Fluid Flow Operations
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Module – 05
Flow of Viscous Fluid - Part 5
Lecture – 14
Theory of Lubrication

Welcome to Fluid Flow Operations. Today we will discuss about the flow of viscous fluid under which the sections Theory of Lubrication.

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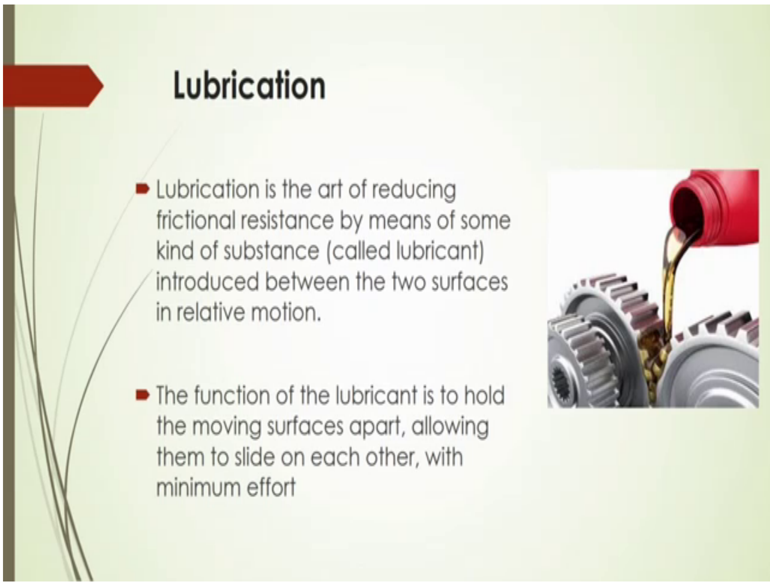

And in this case in the previous lectures, we have discussed about the viscosity effect and the flow of the fluid that is viscous fluid through the pipe, if and some other concedes at laminar turbulent flow and also the boundary layer theory for which how viscosity of the fluid will be affecting on the flow of fluid.

In this lecture, we will discuss about the a viscous fluid which will be applied for a particular cases where the frictional resistance can be reduced by that fluid. So, in this case 1 important term it is called the lubrication, that this is the art of the reduction of frictional resistance by means of some kind of substances which will be called as lubricant.

So, in this case this lubricant is generally introduced between the surfaces which are relatively in motion and in that case whenever surfaces are in motion, there will be some frictional resistance for which energy will be consumed and also the longevity of the equipment depends on that fictional phenomena. And what to reduce that frictional resistance, you have to use some suitable substances which have less viscosity and also reduce that viscosity reduce the friction of the surfaces which are in motion.

The function of the lubricant is to hold the moving surfaces effort, which will allow them to a slide on each other with the minimum effort. So, we have to learn about that lubrication and what will be the different theories of that lubrication, and how that that is the velocity distribution or pressure distribution of the phenomena when the lubricant will be used between 2 surfaces for reducing the friction.

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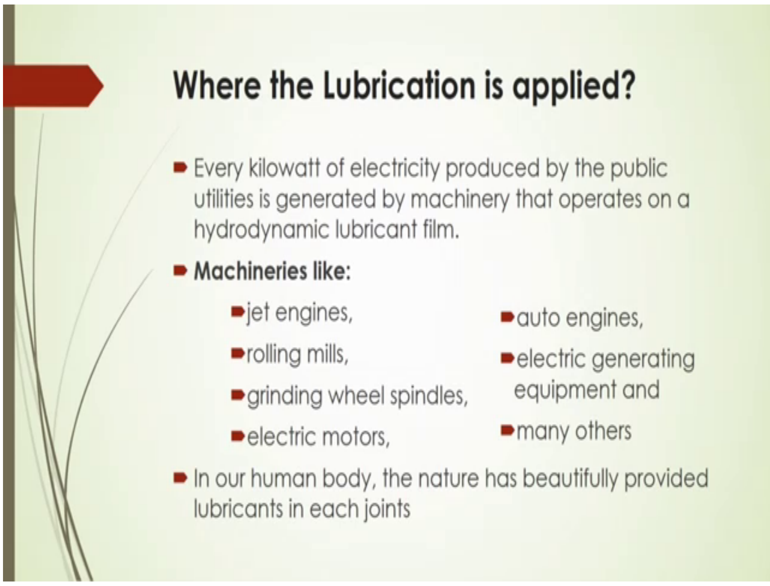

So, before going to that we have to know where actually this lubrication of phenomena is applied. In that case you will see that every kilowatt of electricity that is being produced by the public utilities is generated by machinery that appears on a machine parts and which will be operating on a hydrodynamic lubrication film.

So, we have to know that whether we can actually utilize this lubrication theory to reduce the consumption of energy by reducing the frictional resistance or not. Now the missionaries where this lubricants are bring used like here some examples are given like jet engines there this lubricants are used, rolling mills even grinding wheel, spindles, electric motors, auto engines, electric generating equipment and many of others. You know that where actually that how we can say that really the lubrication is required or not.

You see that in our body the nature has beautifully provided the lubricants in its joint, by which we can move or we can move our boom body parts in different angle. So, there you will see the in the joints, some fluids are used naturally that is called lubricants. So, we can defined this lubricants in the this way that any soften material that prevents the 2 surfaces in relative motion from coming into contact may be called as lubricant in that case. Even if it does not reduce the friction, then also you can call it lubricant.

Main purpose of the lubricant is to reduce the friction. So, the lubricant serves both to separate the raving surfaces and to remove heat.

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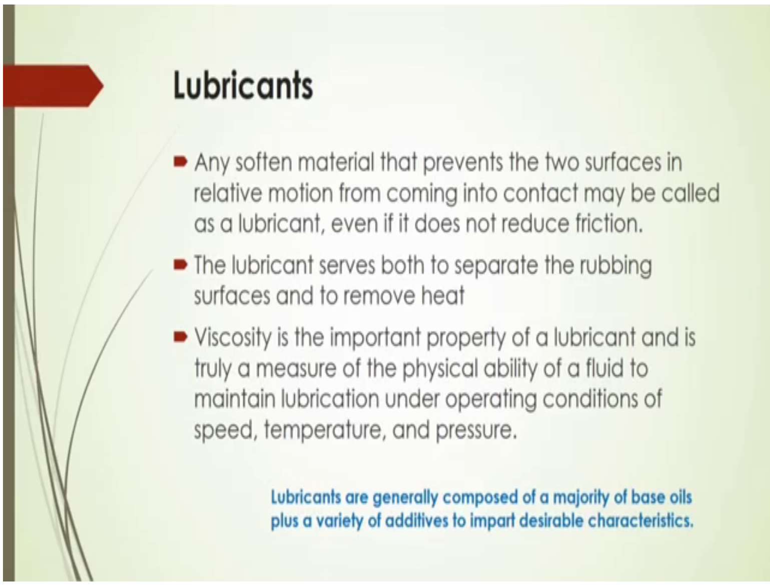

And in this case the properties of that lubricant is important, now viscosity is the important property of that lubricant and is truly a measure of the physical ability of a fluid to maintain lubrication under operating conditions of like a speed, temperature and pressure.

So, the lubricant will have some physical properties in that case viscosity is 1 of the important property; and it may composed of several components. So, we can say that lubricants are generally composed of a majority of base oils, plus a variety of additives to impart desirable characteristics there.

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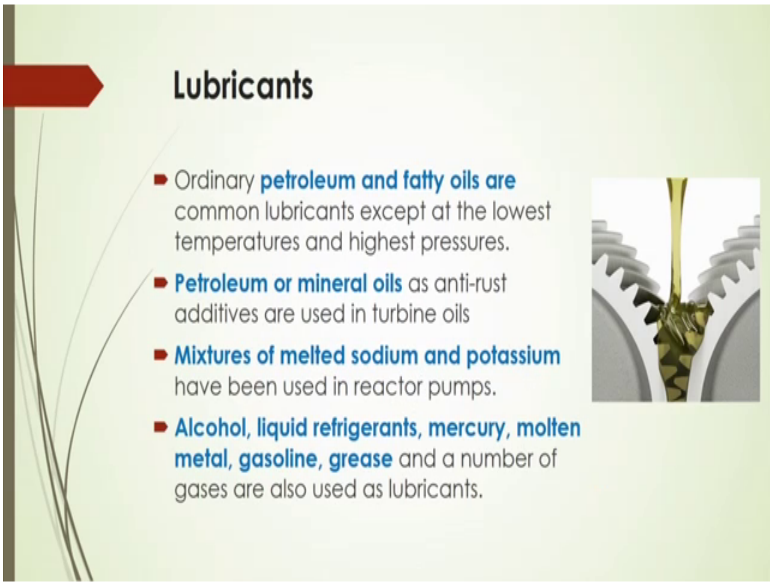

And generally a petroleum and fatty oils are referred as a common lubricants except at the lowest temperatures and highest temperatures.

Now, petroleum or mineral oils sometimes is being used as anti rust additives, that is used in the turbine oils. Also some mixtures of melted sodium and potassium have also been used in reactive pumps as a friction reducing agent. Alcohol, liquid refrigerants, mercury, molten metal, gasoline, grease and a number of other gases also used as lubricants here. So, there are several types of lubricants. So, these are common type of lubricants which are being used in this case.

So, petroleum, fatty oils, mineral oils, mixture of melted sodium and potassium, alcohol different types of alcohols are there, liquid refrigerants, mercury, molten metal, gasoline, grease all those different types of lubricants are being used you see the picture here. So, where this lubricants are being used to just reduce the friction as well as to increase the mobility of the wheel or shaft there

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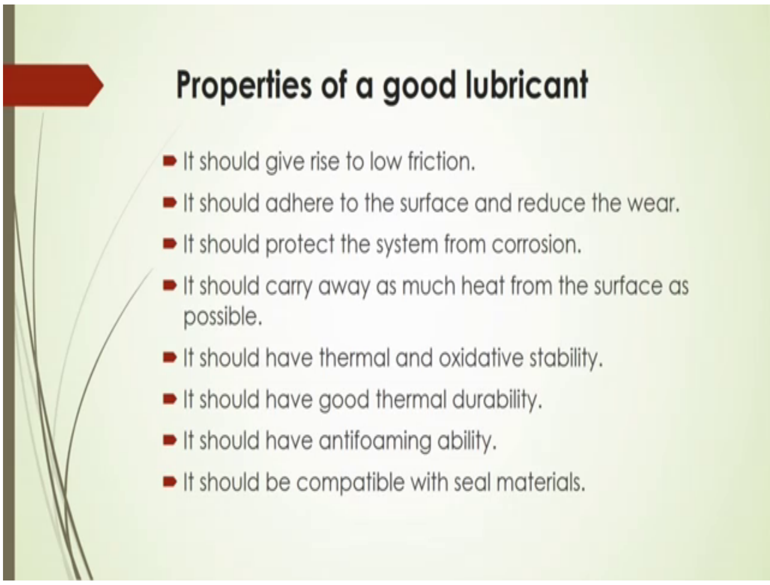

If I say, what will be the properties of a good lubricant? The good lubricant should have such property that it will give rise to a low friction, and it should adhere to the surface and reduce the wear. Also it should protect the system from corrosion; it should carry away as much heat from the surface as possible there.

And the lubricant should be thermally and ox datively stable so, that if there is increase in temperature, then there will be no actually thermal degradation of that fluid or lubricant. And also it should not be reactive at that high temperature with the atmospheric oxygen. So, it should be stable that should be non reactive with the atmospheric air, and also it should have good thermal durability of course, it should long last if you increase the temperature there.

So, thermally durable should be of more important characteristics of the good lubricant. It should have antifoaming ability also. If lubricant will produce home the surfactant types like if any surfactant like if you just mixing water, you will see there will be formation of home. So, lubricant should not produce any home there. So, it should be acting as an antifoam, it should have antifoam characteristics; that means, the good lubricant will not produce any home. Also it should be compatible with ceil materials, what are the materials are being used for ceiling purpose. So, that should be compatible with this good lubricant or good lubricant should be compatible with the sell materials.

So, in this case you have to select the good lubricant based on this characteristics. So, it should rise the low friction, it should adhere to the surface and reduce the wear, it should protect the system from corrosion, it should carry away as mass as heat from the surface as possible, it should have thermal and oxidative stability, it should have good thermal durability, it should have antifoaming ability, it should be compatible with the seal materials.

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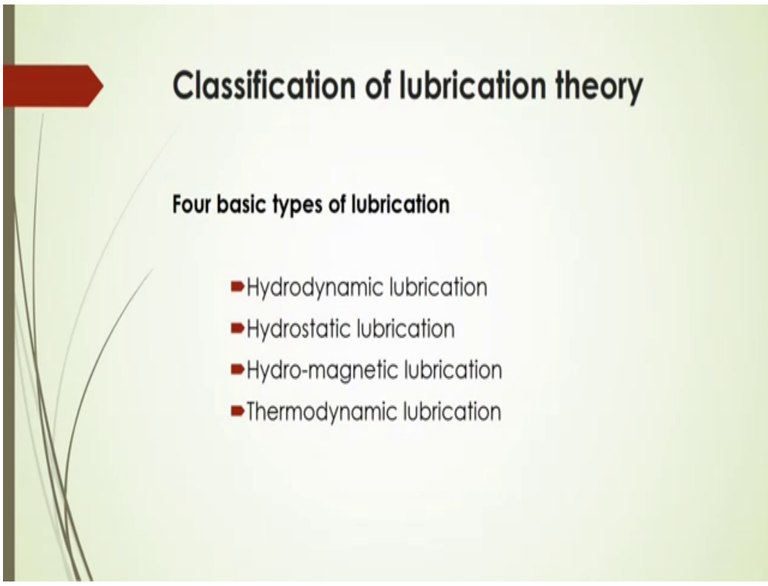

Now, if we talk about the lubrication, there will be a certain principal or theory of that lubrication. We can classify that lubrication theory based on these four basic characteristics 1 is hydrodynamic lubrication another is hydrostatic lubrication and then hydro magnetic lubrication, last 1 is thermodynamic lubrication.

So, based on these four basic types the lubrication theory depends or principles depends.

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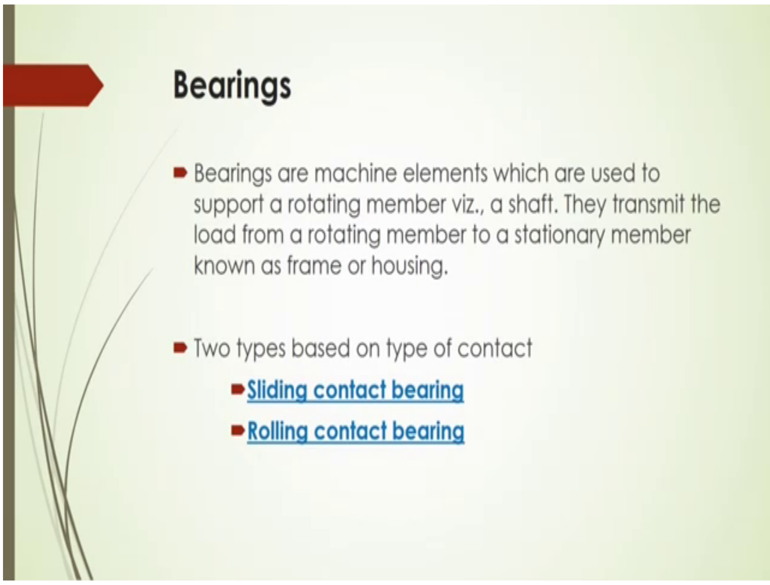

Now, before going to that discussion of this lubrication theory, you have to know something about the bearings where these lubricants are being used and also the principle of the lubrication will be applied. Now what is that bearings? The bearings are machine elements which are used to support a rotating member like a shaft and these bearings transmit the load from a rotating member to a stationary member which will be known as frame or housing. Generally 2 types of this bearings are based on the type of contact are recommended, generally sliding contact bearing another 1 is rolling contact bearing.

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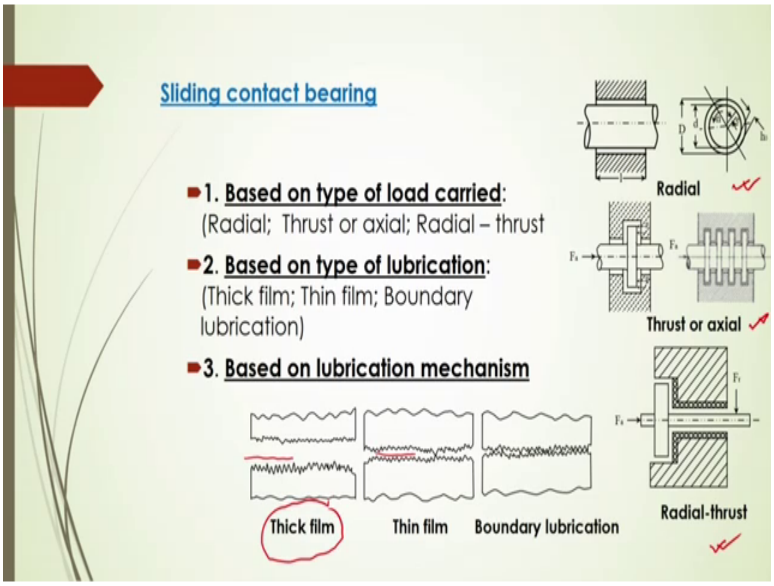

Now, sliding contact bearings see this figures are there different types of sliding contact bearings. The sliding contact bearings are classified into 3 categories 1 is based on type of load carried, based on type of lubrication and the based on lubrication mechanism. Based on type of load carried in that case generally radial, thrust or axial even radial or thrust this different characteristics or different categories of this sliding contact bearings are there. And based on the type of lubrication you can say whether it will be thick film or thin film or whether it should be boundary lubrication or not. So, this 3 categories of these bearings based on the type of lubrications are there; based on lubrication mechanisms also there.

So, based on type of load carried, based on type of lubrications here some pictures are shown there here in this case this thick film is based on the type of lubrication, here see thick film here thin film and their boundary lubrication. So, the lubricants will be used in between this surfaces may be the gap should be higher; that means, here film should be very thicker and this case the thin film here the gap should be as minimum as possible whereas, boundary lubrication which should be colliding of 2 surfaces in such a way that minimum gap should be there.

So, boundary thickness what will be the boundary thickness order, that will work based on that. And based on the load carried in this case radially and thrust or axial here these are radial load, these are thrust or axial load and these are radial thrust compound type of this bearing here

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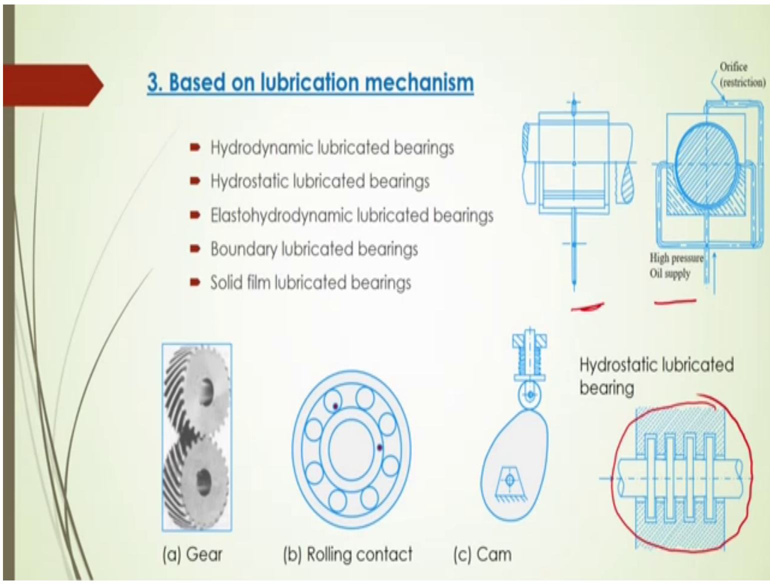

Based on lubrication mechanism, we can say that hydrodynamic lubricated bearings are there hydrostatic lubricated bearings, elastro hydrodynamic lubrication bearings are there, boundary lubricated bearings, solid film lubricated bearings. We will see here some bearings based on the lubrication mechanism here see this is the 1 kind of that is called hydrodynamic lubricated bearings, here high pressure while supply will be there in that case. So, there will be change of that is velocity gradient, within the gap of the film there or lubricant film is there.

So, based on which the that is bearings are being designed. And also you will see there will be a rolling contact here, some cam type and also here there is multi shaft we are multi bearing that is hydrostatic lubricated bearings are there, and some other different types of a lubrication mechanisms are there. So, by in this case we are not going to discuss all those parts here this is not the scope under this course. So, in mechanical devices design and also the properties of the materials based on which the topics could be related to this lubrication mechanism and also the bearing materials.

So, it will be more actually it is to be consulted with the other a text book based on this lubrication mechanism bearings.

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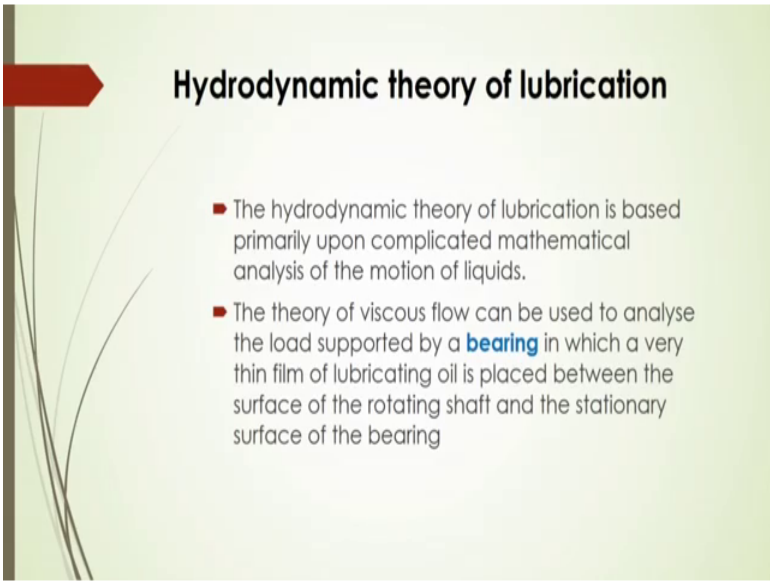

And in this case let us discuss about the hydrodynamic theory of lubrication, which will be more scope of this lecture. And in this case the hydrodynamic theory of lubrication is best primarily upon complicated mathematical analysis of the motion of liquids here. The theory of viscous flow that can be used to analyze the load that supported by a bearing in which a very thin film of lubricating oil and which will be placed between the surface of the rotating shaft and the stationary surface of the bearing.

So, we have to analyze some mathematical formula based on which we can see how this bearings are when it will be moving then how the that is velocity or pressure will be changing with respect to that is the shape of the material as well as the what is that load which will be applied on that bearings. So, we will discuss here.

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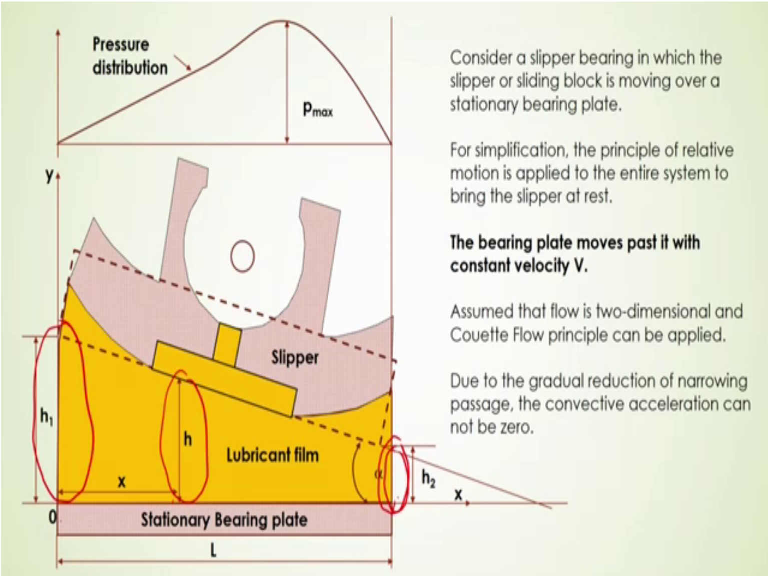

Now, let us considered a sleeper bearing as shown in the figure here in which, the sleeper or you can say sliding block here as shown in the figure; is moving over a stationary bearing plate. Now if we consider the principal of the relative motion, then based on this principle of relative motion the entire system to the system entire that is entire system to bring the sleeper at rest we will that use this principle of relative motion.

In this case the bearing plate let it moves past it with constant velocity V. And also you can assume that the flow is 2 dimensional and it will be the couette flow that we have discussed in earlier lecture, different types of couette flow, having go poisonous flow other different types of flow we have discussed. So, assume that flow is 2 dimensional and Couette flow principle will be applied here. Now due to the gradual reduction of narrowing passage you will see there will be a gradual reduction of narrowing passage in this case height is this, here height is here and here this is the height.

So, this is the cross section here in this case. So, we can say that the reduction of this what is that passage here. So, due to the gradual reduction here in this case of narrowing passage, the convective acceleration cannot be 0 there will be a some acceleration that is called convective acceleration that you have to consider for your analysis.

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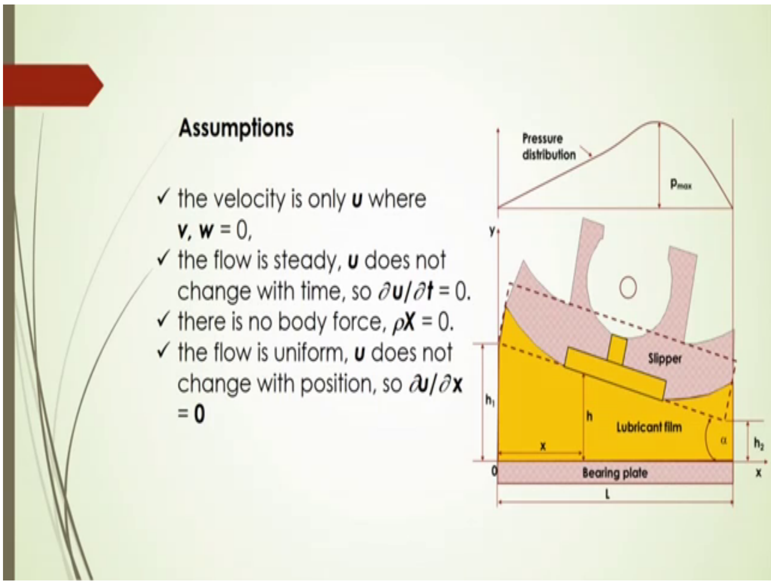

Now in this case we will apply the Navier stokes equation how the velocity profile or pressure will be changes based on Navier stokes equation we will apply here. Now in this case assumption is that we are considering the velocity is only u, where v and w that is in y and z direction the velocity will be 0. As an axial x axis in the x direction there will be a velocity u. The flow is a steady that u does not change with time. So, dou u dou t that will be equals to 0 and there is no body force acting on this. So, in that case the x direction the body force will be equals to 0, and the flow is uniform; that means, here u should not be changed to position. So, dou u dou x will be equals to 0.

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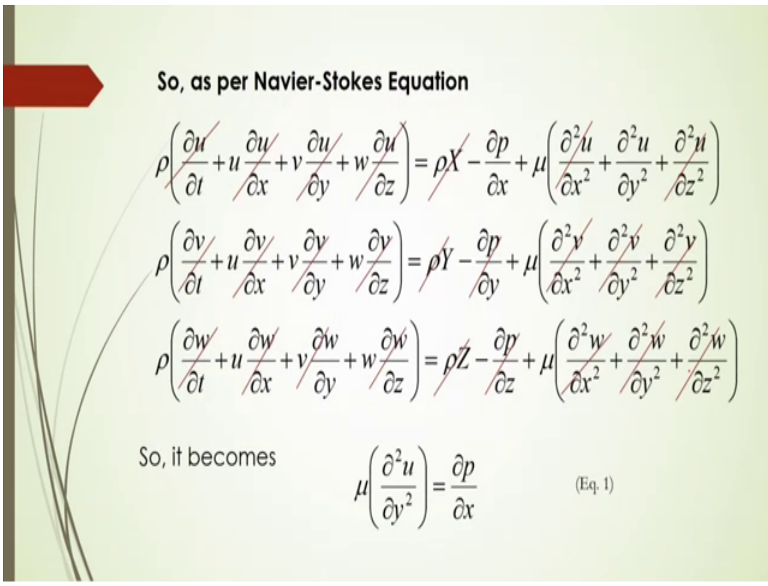

And as per these assumptions we can apply the Navier stokes equation and see this Navier stokes equations are here. Now in the x directions what will be that? The Navier stokes equation in this case at steady state condition this will be cancelled out. So, here have cancelled out the short terms as per assumptions. So, in this case only this terms will be there minus dou p dou x plus mu into dou 2 u dou y square that will be equals to 0. And in the y and z directions all other terms are neglected based on the assumptions

So, finally, the equation becomes like this here mu into dou 2 u dou y square that will be equals to dou p dou x. So, there will be viscose terms and the patient terms are there. So, these equations will give you the pressure distribution whenever some load will be applied on the bearings.

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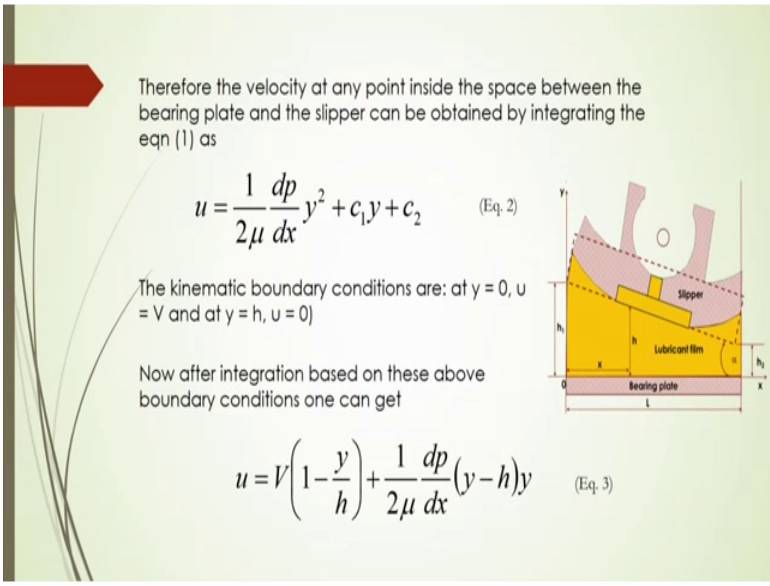

And in this case how the velocity at any point inside; the space between the bearing plate as shown in the figure and the sleeper can be obtained by integrating the equation number 1 here.

So, if we integrate this equation1 we can get this u will be equals to 1 by 2 mu d p by d x into y square plus c 1 into y plus c 2 here c 1 and c 2 are constants of integration. And d p by d x is the pressure change with respect to x and the kinetic boundary conditions if we apply on this equation number 2, as at y is equal to 0 u should be is equal to v ; that means, here bearing plate will be moving with velocity v at y is equal to 0. And at y is equal to h that y is equal to h we can say that u should be equals to 0 here ; that means, there will be no velocity change at this.

That is no sleep condition here now after integration based on these above boundary conditions we can get u will be equals to v into 1 minus y by h plus 1 by 2 mu into d p by d x into y minus h into y. So, this equation number 3 will give you the velocity distribution under the pressure gradient d p by d x at a certain distance y and x.

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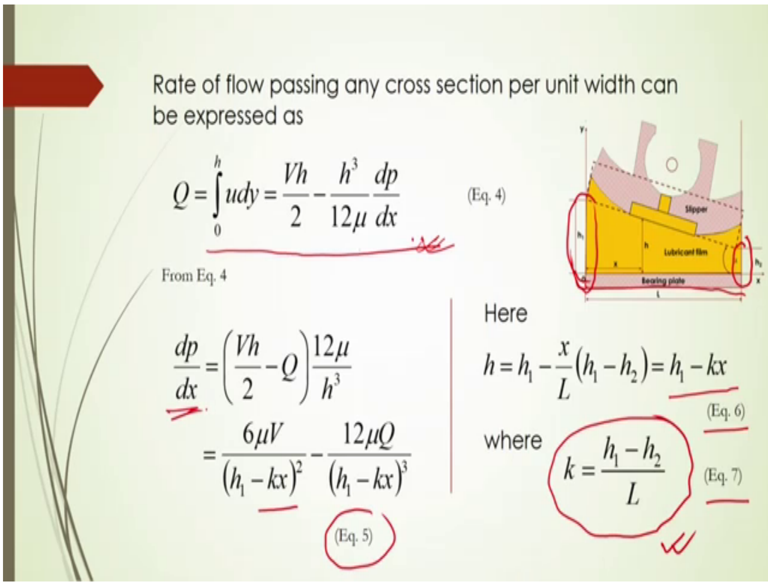

And now based on this velocity distribution, we can find out what should be the rate of flow that passes any cross section per unit width of the bearings, that can be expressed as Q will be equals to integration of u into d y that will be is equal to V a b into s by 2 minus h cube by 12 mu 2 d v by dx. So, after integration with this velocity given in equation 3 we can get this Q will be equals to this that is expressed in equation number 4.

Now from this equation number four we can simplify it as d p by d x will be equals to h by 2 minus q into 12 mu by s q. So, that will be equals to 6 mu v by s 1 minus k x whole square minus 12 mu Q by h 1 minus k x whole cube. Here k is defined as h 1 minus h 2 by L what is that h 1 minus h 2 it is given in the picture, this space is referred this height is referred as h 1 and this is as h 2. So, h 1 minus h 2 divided by total length of these bearing here, it will be represented as k. Now here h minus h 1 then will be equals to h 1 minus x by L from the geometry into s 1 minus h 2 that will be is equal h 1 minus k x.

So, from the geometry and by equation number 6 and 7, we can have this k value by known value of this h 1 and h 2 and after that if you substitute this k value here and also Q h 1 h 2 at a certain x we can have what should be the pressure there. Now this integration of this equation number 5 for this pressure gradient we can get this equation number 8.

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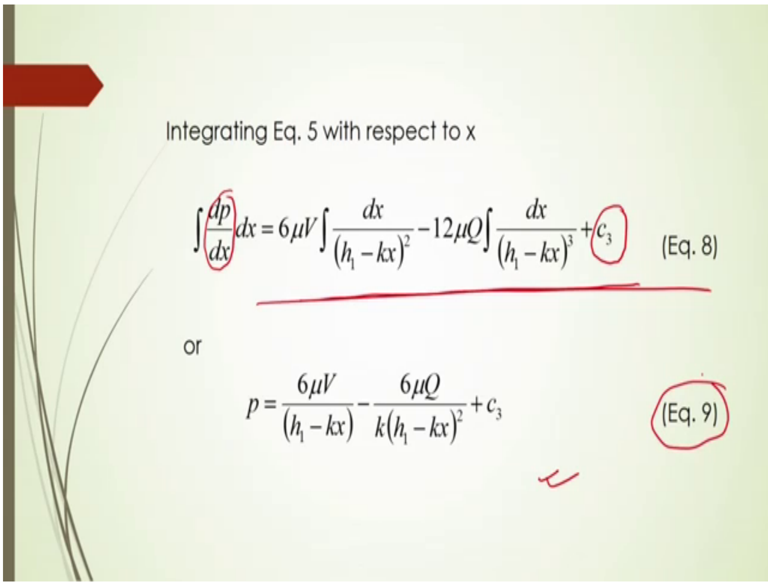

Simply integration of this equation 5 d p by d x into dx this will give you after substitution of d p by dx here and integrating we can get this one. So, in this case another constants will come, it is called constant of integration and after simplification we can say that p will be equals to 6 mu v by h 1 minus k x minus 6 mu q by k into h 1 minus k x whole square plus c 3.

Now, it needs boundary conditions to find out this Q value and c 3.

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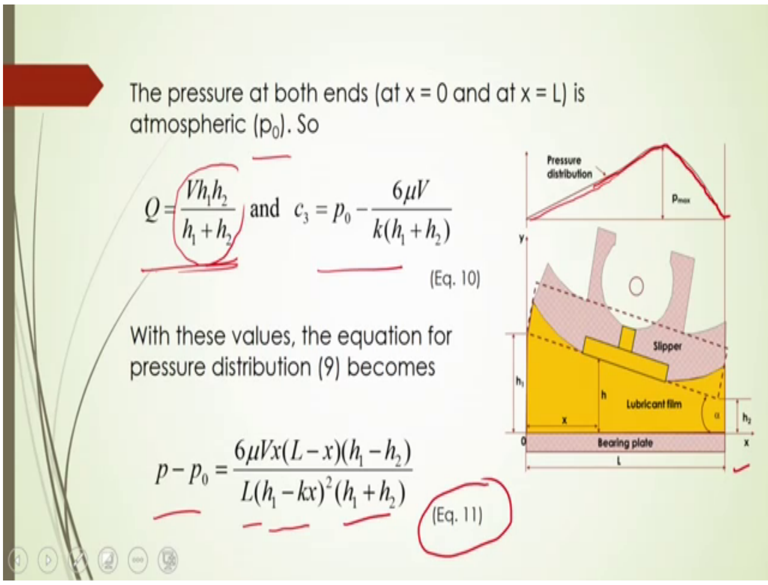

Here now the pressure at both ends we know that at x is equal to 0 and x Is equal to L here, the pressure will be atmospheric it should be represented by p 0. So, after substitution of these boundary conditions in equation number 9, we can solve it for Q and the c 3 constants. So, Q will be coming as known value of velocity and h 1 h 2. So, it will be defined as Q will be equals to h 1 into h 2 divided by h 1 plus h 2 and c 3 will be equals to p 0 minus 6 mu v by k into h 1 plus h 2.

Now with this value of q and c 3 as a function of velocity of this plate and the passage height of this h 1 and h 2, we can have the pressure distribution from equation number 9 and it will be as p minus p 0 is equal to 6 mu V x into L minus x into h 1 minus h 2 by L into h 1 minus k x whole square into h 1 plus h 2.

So, this equation number 11 will give you the pressure distribution along the axis x. So, at any x if you know the value of V and total length L and if you know this height h 1 and h 2 you will be able to find out what should be the pressure force acting on the load that you can acting on the bearings that you can find out. And based on this equation number 11 you can get this profile of the pressure here in this case there will be a certain pressure to be maximum and after that it will be reducing.

So, when the pressure will be maximum at which length of x this maximum pressure will obtain, that you have to find out from this velocity distribution.

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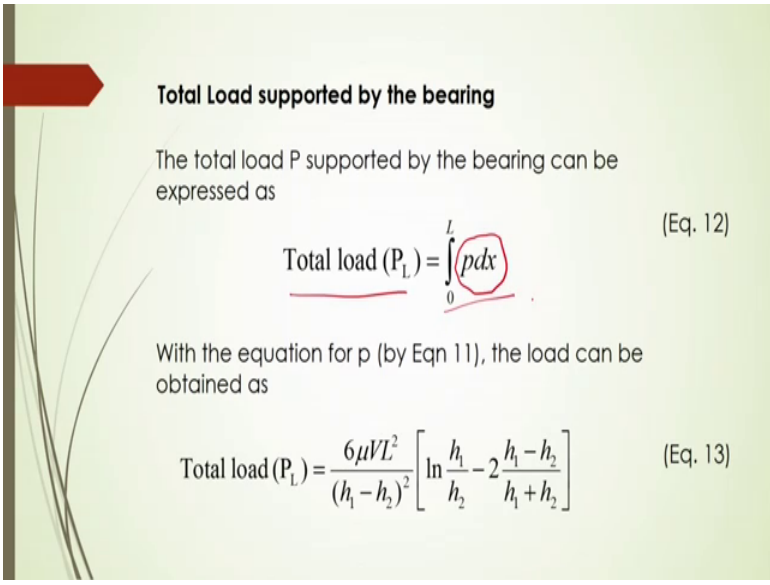

And what should be the total load that supported by the bearing? The total load that p supported by the bearing that can be represented by this to total load as P L. So, it will be integration over the length L and then you can get this total load as 6 mu VL square divided by h 1 minus h 2 whole square into l n h 1 by h 2 minus 2 h 1 minus h 2 by h 1 plus h 2. So, this equation number 13 will give you the total load after integration of this pressure distribution given in equation number 11 an integrating over this whole length then you can get this total load that is supported by the bearing.

Now, what should be that maximum pressure? So, to find out that at maximum pressure you have to consider that the pressure gradient should be 0.

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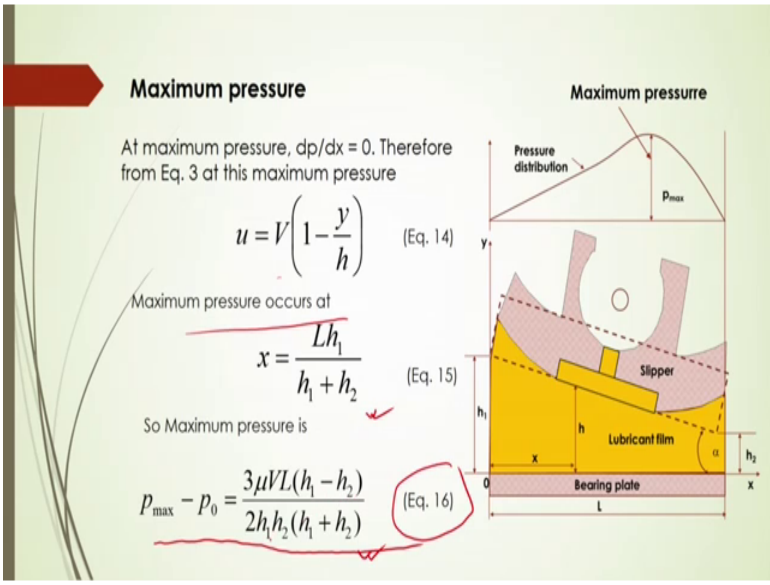

Therefore, from equation number 3 at this maximum pressure you can have velocity will be equals to e V into 1 minus y h. The maximum pressure occurs at here x will be equals to L h 1 by h 1 plus h 2 and after substitution of this x and v value or you can substitute directly the x value in equation number 11 we can get this maximum pressure and which is represented by equation number 16 here. So, maximum pressure relative to the atmospheric pressure will be equals to 3 mu VL into h 1 minus h 2 divided by 2 h 1 h 2 into h 1 plus h 2 there.

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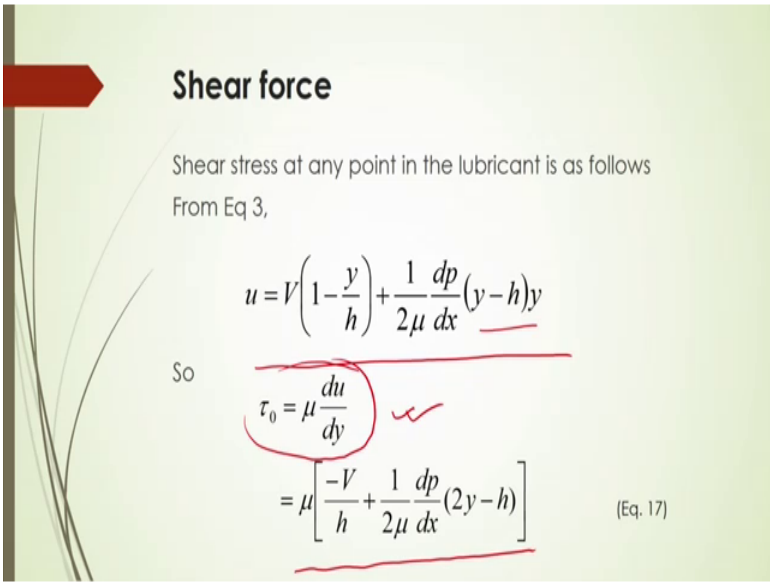

And what should be the shear stress at any point in the lubricant that also can be calculated here based on the velocity distribution.

We know that velocity distribution from equation number 3 as u will be equals to v 2 1 minus y y h plus 1 by 2 mu into d p by d x into y minus h into y as shown in equation number 3. So, shear stress can be calculated based on this Newtons law of viscosity as tau 0 will be equals to mu into d u by d y. So, upon int upon derivative of this velocity distribution we can get, the shear stress as mu into minus v by h plus 1 by 2 mu into d v by d x into 2 y minus h

So, shear stress is a function of this pressure gradient and also velocity of this plate and also what is the gap which is reducing from h 1 to h 2, also this depends on this viscosity of the fluid or lubricant here.

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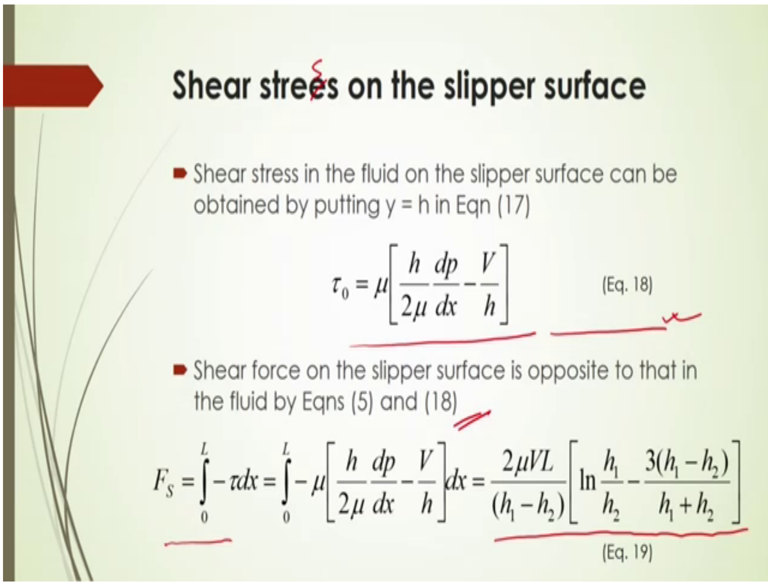

Now shear stress in the fluid or lubricant on the sleeper surface can be obtained by putting y is equal to h an equation number 17. So, at h at any h, what should be the shear stress that can be calculated by equation number 18. And shear force on the sleeper surface which is opposite to that in the lubricant can be obtained by equation and equation 5 any equation 18.

And which will be represented by this here F s will be equals to 0 to L minus tau dx. If you substitute this tau value from equation number 18, then you can get 0 to L to minus mu into this here mu into h by 2 mu d p by d x minus V by h into d x. So, after integration we can get this simplified form of this shear force as 2 mu VL by h 1 minus h 2 into l n h 1 by h 2 minus 3 into h 1 minus h 2 by h 1 plus h 2. So, this is the mathematical expression that you can get after integration of this shear stress over the length L.

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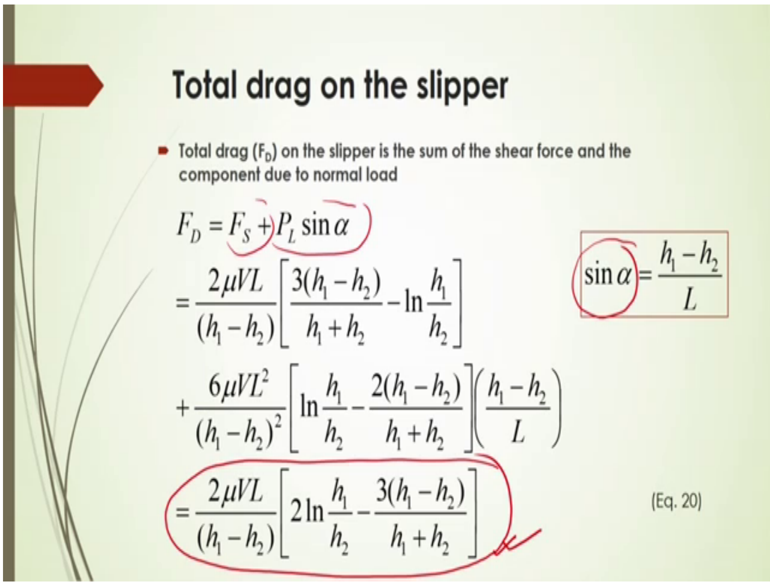

Now, what should be the total drag on the sleeper? Total drag F D on the sleeper is the sum of the shear force and the component due to the normal load

So, F D should be is equal to F S plus here P L into sin alpha here see the shear force and the load force in the x direction. So, here it will be is equal to 2 mu L by h 1 minus h 2 into just situation of F S and P L you can get and after simplification you can get it here. From the geometry you have to find out the sin alpha which will be is equal to h 1 minus h 2 divided by L.

So, finally, the total drag can be a function of viscosity of the lubricant, velocity of the plate at which it will move fast on it and the total length of that as shown in the figure h 1 and h 2 the phases gap that is reducing from h 1 to h 2 that you have to know that h 1 and h 2. So, all based on these values of variables you can get or you can calculate what will be the total drag on the sleep that you can calculate.

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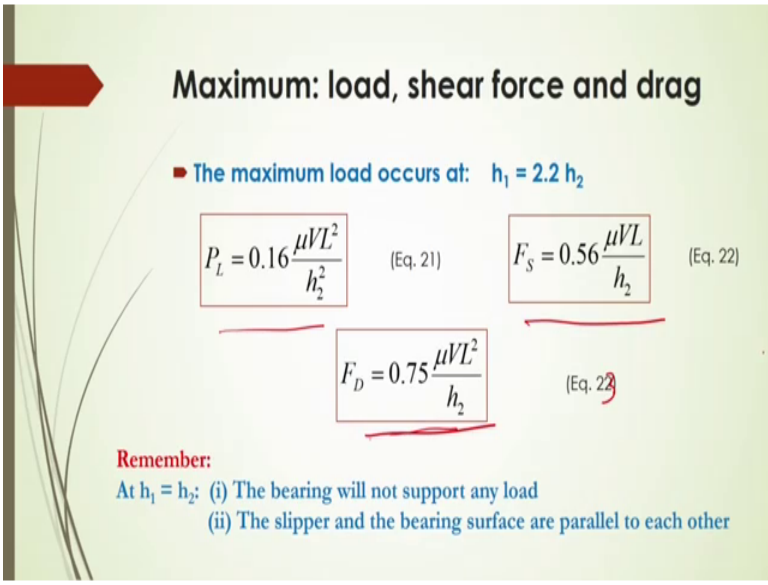

What should be the maximum load what was or shear force and drag force. The maximum load that occurs at h 1 is equal to 2.2 into h 2. So, in that case the P L should be is equal to this and p s F S should be is equal to this and F D total drag should be is equal to this. So, equation 21 22 and 23 will give you the maximum load and that shear force, and the maximum drag force here. And in this case you have to remember that at h 1 if both h 1 and h 2 are same that mean there will be no reduction of this passage, then you can say the bearing will not support any load and the sleeper and the bearing surface are parallel to each other.

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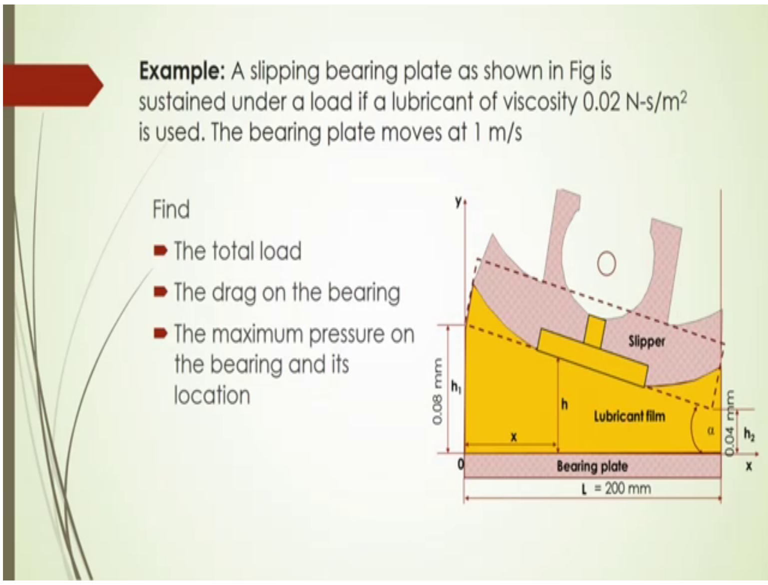

Now, let us have an example for that, a sleeping bearing plate as shown in figure is sustained under a load if a lubricant of viscosity 0.02 2 Newton second per meter square is used. The bearing plate moves at 1 meter per second in this case what should be the total load, what will be the drag on the pairing, the maximum pressure in the bearing and its location.

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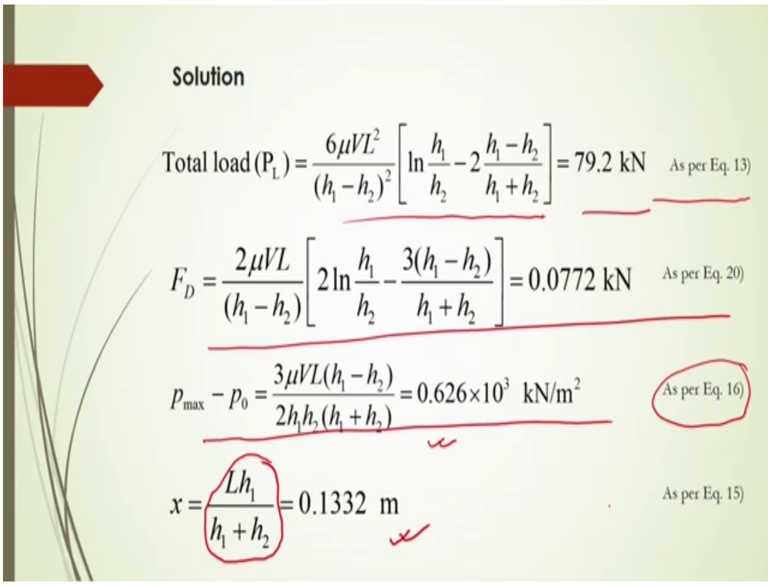

Now, we know that total load will be equals to this as per equation number 13, if you substitute the values here you can easily calculate should be 79.2 as for this problem. Similarly FD based on the equation number 20 you can calculate, again the maximum pressure.

You can calculate as per equation number 16 after substitution, you can get this maximum pressure as this. And this maximum pressure will occur at a length x that be maximum pressure at which this length x will be equals to L h 1 by h 1 plus 2 that will be equal to 0.1332 meter. So, this very interesting that you have to know the gap that h 1 and h 2 viscosity velocity of the plate and the length of the plate then easily you can calculate what will be the drag force maximum pressure and when or where it will occur.

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Now during the operation of this bearings you will see some power will be observed. So, what should be that power absorption in bearings 2 types of bearings you know that for power absorption is called collar bearing another is called bush bearing.

We will discuss only this 2 types of bearing here. Collar bearing is that load that acts along the axis of the shaft as in turbine shafts. The lubricant film here uniform thickness should be considered and it will be maintained by force lubrication system and that will separates the face of the collar from the surface of bearing as shown in figure here. Bush bearing is a shaft rotates such central in this case; the annular space between the shaft and the bush is filled with lubricant. A torque over comes the resistance that is encountered by viscosity of the lubricant. So, in this case the properties of the lubricant should be well known and a good lubricant should be selected for this bush bearing.

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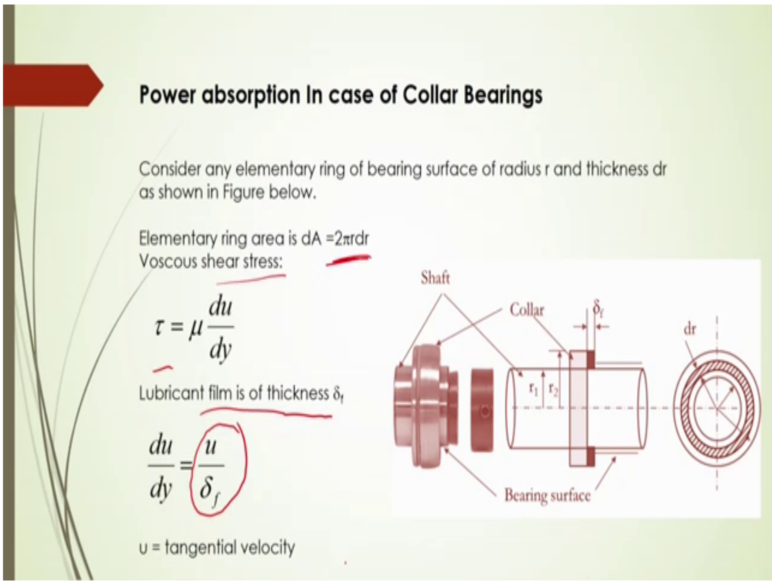

Now, how to calculate this power absorption in case of collar bearings?

Now, consider any elementary a ring of bearing surface as shown in figure, the radius r and thickness dr as shown in figure it is considered. Now elementary ring if you consider what should be the ring area it will be d a and it will be 2 pi r into dr and viscous shear stress will be calculated as tau that will be equals to mu into d u by d y and lubricant film is of thickness if it is delta f then du by dy you can simply say that it will be u by delta f where u is a tangential velocity here though it will be rotating at a certain rpm. So, you have to consider the velocity here in the tangential velocity.

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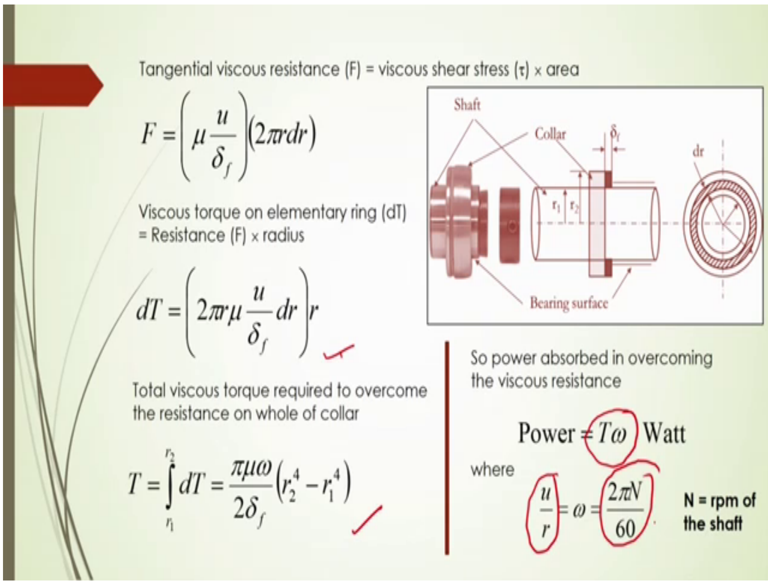

Now, tangential then viscous resistance F will be equals to viscous shear stress into area. And viscose torque on elementary ring that dt that will be equals to resistance f into radius.

So, in that case the small change of this viscous torque on this elementary ring can be calculated as here shown in equation number here, and then total viscose torque required to overcome this resistance on whole of collar can be obtained by integrating this viscous torque within the range of this radius r 1 to r 2. So, it will be equals to 5 mu omega by 2 delta f that will be into r 2 to the power 4 minus r 1 to the power 4 as per integration that you can easily obtain

Now, so power absorption in overcoming the viscous resistance can be then calculated by this product of this total viscose torque and the rotational speed. So, it will be T into omega and in this case omega should be considered as u by r, where u is the tangential velocity and if you know the rotational speed as n that will be rpm of the shaft then you can calculate it as 2 pi N by 60. So, if you substitute this omega in this case what should be the power absorption it will be 2 pi N 60 into T. So, in case of bush bearings similarly we can calculate this shear stress as tau is equal to mu in to d u by d y, where this tangential viscous resistance shaft should be is equal to viscous shear stress into area again after substitution of this d u by d y as u by delta f and here, for the force that you have to consider this area should be is equal to pi into dl.

So, total viscose torque required in this case to work on the resistance on whole of the bearing would be is equal to T into F into d by 2. So, finally, it will come pi into mu into omega into d cube L by 4 delta f. Here again the similar way we can calculate the power absorption as T into omega in this case. So, here T will be is equal to pi mu omega d cube L y 4 delta f. So, we can calculate this power absorption for collar bearings as well as push bearings based on the same principle, only thing is that the viscous torque will be different for this push bearing.

I will suggest you read this text book for further understanding and any other fluid mechanics books also you can follow. So, I think we have learnt something about this lubrication and its theory what are the different types of lubrication theory and how to calculate the load even maximum pressure velocity distribution over the length of the film thickness of the lubricant and also what are the different types of bearings and how these maximum pressure acting on the bearings, and what are the load and what are the velocity distribution for this collar bearing and also the bush bearings that we have discussed in the in this lecture.

I think it will be easier understanding for you, to find out that mechanism of the lubricant how it will be acting on the bearings and how the film thickness will be obtained to design the bearings gaps there and what will be the suitability of the lubricant, a lubricant and how lubrication theory can be applied in this case.

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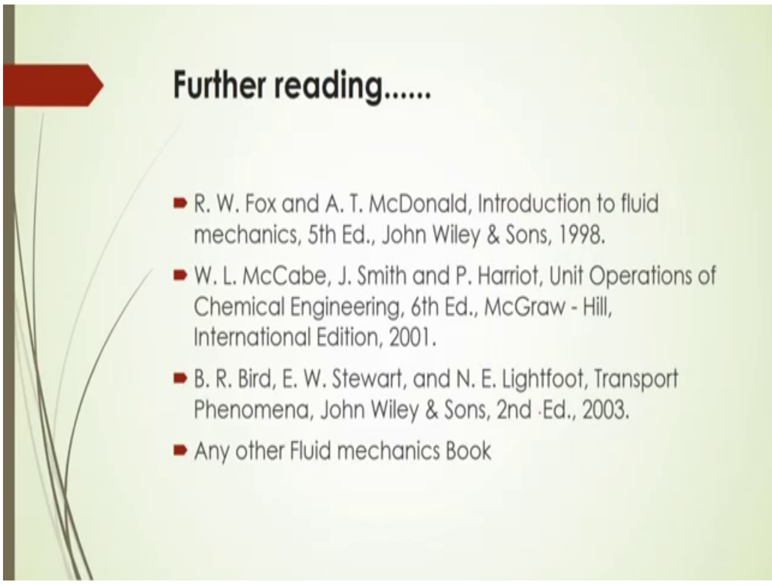

So, for further reading you can follow other different text books, and also the text books what we have suggested in the course. So,

Thank you for attention for this lecture.