Fundamentals of Industrial Oil Hydraulics and Pneumatics
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Module02 Lecture03
Incompressible Fluids-Some Fundamental Properties

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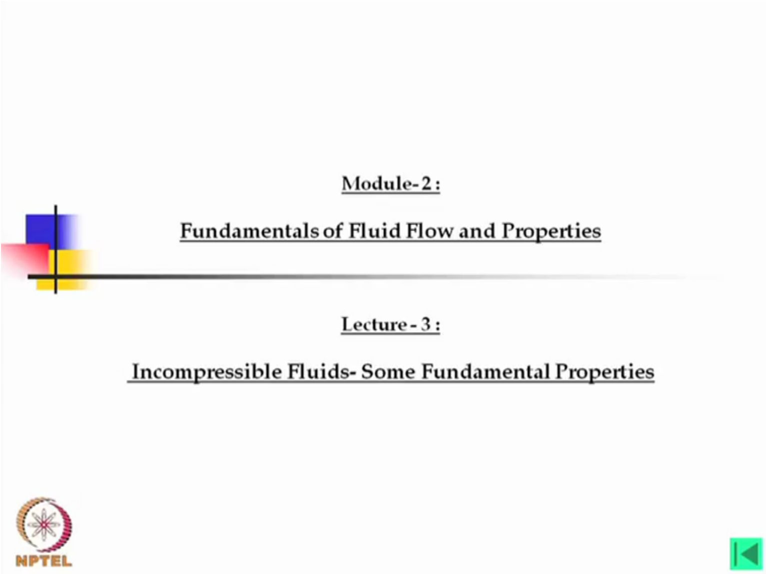

Good day welcome to the 3rd lecture 2nd module. The lecture title is incompressible fluids-some fundamental properties.

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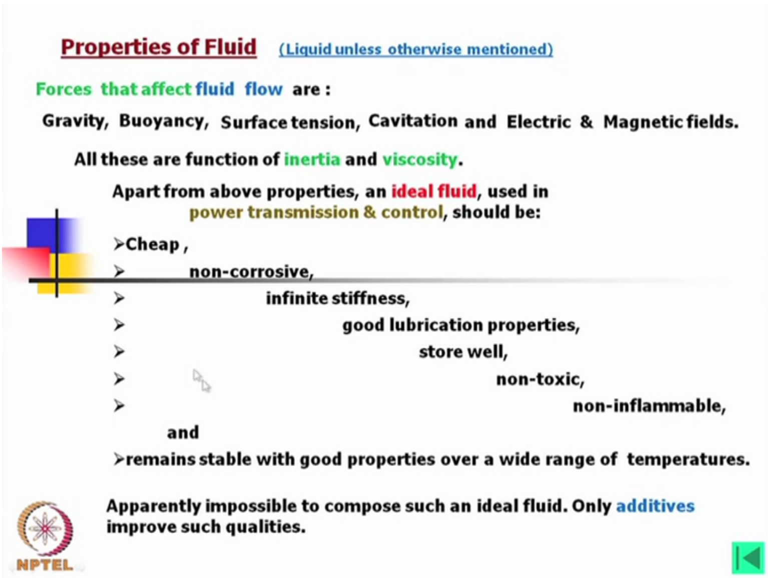

Now I have already mentioned that the fluids are liquid as well as gas, but if we think of the properties. There are different as well as we need different mathematical treatments, while we are formulating or modeling any engineering problem and apart from that, the pneumatics as it is a compressible. These are treated separately than liquid. Also, the oil hydraulics are more used in comparison to pneumatics particularly in outside operations. So in this lecture we shall discuss only about liquid unless otherwise mentioned.

Now forces that affect fluid flow are one is gravity, second buoyancy, third surface tension, fourth cavitation, fifth electric and magnetic fields. These are the modules. All these are functions of inertia and viscosity. Apart from above properties, an ideal fluid used in power transmission and control should be cheap. Now why we have just mentioned it is cheap? Just for your idea I would like to mention, if you would like to use a servo oil, it costs about minimum 200 to 300 rupees per liter and usually even in a small systems, you may need 50 liters of oil. If it is a servo system, in very precision machines like aircraft machine tools, you may need to change this oil some cases every week, some cases in a month. Commonly we can use such oil for 2-3 years after that we must reject that oil. So we have to look into the cost that is why first term is cheap, then a non-corrosive.

Most of the components are ferrous material and we should look into the fact that the oil that should not be corrosive. No rust should come over the ferrous components. Now infinite stiffness. What it is infinite stiffness means we what fluid should be incompressible and stiff in such a way that it should behave like a solid material while it is transmitting force? Good lubrication properties, in fluid power components most of the moving parts are in sliding contact or else rolling contact and where we expect elasto-hydrodynamic lubrication. Therefore, it must have good lubrication properties. Store well, this means that we have to keep some oil in store for the later application. So this we have to this should have relatively longer life. Non-toxic, this is a great problem with fluid power, because when the heat is generated, it vaporizes to some extent and this gas is number good for the health. However, it should not be very harmful and it should not be toxic.

The most importantly it should be also non-inflammable, because in many applications, there is a possibility that it may catch fire, for example in mining application we have to take extra precaution so that the oil do not catch fire and it should remain stable with good properties over a wide range of temperatures. This is another important factor with the temperature many properties of the oil will change and therefore, there will be change in performance particularly where we need a very accurate control. There, it becomes a problem. Apparently impossible to compose such an ideal fluid. However, only additives improve such qualities.

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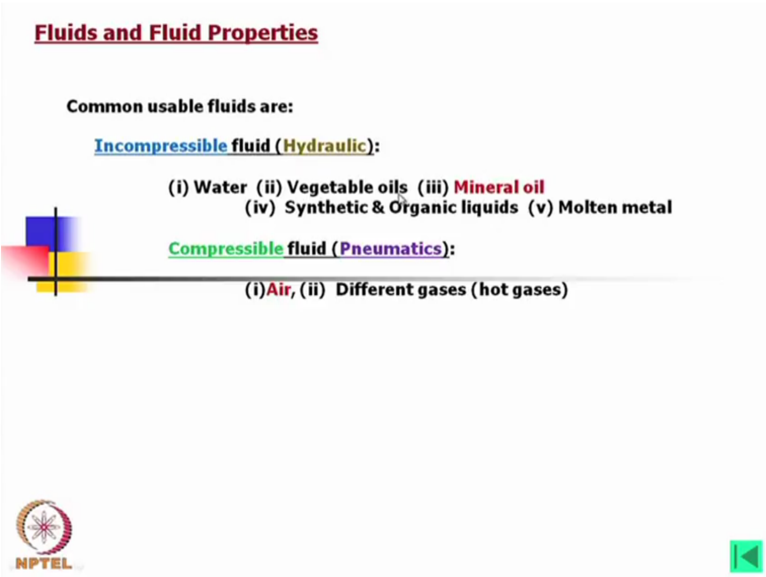

Now we will come to fluids and fluid properties. Common usable fluids are that incompressible fluid hydraulic, one is water, because this fluid power started with water, but it was found it not very suitable for the fluid power. Next there are some vegetable oils, those are also being used at the earlier stage, but at point it was found the mineral oil, the petroleum based oil has a very good properties for the use in fluid power systems. Now apart from that particularly looking into the property that it should not be inflammable synthetic and organic liquids are also being used and last the molten metal that also can be used as a fluid for the fluid power transmission. This molten metal, this is a special applications, but very rare, but still it can be used.

Now although we will come to the compressible fluids later, but here we should I would like to mention that compressible fluids, which are used in pneumatics one is air, most of the cases you will find only air is being used. However, different gases particularly hot gases also can be used.

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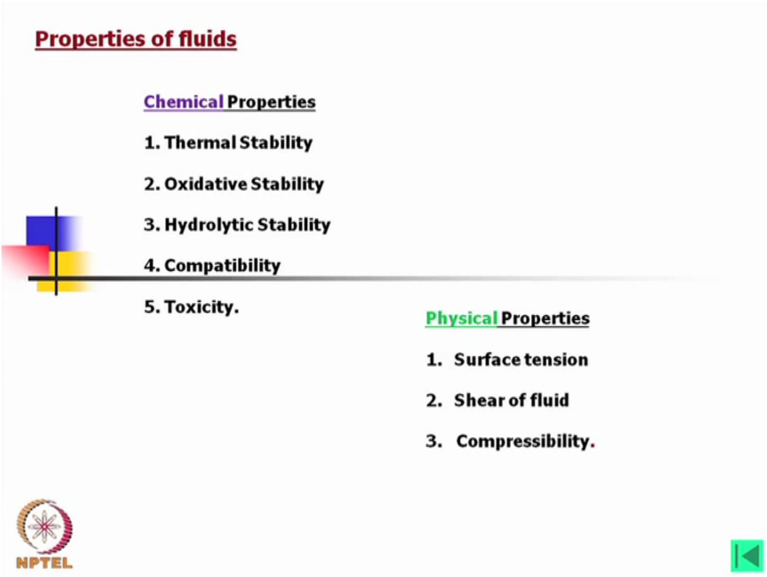

Now we are coming to the properties of fluids. Here, I would like to mention, it is mostly liquid unless otherwise mentioned. Now what are the chemical properties we need to have? Number one is the thermal stability. What does it mean that with the increase in temperature, there should not have should not change the composition of the fluid that means what the chemical properties we have that should not change. Then oxidative stability, the oxidization of fluid is a problem. So we have to look into that. Third hydrolytic stability that is from the that from fluidity point of view we need stability in this regarding.

Fourth is compatibility, it should be compatibility means in this case, it should be compatible with the components. What we are using in the system not only we are using pump, we are using different components. So we have to look into that it should be suitable for all such components as well as perhaps, we can consider that if there is a slight variation from the actual requirement actual composition of the oil still we should get the performance. Now fifth point is toxicity, which I have already discussed.

Then physical properties, one is the surface tension. This is very important in case of the fluids we are using for fluid power. Then shear of fluids that is also important in that case it should be adhere to the components otherwise there will be problem of lubrications and obviously compressibility. If there is change in compressibility during the performance, the performance of system will change.

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Property improving additives

	Property	Chemical used
1.	Antioxidants	Complex Phenols and amines, organic Phosphorous and Sulphur Compounds.
2.	Corrosion inhibitors	Organo-metallic compounds, naphthene esters.
3.	Rust inhibitors	Amines, amides, soaps, phosphoric esters, organic acids and esters.
4.	Anti foams	Silicones, Calcium Soaps, Sodium alkyl, Sulphates
5.	Lubrication improvers	Organo-Phosphorous, Chlorine and Sulphur Compounds, Lead Soaps
6.	Pour Point depressants	Polyalkylnaphthalenes, Polyalkyl, Phenol, Esters, Polymethacrylates.
7.	Viscosity index improves	Polyisobutylene, Polyacrylates.

Now I have already mentioned that properties of fluids can be improved by additives. We cannot take just the mineral oil for the application is in fluid power, particularly looking into there all the properties I have discussed along with that alive. First property antioxidant for that complex phenols and amines, organic phosphorus and sulpher compounds are used. Corrosion inhibitors for that organic metallic compounds, naphthene esters are used. Rust inhibitors, amines, amides, soaps, phosphoric esters, organic acids and esters. Here I would like to mention, if you ask me what are really these chemical compounds or chemicals are I would say that I do not know, but if you name this, it you can procure from the market. Of course, this is not a job of fluid power engineer to mix these compounds with oil rather these are who are manufacturing, this fluid power oil. They take care of this.

Now the antifoam, silicons, calcium soaps, sodium alkyl, then sulphate. Now foam what it is you will find that when any water or water any liquid that is being discharged from a pump like machines, you will find that where when it is putting into the say bucket or anywhere you will find that foam will be there. Now as such that foam may not be that harmful, but with that foam the air bubbles goes inside the oil and that creates a problem. So it is better there should not have much foam. This can be controlled from the outside also using say baffle and separator inside the tank, but these chemical compounds will help in better way.

Now lubricant improvers, organo-phosphurus, chlorine and sulpher compounds, lead soaps. Pour point depressants, I will discuss what is pour point in the next slides. Polyalkylnaphthalenes very difficult to pronounce, but this is the compound that is used poly alkyl phenol, esters, polymethacrylates. Last property, which is very important viscosity.

Viscosity index improver. What is viscosity index that also we are coming into the next slides, but for that we use polyisobutylene, polyacrylates. Now here I would like to mention, perhaps it is not required that you have to remember the name of all such chemical compounds. This is only for an idea what are the properties we need and how it can be improved?

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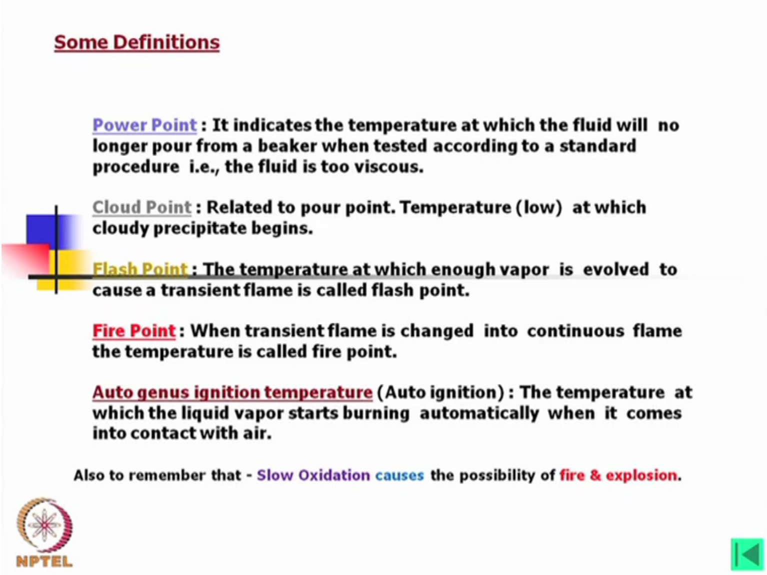

Now along with that we must know some definitions and terminology. Sorry, there is a mistake in this spelling, this is not power point it is pour point. Pour it will be pour point. It indicates the temperature at which the fluid will no longer pour from a beaker when tested according to a standard procedure. This means that the fluid is too viscous. The this you can conduct a very simple experiment, particularly at low temperature if you try to pour well from the beaker to another pot or another beaker, you will find that oil is coming very slowly, it is behaving like that it is very thick and at some temperature at low temperature, it will not at all pour into the next one. So that is called pour point pour.

Next cloud point, related to pour point. Temperature low at which cloudy precipitate begins. This means this is this must be above pour point. Oil is being transfer from one beaker to other, but you will find there are some precipitation like cloud that is called cloud point. Basically this will be a temperature pour point, cloud point these are the temperature. Now flash point, the temperature at which enough vapor is evolved to cause a transient flame is called flash point. What is transient flame you will find at a temperature suppose if you heat a oil then you find at certain temperature the flash of fire is coming on the oil, but again it is coming and going that is called the flash point.

Now next to that if you put more heat on that we will reach fire point. When transient flame is changed into continuous flame the temperature is called fire point. Now there is one important factor is that at the fire point you will find that oil is a flame is on the oil surface top surface, but still the whole fire is not caught on the oil and that point is called auto genus ignition temperature? The temperature at which the liquid vapors starts burning automatically when it is come into contact with air, okay. Possibly, it will be like that after the fire points still there this vapor will come. Now this vapor when this vapor is coming into the contact of the air automatic it will get fire.

Now this may happen where the temperatures are very high. So one is that we have to cool the oil what we are using as well as we have to look into that. It should not reach into auto ignition point. Now here I would like to mention that usually the mineral based oil temperature may be upto 75 degree for safe operation. Normally in our country the ambient temperature in summer may be 45 to 50 degree centigrade inside the say inside the factory, it might be for 50 degree centigrade very hot summer. Now at that point oil temperature may go as I as 75 degree centigrade to 80 degree centigrade, which is very closed to the flash point and in winter you may find that oil temperature may be as I as 65 degree centigrade whereas, pour ambient temperature is may be within 20-25 degree centigrade. So we have to maintain this temperature for the safety of the machines as well as for the performance, because if the temperature changes along with that viscosity will also change, where you will need very accurate control that will affect the operation.

Now also to remember that slow oxidation causes the possibility of fire and explosion that we have to keep in mind. So while we are selecting a oil and for the environment where we are using the machines we have to consider all such things. In fact if you look into the catalog (())(22:01) for a while there it is mentioned with different graphs with informations. So you can select a proper oil looking into that. However, if you become an application engineer you will find, normally those who are manufacturing the fluid power components, they also provide the suggestion what type of oil can be used for what type of operations.

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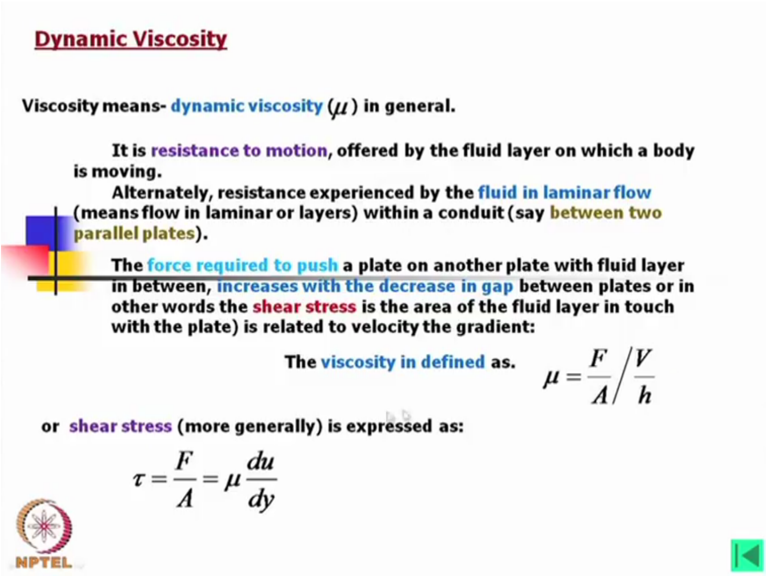

Now we will come to an very important property, which is called dynamic viscosity. Now viscosity means when we mention that viscosity of the oil, we normally mention the dynamic viscosity. It is denoted by Mu in general. It is resistance to motion offered by the fluid layer on which a body is moving. Alternately, resistance experienced by the fluid in laminar flow means flow in laminar or layers within a conduit, say between 2 parallel plates even if, if it is moving inside a circular conduit say pipes, it may be flexible hose may be solid pipe like a steel pipe. There will be the role of viscosity particularly at the contract and also among the layers of the oil.

The force required to push a plate on another plate with fluid layer in between increases with the decrease in gap between plates or in other words this shear stress is the area of the fluid layer in touch with the plate any related to viscosity the gradient. Now this viscosity is defined as Mu is equal to F by A divided by V by h where, F is the force, A is the area over the area, V is a velocity and h is the gap or shear stress more generally is expressed as tau is equal to F by A equal to Mu into du by dy. Here, I would like to mention that what type of force is there that we have applied a force and the layers between the plates or even inside the conduit. They are shearing from each other, either from the metal surface or within the fluid layers. So we have to consider the total area which is under shear. So F by A that will be the shear stress and V by h directly gives you the velocity gradient, later when we will analyze this flow you will know more about this. How the V by h can be expressed du by dy.

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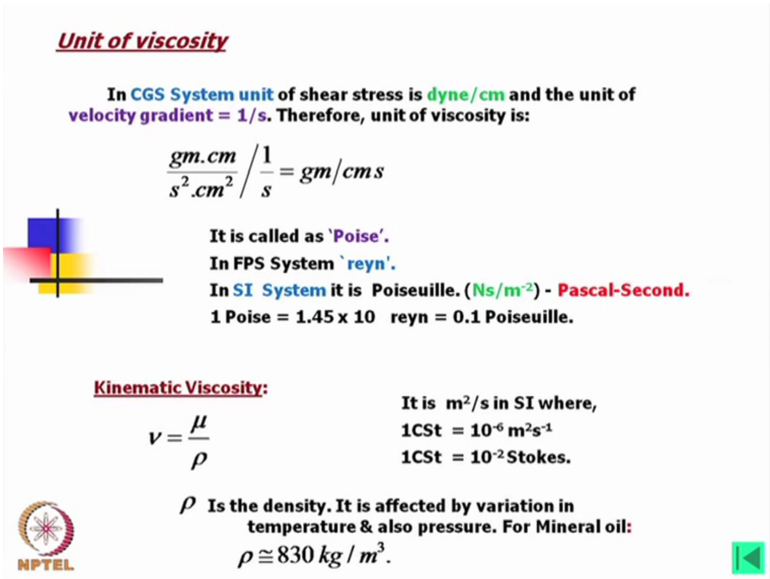

Now what is the unit of viscosity? In CGS system, unit of shear stress is dyne per centimeter and the unit of velocity gradient is one by second time one by time. Therefore, unit of viscosity of is gram centimeter per second square per centimeter square divided by one by S that time. Ultimately, it becomes grams per centimeter second. It is called as poise, more usually we use the term centipoise, you can understand meter centimeter. Similarly, poise centipoise. In FPS system, it is reyn. In SI systems which is normally used nowadays. It is poiseuille and it is newton second per meter square or simply Pascal-second newton per meter square second Pascal-second.

Now the relation is that one poise is equal to 1.45 into 10 reyn and is equal to 0.1 poiseuille. Now kinematic viscosity although viscosity means we normally mention dynamic viscosity and many or almost all calculation you will find that viscosity is being used not the kinematic viscosity. However, the kinematic viscosity is nothing but the dynamic viscosity divided by the density. Here, rho is the density, Mu is the dynamic viscosity. Now one important aspect is that with the change in temperature, there will be change in viscosity, but density may not change very much. So definitely this kinematic viscosity will change with the temperature.

Now it is meter square per second in SI units and one centistoke is equal to 10 to the power minus 6 meter square by or per second and one centistoke is equal to 10 to the power minus 2 stokes. Now the rho is the density, it is affected by variation in temperature and also pressure for mineral oil Rho can be taken approximately is equal to 830 kg per meter cube. It normally varies from 830 to 850 kg per meter cube.

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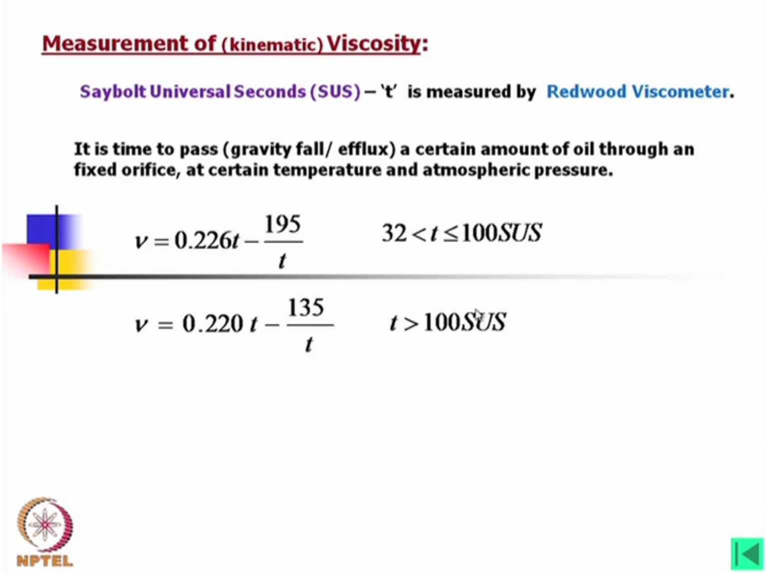

Measurement of kinematic viscosity. Saybolt universal second is a time is measured by redwood viscosity. What it is? A certain amount of oil is taken and we can say, it is time to pass or that is usually gravity fall or efflux a certain amount of oil through an fixed orifice, at certain temperature and atmospheric pressure. The time which is counted that is called saybolt universal seconds. There are other instruments than the redwood viscometer, which are also used. Anyway, it has been found that below 32 seconds that means where the oil is taking time 32 seconds less than 32 seconds, then the results are erratic (())(31:21) and this is an empirical relations which we can use where t is greater than 32 but less than 100 SUS, t is the time and if it is more than 100 then we should use this formula. It will directly give you the kinematic theory kinematic viscosity of the oil.

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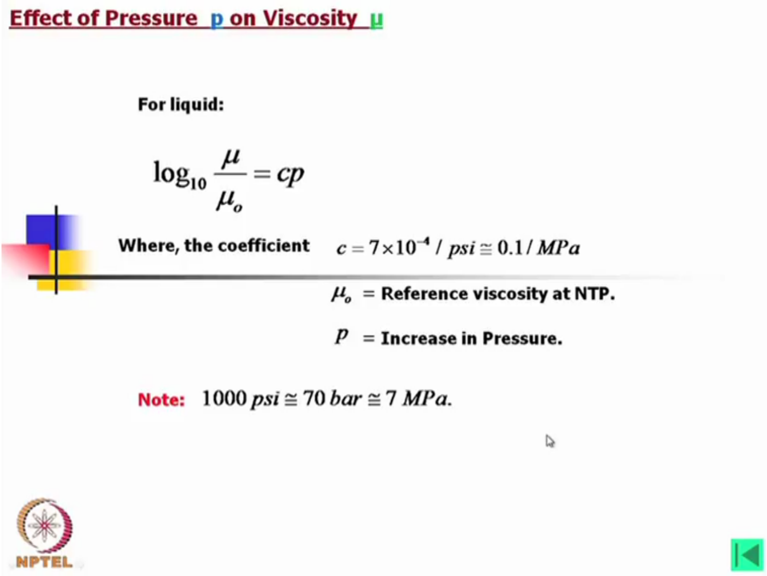

Now if the pressure P on viscosity Mu that is on the dynamic viscosity. This relation is given by log to the base 10 Mu by Mu0 is equal to CP, where the coefficient C is equal to 7 into 10 to te power minus 4 per psi which is almost equal to 0.1 per mega Pascal. Now here Mu0 is the reference viscosity at normal temperature and pressure. Now P is increase in pressure and one tips I would like to give you that in many cases you will find the pressure is exploit (()) (32:55) inward or psi. if we would like to convert into mega Pascal's or Pascal's then we should remember these relations and for a fluid power engineer, it is very important to remember this that 1000 psi is almost equal to 70 bar is equal to 7 mega Pascal or 7 into 10 to the power 6 Pascal's.

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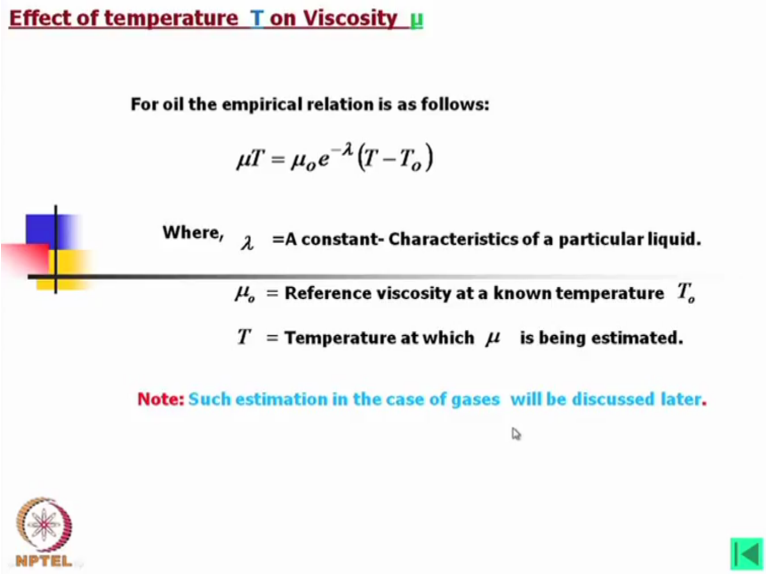

Now effect of temperature T on viscosity Mu. For oil the empirical relation is as follows. MuT is equal to Mu0 e to the power minus lambda into T minus T0, where lambda a constant characteristics of particular liquid, Mu0 is equal to reference viscosity at a known temperature T0, T is the temperature at which Mu is being estimated. Note such estimation in case of gases will be discussed later. Why I have mentioned this one, because many people confuses they think that this also can be used for the gases, it is not there we have to use a different formula.

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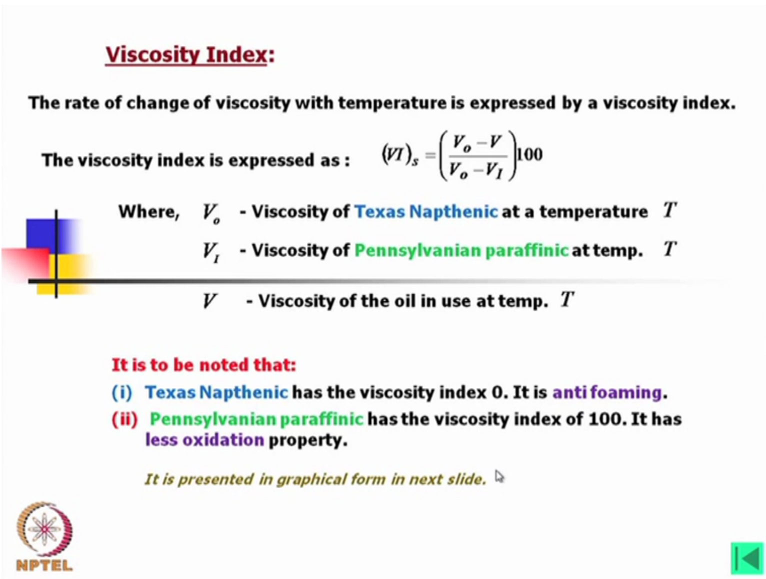

Now one important factor is the viscosity index. What it is? The rate of change of viscosity with temperature is expressed by viscosity index. It is expressed as the VIs subscript s is the viscosity index is equal to V0 minus V divided by V0 minus VI into 100 and V0 is equal to viscosity of Texas naphthenic at a temperature T. Now we would like to find out the viscosity of a oil use at temperature oil in use at temperature T and what we are doing we are comparing with two reference fluids, one is that Texas naphthenic and another is Pennsylvanian paraffinic for which the viscosity is indicated by Vi.

Now what are these two? These are you know the place Texas and you know the place Pennsylvania, there it is the product or mined from they that places and it was found they have some differences with respect to the change in viscosity with temperature. So these two particular well was kept as a reference and then how it is done. It is to be noted that Texas Naphthenic has the viscosity index 0. It is antifoaming very good antifoaming property whereas; Pennsylvania paraffinic has the viscosity index of 100. It has less oxidation property whereas, not the antifoaming. Now it is presented in graphical form in the next slide.

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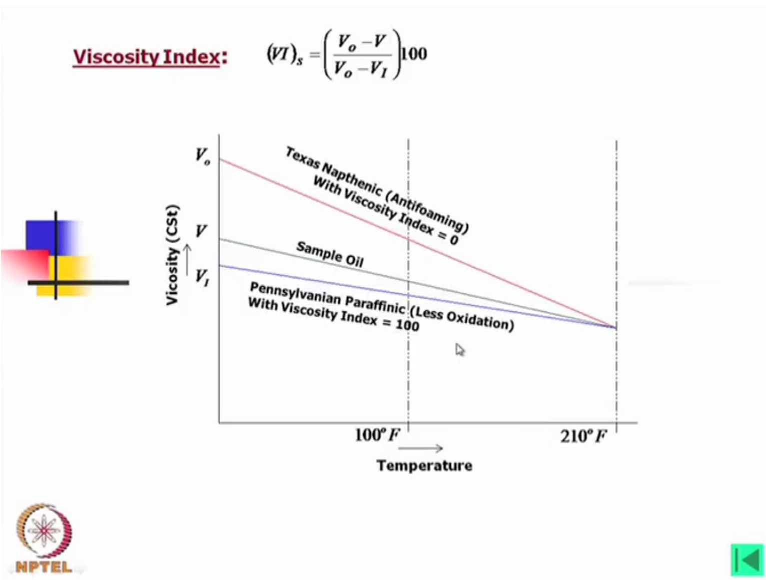

Now look at this graph. Here is the temperature and we have say we have drawn a line at 100 degree Fahrenheit and then 210 degree fahrenheit. What does it mean? After 210 degree fahrenheit all such oils will have almost the same viscosity, but with the lower in temperature what we find that say this viscosity we are presenting in centistoke and the red line is for the Texas Naphthenic for which viscosity index is 0 and Pennsylvania paraffinic oil is having the viscosity index 100 and sample oil will be somewhere here. So knowing these viscosity index we can easily calculate what will be the viscosity at different temperature and definitely if you look into that if we wish if we need the thermal stability should be more, it should be close to the Pennsylvania paraffinic, but again this will not have the good antifoaming property.

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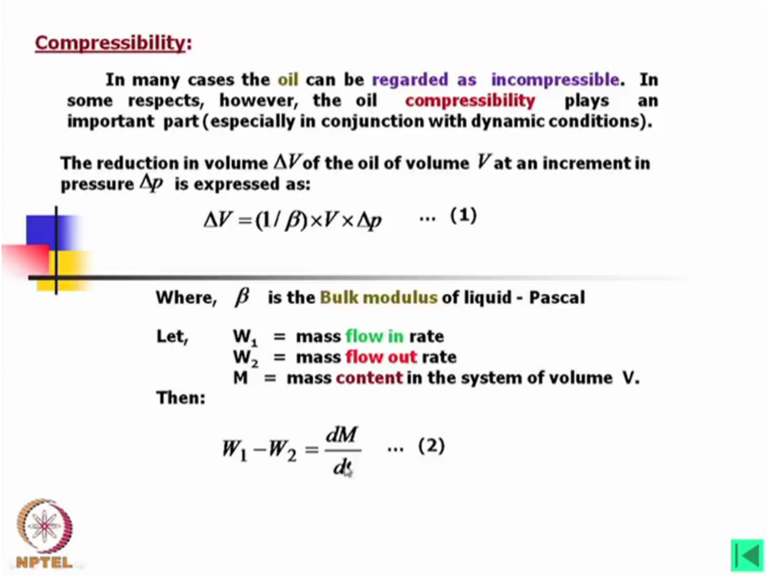

Now another important factor we should consider, which is called compressibility. In many cases, the oil can be regarded as incompressible for mathematical treatment of a systems of the fluid power systems with hydraulics. In many cases, it is considered the comparably incompressible fluid and we develop the model in that way. However, where we need to calculate the system performance, particularly let us consider the vibration or the system dynamics at transient. There we need to consider the compressibility also. In many cases, this compressibility is used as a (())(39:47) to parameter.

In some respects, however, the oil compressibility plays an important part especially in conjunction with dynamic conditions. So each I have described now. The reduction in volume delV of the oil of a volume V at an increment in pressure del p is expressed as, delV is equal to 1 by beta into v into del p, where beta is the bulk modulus of liquid. Its unit is Pascal. Now let W1 is mass flow in rate. Now we should consider control volume. In that control volume, let us consider W1 mass flow in rate and W2 is the mass flow out rate. Now this is normally for an incident, because if we considering the long run and definitely it cannot conserve the flow inside. M is equal to mass content in the system of volume V then W1 minus W2 is equal to dM by dt. This is you can easily understand.

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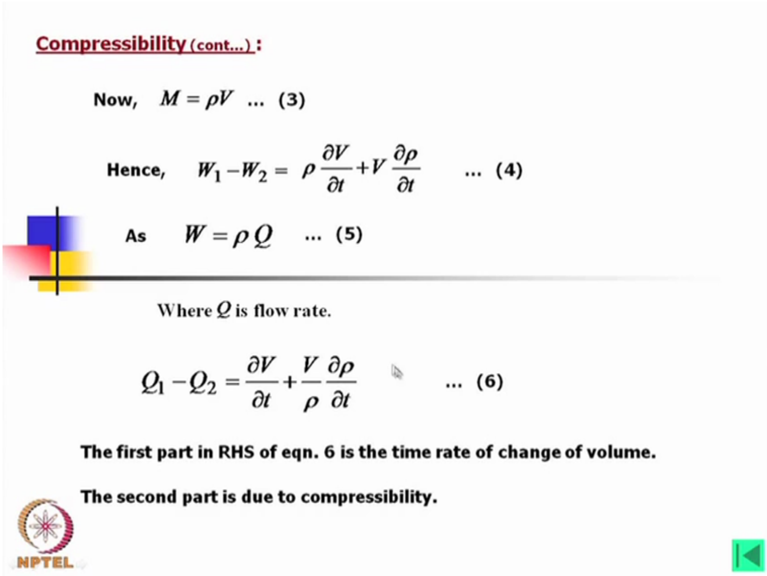

Now what is if we will is to know the compressibility then what we do? We now express the mass into the density into the volume. Then W1 minus W2 is equal to Rho dV by dt plus V dRho by dt, because we have to go for the partial differentiation, because of the reasons that with time both may change due to change in temperature and other. So we have to consider we have to write the equation in this form. Now again W is equal to the density into flow rate Q where, Q is the flow rate. Then we can express Q1 minus Q2 is equal to dV by dt plus V by Rho dRho by dt. The first part in right hand of equation 6 is the time rate of change of volume. Normally we will write Q1 minus Q2 is equal to dV by dt, but there is another term which is here. This second part is due to the compressibility. If we consider the fluid is 100 percent incompressible then this part will be zero.

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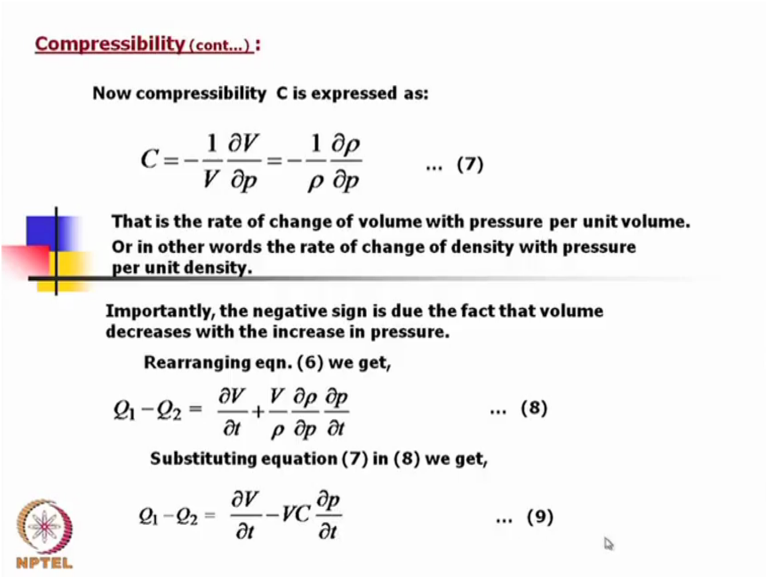

Now compressibility C is expressed as, C is equal to minus 1 by V dv by dp is equal to 1 by Rho dRho by dp. This can be related, because this volume V is directly proportional to the density. That is the rate of change of volume with pressure per unit volume or in other words, the rate of change of density with pressure per unit density. Importantly, the negative sign is due to the fact that volume decreases with the increase in pressure. Rearranging equation 6 we get Q1 minus Q2 is equal to dV by dt plus V by Rho dRho by dp into dp by dt. Now substitute the equation 7 in 8 we get, Q1 minus Q2 is equal to delV by dt minus V into C del p by del t.

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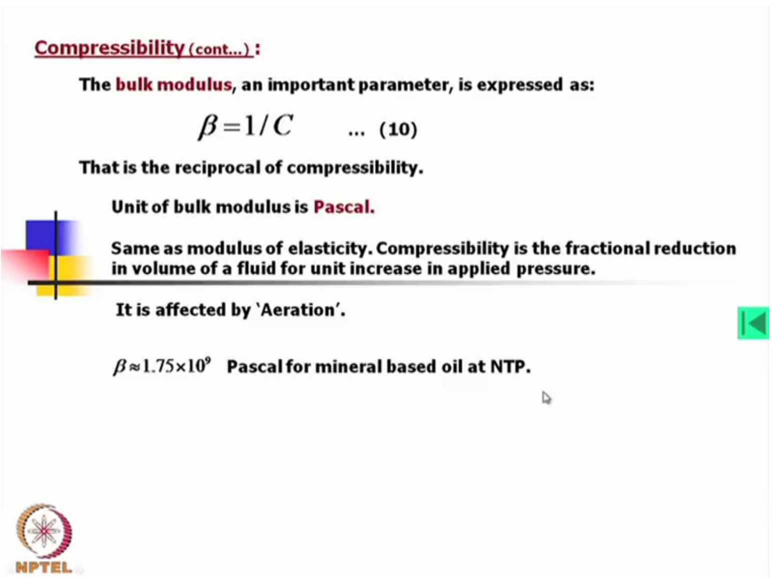

Then the bulk modulus an important parameter which I have mentioned is expressed as the beta is equal to 1 by C. This is reciprocal of compressibility. Unit of bulk modulus is Pascal already I have discussed, same as modulus of elasticity compressibility is the fractional reduction in volume of a fluid for unit increase in applied pressure. Now this bulk modulus is affected by aeration. What it is? Now before going into that I would like to mention for your reference beta that is the bulk modulus can be taken as 1.75 into the 10 to the power 9 Pascal's for mineral based oil at NTP in normal cases. However, it might be slightly higher also in some cases.

Now this can be calculated or usually you will find that this is provided by the manufacturers of oil. So if you need to carry out some calculation where the bulk modulus is involved, you have to either follow that reference or you have to make a experiment to find out these value.

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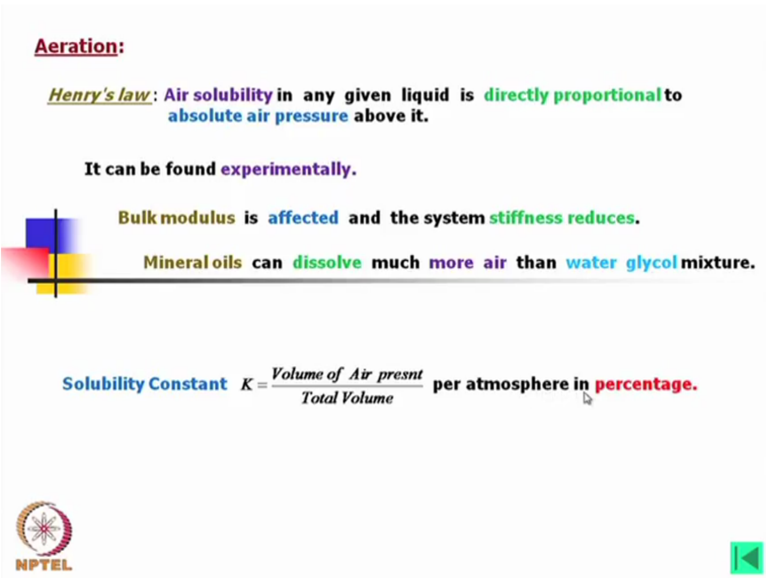

Now aeration it is actually air solubility in the liquid. There is a henrys law and according to that air solubility in any given liquid is directly proportional to absolute air pressure above it. Just try to visualize air solubility in any given liquid is directly proportional to absolute air pressure above it that means if you trap the oil in a vessel and pressurized it, the solubility will decrease, but for a particular oil when it is exposed to the atmospheric pressure, it is having own aeration inside it. That can be controlled by additives, but cannot be perhaps fully eliminated.

Now it can be found by experiments. Bulk modulus is affected and the systems stiffness reduces with the aeration. Mineral oils can dissolve much more air than water glycol mixture.

This means that oil mineral oil will have more dissolved air inside. Now solubility is constant K is given by volume of air present divided by the total volume per atmosphere in percentage.

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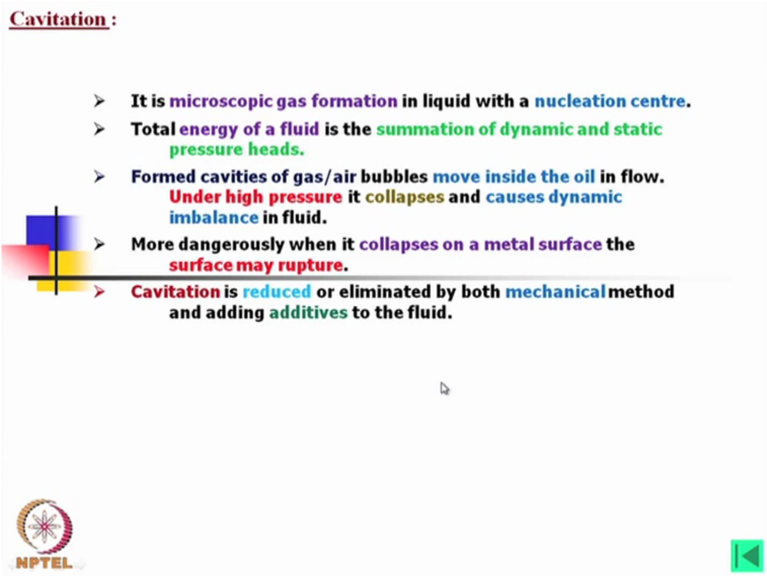

Now another associated properties of fluid or the phenomena is cavitation. It is **it is** very harmful for fluid drive. It is microscopic gas formation in liquid with a nucleation centre. What happens as I have told we cannot avoid the air inside the oil? Now under pressure that air particles, they form a bubble and the total energy of fluid is the summation of dynamic and static pressure heads, okay. Then they formed cavities of gas by air bubbles or air bubbles move inside the oil in flow under high pressure, it collapses and it causes dynamic imbalance in fluid, 2 things will happen, one is the dynamic imbalance in fluid. What it is that immediately there will be some change is the fluid property when that bubble collapsed inside the oil, say for example, we are using a servo mechanism for controlling some motion or position.

Now while it is doing that job if this happens that will affect the performance. However, how the control can be made such that even in such dynamics can be taken care of, but always we have to reduce the bubbles as much as possible and we have to reduce this such cavitations. Now more dangerously when it collapses on a metal surface, the surface may rupture. In case of say for example gear, you know the scuffing the gear surface will rupture due to this local stresses. Here also if the bubbles collapses inside the fluid, there will be dynamic imbalance, but if it collapses oil in a in between the layer between the oil and the surface, it may rupture the surface. Cavitation is reduced or eliminated by both mechanical method and adding additives to the fluid. Mechanical methods means that we can say for example we can use the baffles and other things. Also we can design the machine component in such a way, it will have less effect due to the collapse of the bubbles.

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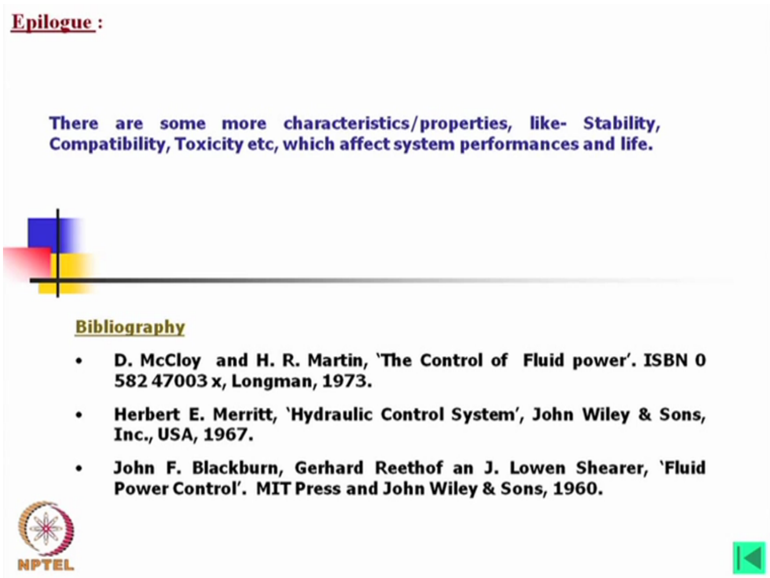

Now in Epilogue, I would like to say, there are some more characteristics properties like stability which I have not discussed, compatibility we have not discuss separately, toxicity etcetera, which affect system performance and life and while you were calculating or picking some calculation for the dynamic analysis or any analysis, sometimes we need to consider all such thing. However, for details you can follow these 3 books. For the properties I would like to mention this first book and the last one, D. McCloy and the Blackburn and Reethof. However, in the Merritt books also there is some properties, but this is more useful for carrying out the calculation for valves and any systems and thank you for listening.