be a varied nature, incompliance into that if we take a thick plate and then we make this area (convergent) sorry divergent, okay.

So this making this orifice there are some specified angle which is not mentioned here but you can find from the book but here now usually in this portion I mean the entry point the upstream position you can take a section consider a section which is slightly away from the orifice the section u and here you can consider the velocity is 0, there is no velocity almost the pressure is there but no velocity.

On the other hand definitely when it is coming out from the orifice there will be the velocity and you will find at a distant from this orifice we get the minimum area which is called Vena contracta, okay. So this means that we cannot we are not in a position to measure the pressure and other things here, we possibly we will measure this pressure and may be area and other things at a distance.

So estimating (the position) sorry the area of the Vena contracta is also important and the maximum velocity will reach at this point, you can see this is the pressure characteristics of this jet through the orifice, okay. In the surface ideal orifice which I have shown the flow becomes a jet at high Reynolds number, okay and this is desire jet flow is desire for many valve operations.

The narrowest section of the jet is called Vena contracta which I have explained already. In the downstream of Vena contracta the flow again defuses and spreads which is shown here. The energy equation of the flow can be expressed as now this is known equation already you know the at this section pressure half into Rho v u square whatever may be the velocity is equal to Rho vc half Rho v c square that is at the Vena contracta we have considered the Vena contracta plus del p f, this del p f is the friction loss from section u to Vena contracta section u to Vena contracta.

This will be the characteristics equation for this flow and this loss will be there otherwise if this loss would not be there then perhaps we could have write these equations and if we consider that u section at a distance where this is equal to 0, then p u will be p vc whatever the pressure is there plus half Rho into vc square or in other words if you can measure the pressure this pressure is most of the cases probably will be known and this is also a known factor and we can then calculate what will be the velocity there.

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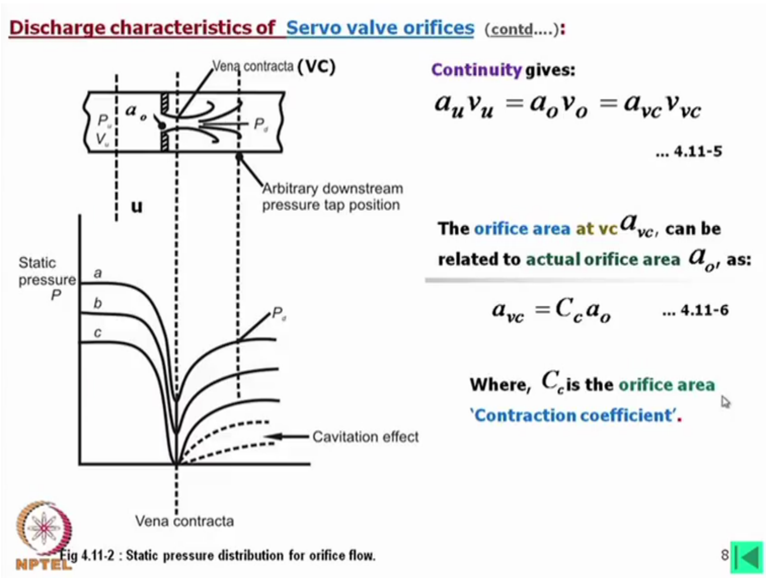

Now from the continuity we would find that a u v u is equal to a 0 v 0 at a vc and v vc. Now if a u in fact this is a u here at that for a known case known pipe we can write down this equation but if it is from a very large trunk we should not consider because this we as such gives this is equal to 0 because no velocity is there, it is normally if we put in a pipe then we consider this and this and this, this is known, this will be also probably known because if knowing the flow rate we can easily calculate and from there we can probably calculate what will be the area of the Vena contracta if we can measure the velocity there.

The orifice area at Vena contracta a vc can be related to actual orifice area a 0, as a vc is equal to C c into a 0. So this C c is called area coefficient or contraction coefficient normally contraction coefficient, where C c is the orifice area contraction coefficient.

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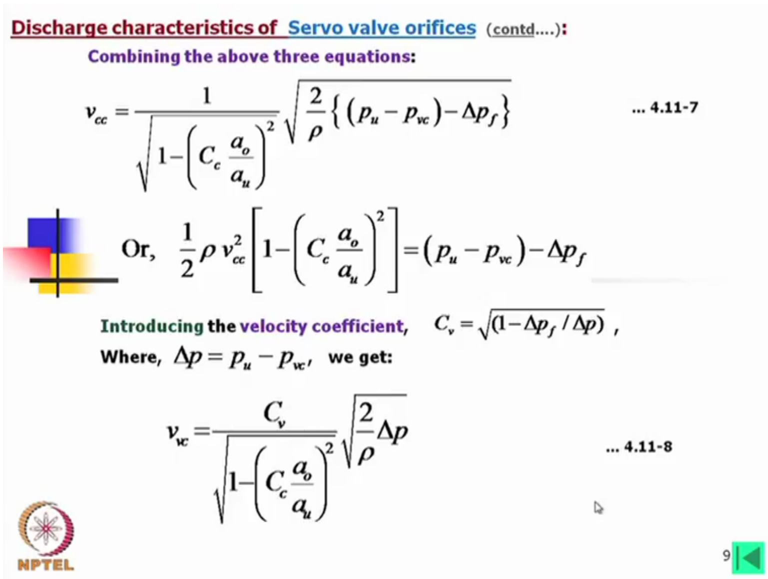

Now combining the above three equations whatever we have earlier considered we can now write down this equation that velocity at I think it will be V c Vena contracta is equal to (1 by 1 by Rho) sorry 1 by root 1 minus the contraction coefficient into the geometric area divided by the area at the entry point by whole square and then under root 2 by Rho the pressure at upstream, pressure at Vena contracta and this loss, this we mention as a friction loss actually this we measure in terms of pressure drop but that loss is really due to the orifice resistance which basically the resistance the frictional resistance there.

Then this equation is modified to this for and then we can introduce the velocity coefficient this part del p f by del p is the total pressure drop we can introduce a velocity coefficient where del p is equal to p u minus p vc, pressure at Vena contracta and with this coefficient this equation is written in this form, okay. So this will be the vc at Vena contracta, so we can write down these equations, the pressure drop can be measured and this is already known and this is also known factor and the contraction coefficient that is experimentally so if these are known then we can calculate the velocity at Vena contracta, okay.

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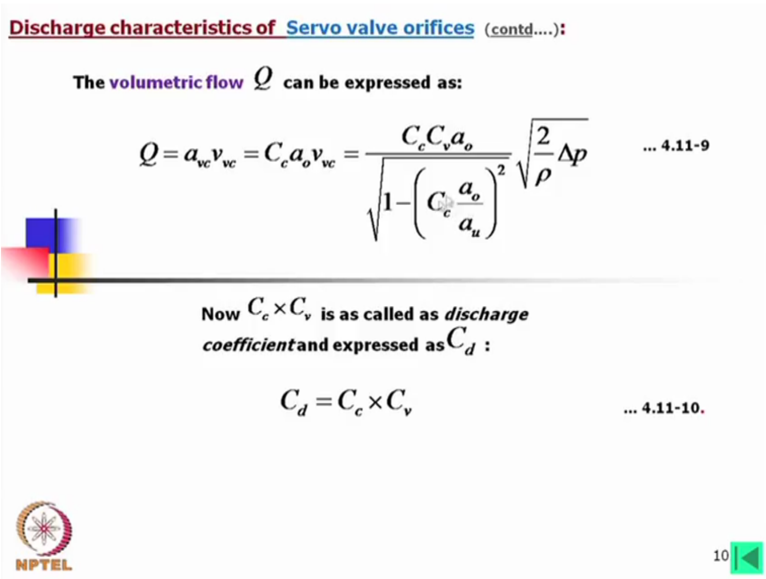

Now the volumetric flow Q can be expressed in this form if we remember the earlier equations then we can rewrite this equation in this form, okay. So here we are getting the C c into C v which is called the discharge coefficient and expressed as C d is equal to C c and into C v. Now this is this already you know but still it is explained here how we have arrived into this.

Now in many cases for the valve we need not know this C c and C v separately, we can simply estimate the C d in most of the cases however in some cases we need to know that C c will show that.

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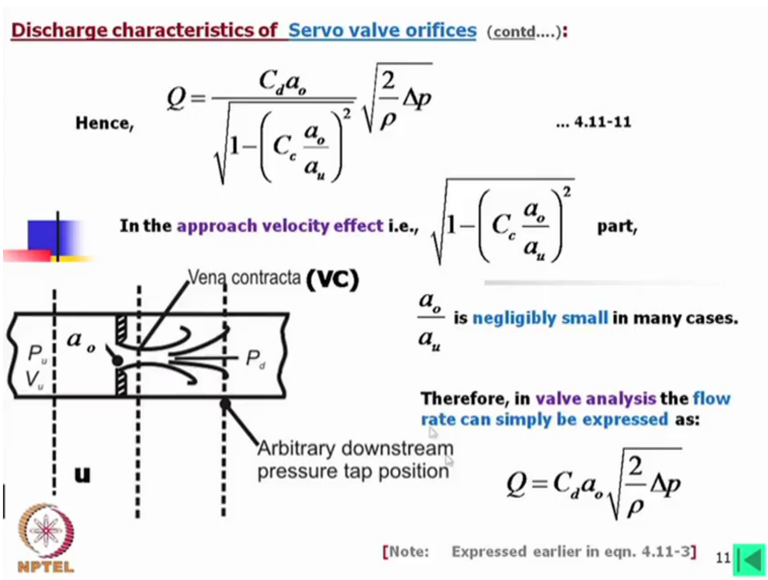

Now we have replaced C v into C c with C d, so this has come into this form. Now in many cases you will find that this quantity a 0 by a u is very I mean a u is very high in comparison to a 0. So totally this quantity becomes very small and we can in most of the cases we can neglect this part or this means that we can consider this part as 1, this part is equal to almost 0 and this is 1.

So for a example in a valve usually the flow channel you will find may be 5 millimetre, 6 millimetre, or 10 millimetre whereas the orifice hole that will be 0.5 millimetre or may be 1 millimetre, so if you now if you calculate this part this is very close to 1. So we can simply consider this formula, okay. However this quantity is called approach velocity effect because this is related with the area at the upstream but again you should look that contraction coefficient is associated with that.

So in case of this if this ratio is significant, so we have to know this contraction coefficient to calculate this part, is negligibly small in many cases a 0 by a u which I have already explained and therefore in valve analysis the flow rate can simply be expressed as Q is equal to C d a 0 under root 2 by Rho del p. Now this expression already we have used earlier in 4.11-3 equations.

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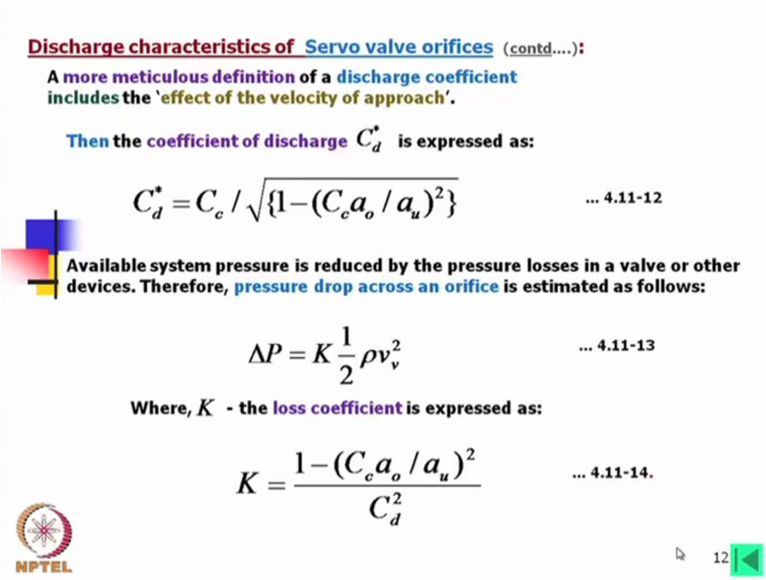

A more meticulous definition of a discharge coefficient includes the effect of velocity of approach. So for more accurate calculation to characterize the servo valve we need to consider this part. So therefore the coefficient of discharge that C d star is expressed as C c divided by 1 minus C c a 0 a u whole square. Now in this case that I would say that the C v part is already considered in the calculations so just by doing this calculation we can arrive into a next C d part that C v which is velocity coefficient this is in the range of 0.98 of that range always.

Available system pressure is reduced by the pressure losses in a valve or other devices. Therefore, pressure drop across an orifice is estimated as follows this already we have expressed and K is the loss coefficient, so K is now called the loss coefficient which is expressed by this formula if you just equate you will find this formula that means actually K the loss coefficient or the characteristics valve rating characteristics we should calculate this K using this formula.

Now this usually we find experimentally, this is also find experimentally, this can be measured and from there we can calculate what will be the K. In many cases for servo valve this rate is also supplied by the manufacturers.

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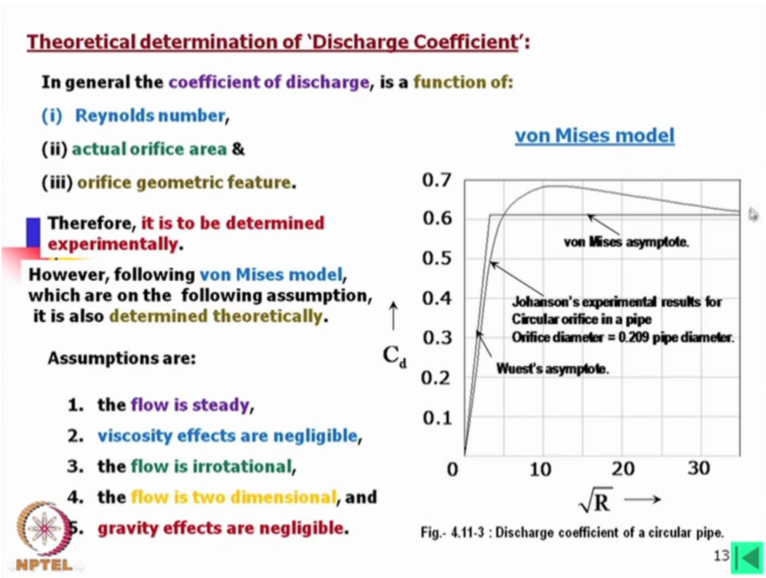

Now also we can find the discharge coefficient theoretically, this means again I would say this is not the pure theoretical or analytical rather based on experiment we can estimate a estimate the discharge coefficient for some cases, how? In general coefficient of discharge is a function of Reynolds number so we must know it, actual orifice area this will be known also, orifice geometric feature that is important whether it is a short tube, whether it is flapper type, whether it is a surface orifice, whether it is annular, whether it is a ring type etc, etc with poppet so that feature we should know also.

Therefore it is to be determined experimentally I mean that with this we can relate but first of all we should find experimentally and from there we can have some empirical relations by which we can find it. However the von Mises model is followed to determine this value theoretically or we should say to estimate a value not analytical but an estimated value can be found out from von Mises model.

Now for that again if we would like to use this model we have to first assume that the flow is steady or in other words this we should apply when the flow is steady. Viscosity effects are negligible that means viscosity is not changing much. The flow is irrotational, the flow is two dimensional and gravity effects are negligible, gravity effects means I would say that it might be from a level to other level it is flowing but this is there the velocity is so high the pressure changes due to height change is negligibly small.

But the flow is two dimensional what is two dimensional in a what is two dimensional flow we call the two dimensional means in that case the in the either direction of flow if we consider a direction of flow then from there it can flow in other directions but there should not have it is flowing through a conduit there should not have any cross flow there should not have any cross flow.

This flow is two dimensional means we neglect the cross flow if I consider a pipe there is a no cross flow also there is no rotational flow, it is irrotational. So we should consider this are all a stream line flow or laminar flow, however in valve orifice mostly the flow becomes turbulent that we should know. Now what is von Mises model? This is the von Mises model you see this if you look into this curve is an experimental curve which was conducted by Johnson his name is Johanson not Johnson Johanson's, okay he experimental found out that coefficient of discharge with respect to the Reynolds number but for this scaling we have take root R.

Now what we find that this curve he consider that the orifice diameter inside again I would say orifice means it is not simple hole the proper orifice ideal orifice it was taken with a divergent in the direction of downstream but the size of the hole was 0.209 of the pipe diameter that means almost 20 percent of the pipe diameter. For that orifice he tested and then he found that after this value is 40 that means not even 40 when less than that this is almost coming a straight line.

Now then for this part I mean where the Reynolds number is low then Wuest's asymptote is used, say this line it is as you can see it is almost close to this, after that we consider the von Mises asymptote and in most of the cases except at the very low flow rate we can use this value, value whatever is coming over here for the most of the valve calculation because of the reasons that R is will be within that range.

It is say if I consider say 40 into 40, 1600 that much is the Reynolds number for that we can consider 0.6 in fact we can consider it is 0.61 from the range of R perhaps it is 1000 we will see in the next slides, okay. So this model we normally use for valve calculation. However if our Reynolds number comes within this range then we have to careful about that, okay. Now normally what is done the flow is the orifice sizes are selected for the particular flow range is such that we can be at this zone.

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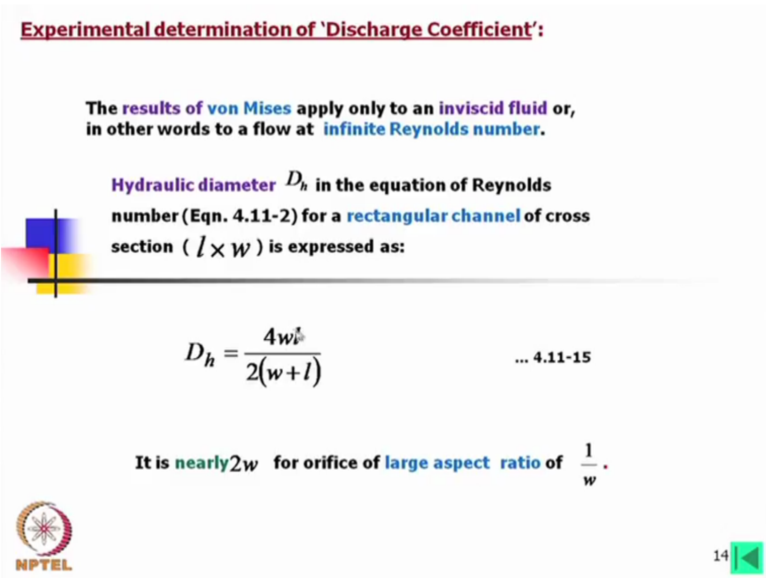

The results of von Mises apply only to an inviscid fluid, now again this is a inviscid fluid you can understand that with the viscosity definitely it changes, I mean he developed this model for inviscid fluids, okay. In other words to a flow at infinite Reynolds number that means (very) this is applicable model is applicable where the Reynolds numbers are high we should take these words to this meaning, okay.

Now there is also quantitative value is given here will come to that but here again let us consider the this hydraulic diameter in the equation of this Reynolds number for a rectangular channel is l into w, where l is the cross sectional length it is please note it that it is not in the if

I consider the rectangular section l is the length and w is the width or the thickness, do you understand my point?

So for that we can express definitely the area will be w into l, so 4 into w into l and the perimeter will be 2 into w plus l. Now it is nearly to 2w for orifice of large aspect ratio that is 1 by w (for if the large) this aspect ratio is large in that case this will become 2w in many cases this is consider as a 2w, okay. I think in earlier equation it will be l by w by mistake it is 1 by w written there, so aspect ratio means l by w.

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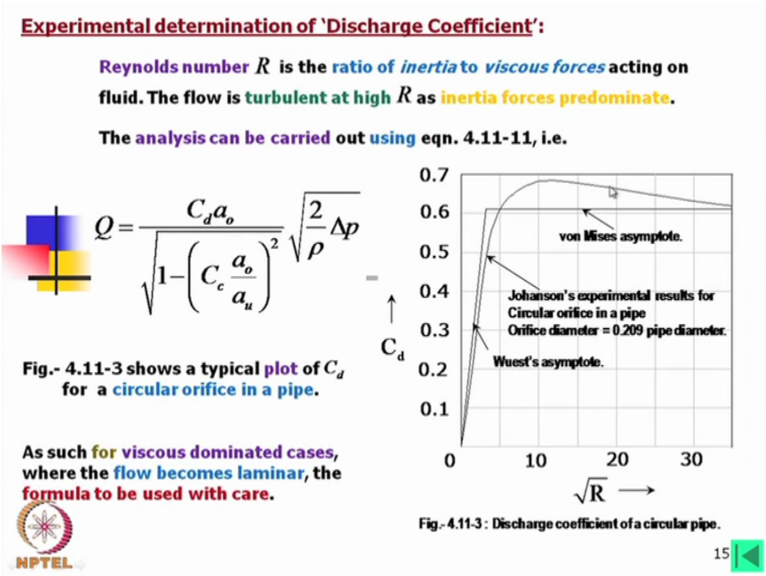

Now Reynolds number is the ratio of inertia to viscous forces if you remember the formula this will be definitely inertia by viscous forces acting on the fluid. The flow is turbulent at high Reynolds number as I told if the Reynolds number is high in that case it becomes turbulent that means in many cases in the orifice flow you will find the after the orifice the flow is turbulent.

Now we will say once it becomes turbulent we cannot estimate many things mostly in case of turbulent flow we have to find out those characteristics by experiments. In fact we may not need to know the very close characteristics at that zone because after sometimes again it will become laminar. However one thing I just would like to give you as a clue that this turbulent flow after the orifice gives better valve responses, response of the valve will be for better than if it remains laminar, okay.

The analysis can be carried out using the equation 4.11-11 which we have already expressed earlier, now with using these equations the C d plot is shown here so from that we can consider the C d and the other values we can consider and we can easily calculate Q. As such for viscous dominated cases, where the flow becomes laminar, the formula to be used with care, I what I was explaining this means that in that case Reynolds number will be low we have to take care. Suppose it comes in this zone probably we have to consider the actual C d whatever is there.

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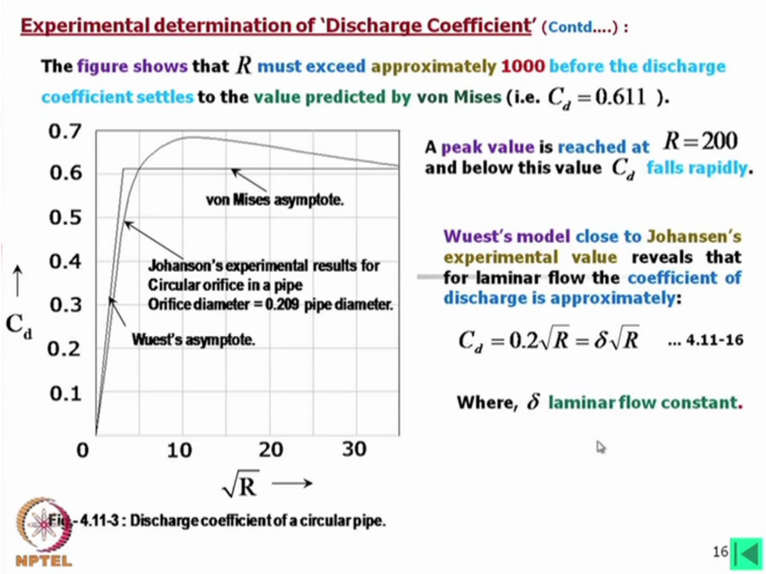

R must exceed approximately this Reynolds number must exceed 1000 before the discharge coefficient settles that means it is around here, okay around here because square root of 1000 is how much it is 3 point something, 30 point something 30 point something it will be. So very close to that not even 31, 31 is no 33, 33 into 3 into so it will be something between 31 and 32. So it very close to this and from here we may consider it is almost linear and stable and we can take for that 0.611, sometimes we use 0.62 or simply 0.6.

A peak value is reached at R is equal to 200, that means here here this is the peak value and below this value C d falls rapidly. Wuest's model close to Johanson's Johanson's experimental value is approximately given by this equation C d is equal to 0.2 and root where instead of 0.2 we use sometimes delta which is not exactly 0.2 but very close to that and this we call laminar flow constant.

Now this d value I would say why we have use delta here, normally for hydraulic oil we can use to and delta depending on the oil we can have this value is different.

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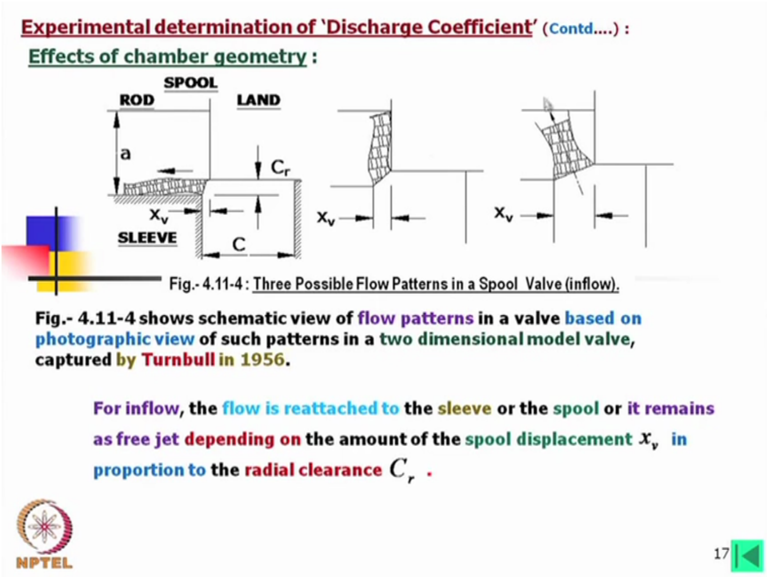

Now effects of chamber geometry, now what we have consider we are looking into a small portion of a spool, this is the spool rod or steam, this is the land portion and this is our what will we would call the sleeve or may be the valve body itself, this is the sleeve. Now usually this in this sleeve whatever this radial clearance this side will also have the same radial clearance but what I have shown here that we are considering the particular the one side orifice and we are considering the what may be the flow pattern there.

In fact the experiment was conducted it that way, this was very closed, this is from the actual photograph, this was developed. Now in this case of course in case of land and if this is a closed overlap so there is negligibly less flow. So we can also even if real case we can consider this will be the flow pattern, the three flow patterns are like this. This was conducted by Turnbull in 1956 long back about 55 years back this was conducted and he took some photograph and from there it was found that for inflow what is we call inflow that from outside it is going inside the spool chamber, so that is called inflow.

The flow is reattached to sleeve or spool or it remains as free jet depending on the amount of spool displacement in proportion to the radial clearance C r that means if you compare C r by X v with that ratio it will depend on for a certain pressure of course whether it will be attached to this or it attached to this or it will remain as a free jet, okay.

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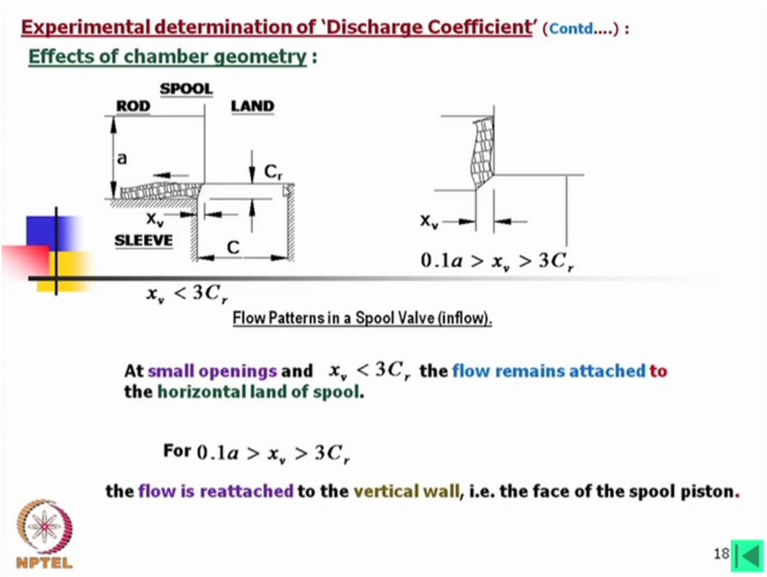

Now in this case if this spool displacement is less than three times the clearance then the flow remains attached to the horizontal land of the spool (sorry I think here I have made a mistake) it is horizontal land of the body. Then if it is 0.1a within this range less than 3 of the radial clearance but higher than 0.1, of sorry it is less than this but higher than 3C r, in that case we will get that reattached to the vertical wall, of the face of the spool pistons.

Now this perhaps it is a attached to the vertical we can say this will be attached to the sleeve but it will be parallel to the land parallel to the land of spool like that or it might be it is written the flow will takes places like this it will always touch there.

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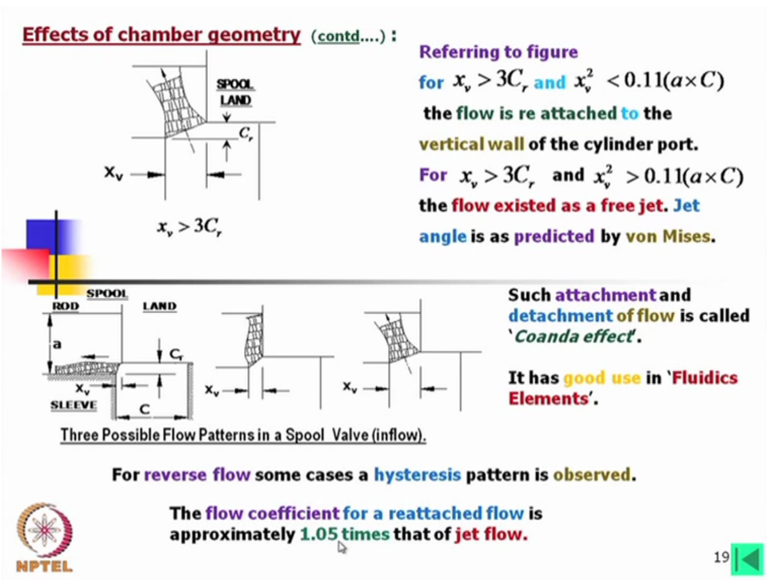

Then if it is slightly higher say if this X v is 3 times the clearance that is the spool displacement is 3 times the clearance and also this condition is satisfied you can see these conditions this is in the ratio of a into C is this distance a is this distance then in that case flow is re attached to the vertical wall of the cylinder port, whereas if this is satisfied but this value is greater than the 0.11 into a into C the flow existed at free jet. Jet angle is predicted by von Mises, okay.

Now I have shown that what will be the flow pattern and then such attachment or detachment of flow is called Coanda effect which has used in Fluidics Elements and the reverse flow some cases hysteresis pattern is observed, what is there hysteresis pattern? You will find that for the reverse process what will happen the Reynolds number is changing but with that change in Reynolds number it is not following the exact role, so you will find that there will be some hysteresis. So these are important for the control point of view and the flow coefficient of a reattached flow is approximately 1.05 times that of jet flow, okay.

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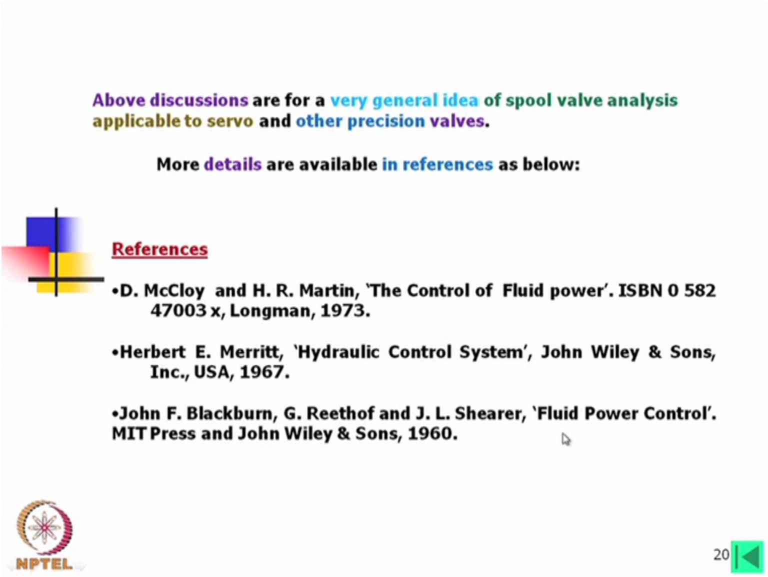

Now above discussion is very general only with respect to the may be the spool valve but for each and every type of orifices so we should have the analysis or may be the formula we have to follow accordingly. I have discussed only small portion from these references, okay. So to know details about that we should go through these books unfortunately in the scope of this lectures we cannot discuss much more only thing wherever the specific case will come we will refer that exact orifice sizes and their characteristics, okay thank you very much for listening.