Tribology

Prof. Dr Harish Hirani

Department of Mechanical Engineering

Indian Institute of Technology Delhi

Module #04

Lecture #14

Hydrodynamic Lubrication

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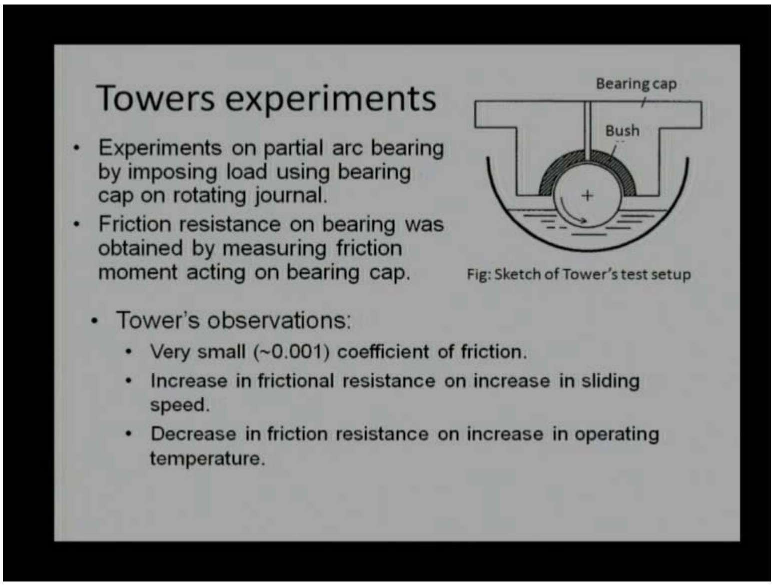

Towers experiments

- Experiments on partial arc bearing by imposing load using bearing cap on rotating journal.
- Friction resistance on bearing was obtained by measuring friction moment acting on bearing cap.

Fig: Sketch of Tower's test setup

- Tower's observations:
  - Very small (~0.001) coefficient of friction.
  - Increase in frictional resistance on increase in sliding speed.
  - Decrease in friction resistance on increase in operating temperature.

Welcome to 14th lecture of video course and tribology. Today's topic is hydrodynamic lubrication. That is one of very interesting topic for me. It does not give any wear. It separate two surface completely and it be as a load. It allows relative motion without much damage, or we say without any damage. That is why it is a interesting topic and one of the very favorite topic for me.

This hydrodynamic lubrication is started with towers experiments. We did few experiments on partial arc bearing. This set up is shown a tower set up has shown is shown in this figure. Let us say there is a bearing cap, bush then rotating shaft, rotor and there is a bath filled with liquid lubricants.

When tower did experiments by loading this bearing bush and allowing shaft to rotate. He found very low coefficient of friction. That is why I say that it was difficult to measure the friction for that time, but, lever arrangement and pin joint arrangement he did and could measure the friction. We cannot say it was a friction measurement was accurate, but, whatever the data came they were very relevant and more related to science.

That is why we can say towers observation he found very low co efficient of friction. I use a word use a symbol tilde which indicates the approximate value. It does not give accurate value. It was approximate value the coefficient friction point naught naught 1 very low co efficient of friction always desirable by all researchers, all scientist, all engineers.

In addition to those observation, towers commented on a sliding speed indicated that coefficient of friction noise; the friction force increase with the sliding speed its quite contradicting with that time existing friction loss. Take an example of coulomb it says a friction force does not depend on the relative velocity or sliding velocity by tower experiment proved. That coefficient of friction or friction resistance increases with increase in a sliding speed.

Another interesting observation came from his experiment was that friction resistance decreases with increase in a temperature. There is another important observation of course, we cannot say these are the final findings whatever experiment were done by the tower were very limited in within the range only. So, these observations remain in the range it does not mean it is always true, coefficient of friction really decreases. Some time with a increase the velocity or sliding velocity and co efficient of friction increases with the increase in temperature also.

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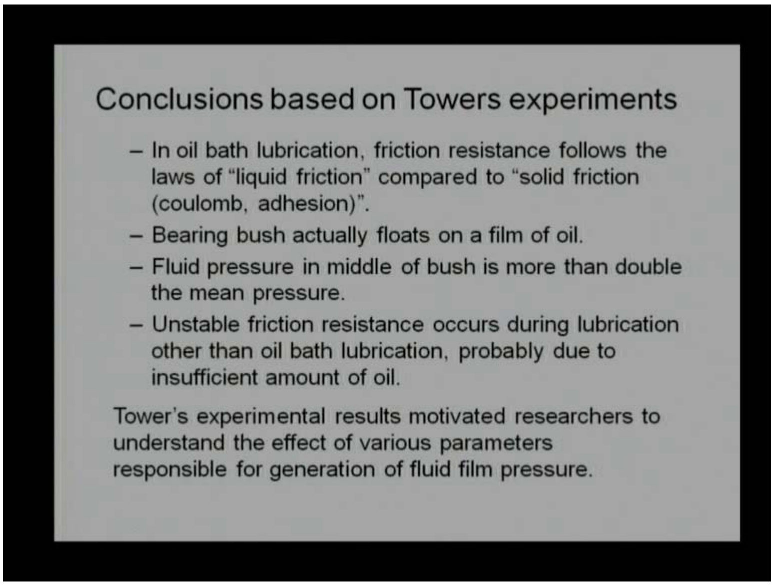

Conclusions based on Towers experiments

- In oil bath lubrication, friction resistance follows the laws of "liquid friction" compared to "solid friction (coulomb, adhesion)".
- Bearing bush actually floats on a film of oil.
- Fluid pressure in middle of bush is more than double the mean pressure.
- Unstable friction resistance occurs during lubrication other than oil bath lubrication, probably due to insufficient amount of oil.

Tower's experimental results motivated researchers to understand the effect of various parameters responsible for generation of fluid film pressure.

So, that is why we are mentioning the word that this observation were made by towers experiment or were concluded from towers experiment. Few more observations from the tower experiment is that are those oil bath lubrication. We use a oil bath lubrication completed filled or shaft was submerged in lubricant.

That is why he say that most of the coefficient of friction experiment or friction related experiment were can be termed as a liquid friction force or friction occurring because of the liquid. That is what that these were observation not related to the coulombs experiment or ammeter experiments are with the based on the more on the liquid.

Another observation was that it could find really a floating of shaft in liquid without really in contact. So, that is a floating is possible or we say that levitation is possible when use a liquid lubricant. Another important observation he found the fluid pressure was a maximum at the middle and that was almost two times compared to mean pressure.

That was a interesting observation that pressure does not remain uniform in bearing it comes the maximum value at the center and it is a twice that two times a mean value. That means, what we do calculation in ordinary mechanical engineering we find that average pressure whatever the load divide by area and then calculate what will be the mean pressure. And choose a material accordingly, but towers experiment clearly indicated the max pressure will be more than mean pressure. If it is in his view it was a two times.

However, we have done number of experiment that we have found mean pressure maximum pressure can go even a 10 times compared to mean pressure. Another interesting observation from towers experiment can be concluded or can be noted is that unstable friction resistance. Whenever there is a starvation, when there is a lesser lubrication, where there is more or like a condition happening at the mixed lubrication. Friction force were unstable it was not giving a constant same value again and again. You do number of experiment and every time you find some difference in experimental results.

So, results were not repeatable or repetitive. In that case mean value on a standard deviation was important. What we can say that friction force in a mixed lubrication condition or a starvation condition will be on a statistical quantity. Where there will be we need to define a mean value as well as we need to define a standard deviation. However, for liquid lubricant he found more or less a steady coefficient of friction and results were repeatable.

So, that is the importance of liquid lubrication. If it is a complete hydrodynamic lubrication what are the term can be given in hydro dynamic lubrication then coefficient of friction will remain steady. It can be repeatable or then we can calculate or we can design accordingly. Now, another conclusion, final conclusion we can say that it comes from the tower experiment is his results, his experimental results. He really motivated researchers, to understand the physics of various parameters, effect of the various parameters on a fluid from pressure generation.

Whether, is it is possible to generate a fluid film first thing. Second thing is what are the parameters which are affecting these results? So, it motivated researcher to do number of experiment and thinking from different angle, thinking from viscosity angle, thinking from geometry point of view, thinking about the application of lubricant with from different location. And that is why the number experiments results; experimental results are available and people generally quantify those with the some physics also.

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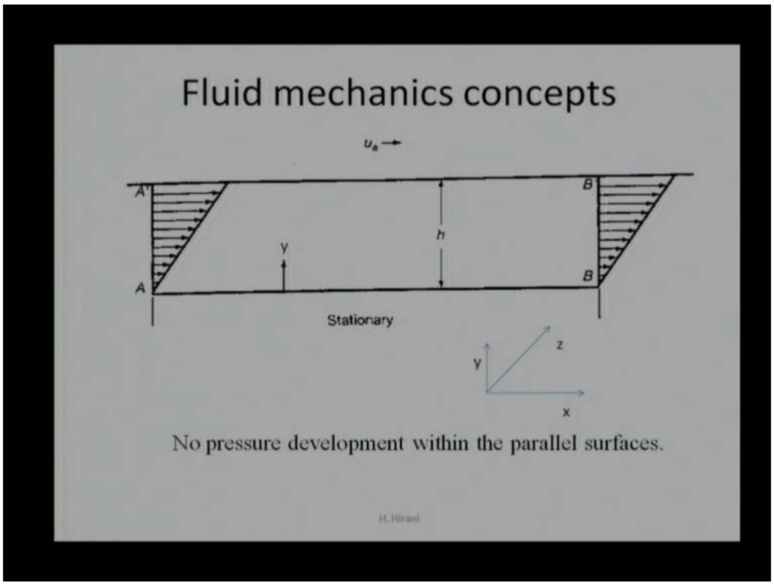

Fluid mechanics concepts

No pressure development within the parallel surfaces.

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To understand what the tower did. We will take very simple example, what we say that simple geometry. We can see there A dash or B; A dash or B dash is applied is moving with the velocity U a .Sometime we call is A prime and B prime instead of A dash and B dash. So, a prime and B prime is another plate A B which is a constant it is a steady. It does not move. It is a more like rigidly fix at a one place and this plate is sliding at velocity U a.

There is a coordinate systems shows that we are assuming x direction from A to B or towards that side and z direction is a perpendicular to this screen. And it can give a depth arrangement, while y is a film thickness. y is a or we say that film thickness is in direction of y that is a coordinate. Generally this separation is smaller when we talk about the hydrodynamic lubrication. It may be turning out to be a 0.1 percent or lesser than that 0.1 percent of overall dimension or radial dimension or sliding dimension or radial dimension or sliding dimension tangential dimension.

So, that gap generally we keep very very low. So, if we want to find out any pressure generation between the surfaces. Now, what is observation from coming from this slide or this arrangement? Whatever the velocity at the entrance should remains the same velocity at the exit. If we neglect the coefficient of friction, if we neglect the friction; skin friction of the pipe or the skin friction of the plate. If we assume the there is no friction is negligible.

So, whatever the energy at the given at the entrance should be the same at the exit and this is the velocity profile. So, whatever the kinetic energy at the entrance should be the same as the kinetic energy at the output or exit. And there is no any other direction we are assuming that there is no exit in that direction is the exit is only the direction x direction and entrance is only in z direction. And further we are assuming at this plates are completely filled or does not have any porosity. So, liquid cannot enter in this plate or liquid cannot preserve this liquid at all.

So, with this kind of arrangement this is a very simply. I think at the velocity of the entrance will be remaining the same velocity of the exit. If you are assuming friction or pi friction or plate friction is negligible. And then we do not find any pressure development which was observed by the tower or which was concluded from tower the pressure will be higher at the middle point and it will be two times compared to mean pressure.

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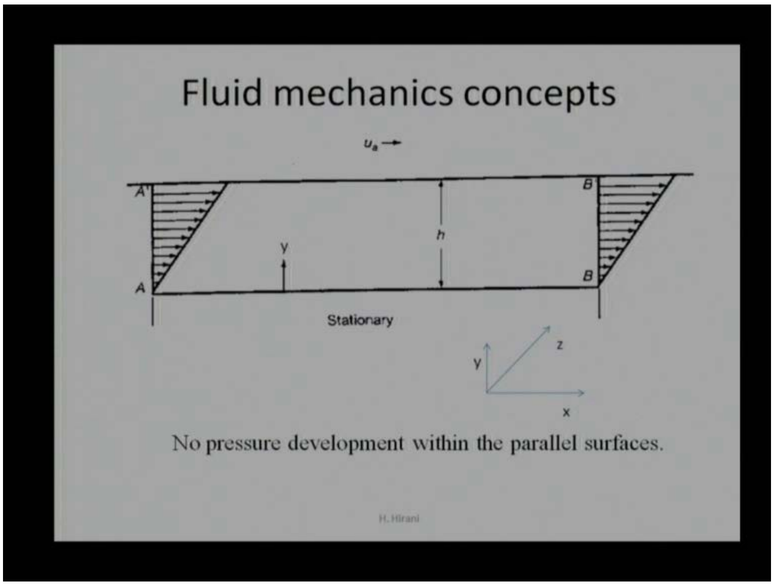

Fluid mechanics concepts

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However, if you see this slightly difference arrangement we say that now plate A B. It was a stationary earlier is inclined at an angle alpha. This angle may be 0.5 degree, 1 degree and 1.5 very low value. Even in that case what will happen? The film thickness will not remain constant. Film thickness or separation between the two plate will not remain constant. It will turn out to be a function of x l direction or we say that film thickness continues to be vary in the x l direction or in x direction.

Because of this arrangement what will happen? Say that area B B bar or we say B B dash or B prime will be lesser than area of A A prime. When the area is decreasing if we assume the same kinetic energy or kinetic preservation of kinetic energy then velocity profile velocity should go higher side, but we know the slip theory. And we say that whatever the maximum velocity of the plate fluid velocity cannot be more than that.

The maximum velocity of the plate whatever the plate comes fluid have will be having maximum velocity equal to the plate velocity. It will not go beyond that velocity or in other word there will be not be any mass conservation. May be more liquid is coming in, but, lesser liquid is going out. And there is no possibility of the storage of this liquid. Then where does this liquid goes? Naturally, physics has to change down.

Some additional aspect will come we say that there will be a pressure positive gradient to increase a mass flow. Positive pressure gradient at the exit and negative pressure gradient at the entrance. Initially, when there was there will be parallel plate, no separate variation in separation film thickness was the same; velocity remain constant.

However when we are giving a conversions, we are giving some table; we are giving some angle to the plains. Then what is happening there is a change in velocity profile also. At the velocity if I assume even the same suppose when the pressure is going to change or mass flow rate to be increase at the exit. Then the additional pressure gradient is coming as a positive pressure gradient which is going to increase the mass flow. While at the entrance pressure flow should decrease to some extent.

And that is why pressure gradient is generated or negative pressure gradient which is retarded the fluid flow. That is why the film conservation of the mass; if I use a theorem we find the pressure is negatively generated here which is retarded the flow positively generated here which is pushing flow out or helping a mass flow rate.

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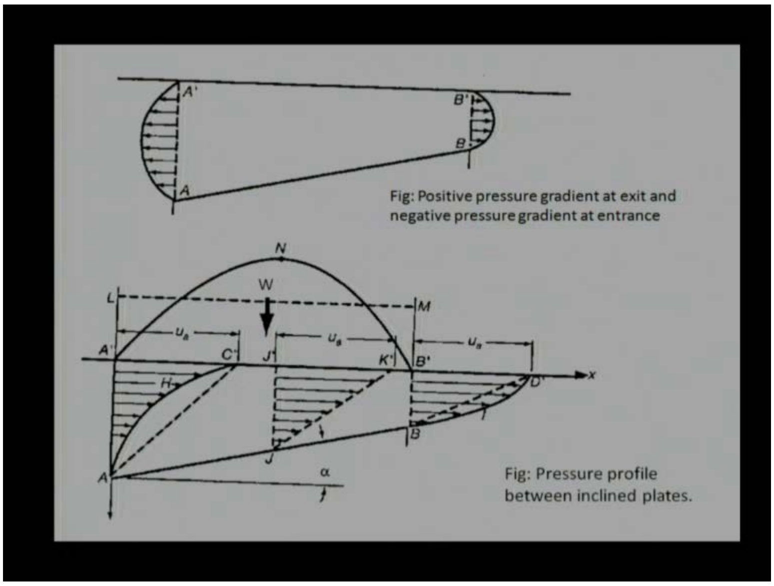

Fig: Positive pressure gradient at exit and negative pressure gradient at entrance

Fig: Pressure profile between inclined plates.

We can think in this direction or if we try to sketch we can say the pressure is positive. Let us at the exit where the B and B dash or B prime is same while negative pressure at entrance A and A prime. Now, if we superimpose mass flow rate. What we get? There is a velocity profile. In addition to that pressure flow mass flow rate will happen because of the pressure.

Similarly, there is a velocity profile will be the same, but, no negative to pressure gradient is retarding the flow. That means it is reducing the flow mass flow rate. At the entrance the things are happening in the both the end. At the entrance flow is retarded, at the exit flow is pushed out is driven by the positive gradient. That means this was not only the velocity now the pressure is acting in this.

If we try to plot it we know very well two boundary condition will remain. At the entrance pressure is almost negligible or the gas pressure whatever the pressure which was given to us. Then to the surfaces while at the exit again if we assume the ambient pressure or gas pressure is a 0. Then we find a maximum pressure happening at the middle point. Pressure at the entrance is 0 is the gas pressure on the exit. The again the gas pressure the pressure is 0 and pressure maximum happening at the center and this is just to find towers experiment.

That means, what tower did whatever the experiment he perform, because of the floating arrangement of the rotor or floating arrangement of push. Then unequally position was changed and there was some convergent rejection or some change in geometry which reduce a mass flow rate at the entrance and the push the flow rate at exit was made. That is a hydrodynamic lubrication.

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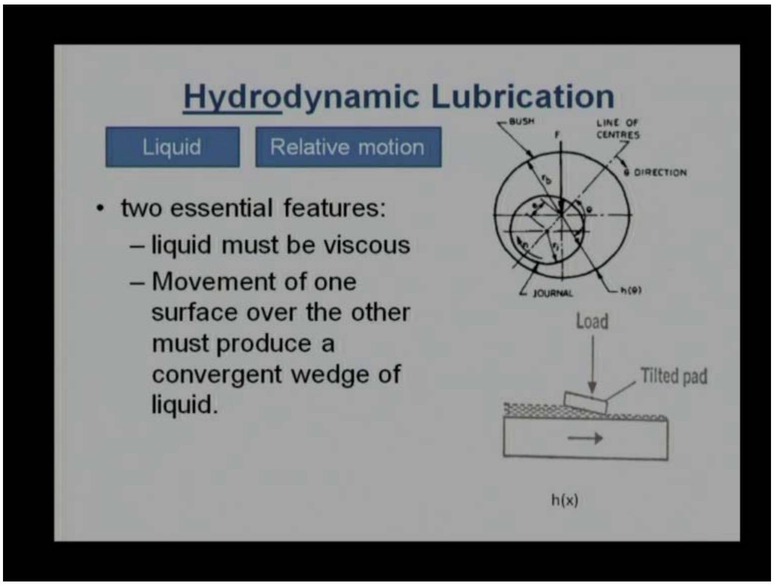

Hydrodynamic Lubrication

Liquid

Relative motion

- two essential features:
  - liquid must be viscous
  - Movement of one surface over the other must produce a convergent wedge of liquid.

What we can say that hydrodynamic lubrication we require a liquid, we require relative motion. This liquid we are using the word which covers up of hydrodynamic action and it has been known since more than 125 years.

However, if we replace this liquid with air or some gas is still this kind of action will happen, if there is a relative motion and there is a gas. Then still the similar mechanism will happen only the pressure generation will not be that high as in the case of the liquid, is in being viscosity of gas is much much smaller than viscosity of the liquid. May be say almost 1000 lesser then pressure generation also will be lesser or another case.

If for high load application, we can use the aerodynamic lubrication where almost load is negligible or almost ambient pressure is generated. In that case it we can use a gas lubrication or gas as a lubricant. While otherwise where ever the moderate lubricant comes we need to use a liquid lubricant.

These are the two typical examples whenever we start discussing about hydrodynamic lubrication. These all are the exaggerated it is not a really in dimension. As in mentioned clearly on that clearance between that two surfaces need to be very very small. If clearance or separation between two surfaces will not be very small and then whatever the theory which know to describe the lubrication the hydrodynamic lubrication will not be remain valid. That validity of this whole mechanism is that separation is very small and pressure gradient is not generated in that direction.

So, this is known as the thrust bearing or tilting bearing. We can see there is a also a wage formation. The film thickness is decreasing whatever we are discussed in previous slide that moving place was tilted. While in this case you can see the stationary plate is tilted moving plate is remaining same angle.

So, there is a emigration of course, is the only the relative angle which matters which ever plate is tilted. It does not matter too much to us. It is only relative angle relative velocity which matters a hydrodynamic lubrication or hydrodynamic lubrication is governed basically by relative velocity and viscosity. That can be studied in that two essentially features for hydrodynamic lubrications of liquid must be viscous.

There is be liquid need to be a layered structure and a connected to each other and then we require some force to push this liquid out. That much is a need to have some viscous nature and by enlarge almost every liquid has that kind of characters. So, another one is that there is a need of convergent range. If the geometry is giving either is can be floating because of loading arrangement climatic changes is shown and then there is a some wage action can see there is a wage action over here. As there is a more, if I assume there is a theta is equal to 0.

We are taking a polar coordinates that this is the maximum film thickness position. We I mean theta is reaching to pi or 180. Thickness is minimum or separation between two surfaces is minimum. That is called a minimum film thickness location. And path from maximum film through the minimum film thickness is convergent. We can see that slowly slowly it is getting converged.

However, interesting thing is that when there is convergent there is a equaling divergent also in other side. The whatever the pressure is generated in this domain it should be lapse back as is should go back to the negative direction. And we should get overall load capacity is equal to 0, but it does not happen really. In the case of the liquid what happens? If the pressure is lesser than ambient pressure the liquid gets separated. It does not go below the 0 pressure or is may be lesser than vapour pressure. What we call as a cavitation. Liquid streamers form and there are always some gap between the streamers. That is why we overall get the positive results or pressure load carrying capacity from the hydrodynamic bearing arrangement or arrangement which is shown in this diagram.

Similarly, arrangement is shown here this is a tilted pad bearing. The sliding happens because of the tilted angle pressure generation will be there. However, we have observed that instead of maximum pressure at the middle point. Pressure is always on a higher on exit side towards exit side or it will be slightly shifted from the mean value, mean line to exit side.

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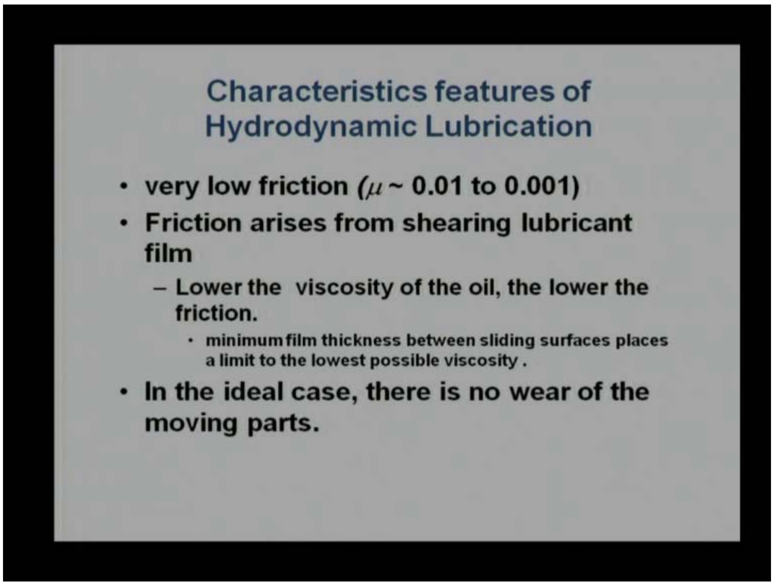

Characteristics features of Hydrodynamic Lubrication

- very low friction (μ ~ 0.01 to 0.001)
- Friction arises from shearing lubricant film
  - Lower the viscosity of the oil, the lower the friction.
    - minimum film thickness between sliding surfaces places a limit to the lowest possible viscosity .
- In the ideal case, there is no wear of the moving parts.

Some characteristics can be described and terms of characteristic parameter. We say that one of the interesting or observation from hydrodynamic lubrication is a coefficient of friction is very very low which is favourable which should stick to that. And whatever the friction loss happens it they this kind of a friction happens because of the shearing of the liquid. That means, viscosity is required to carry the load, but viscosity is not required because it is going to cause more and more friction.

That is why we say that lower the viscosity of the oil, lower the friction force because shearing of the if the viscosity is more lesser will be shearing and lesser will be friction. However, the problem comes if there is liquid is not able to with stand the load. It is simply squeezed out in no time. Then there will be metal to metal contact and hydrodynamic lubrication will not axis after that.

So, to maintain hydrodynamic lubrication we need to have viscosity of the lubricant. That is why we require viscosity, but we do not require viscosity. And that is why there is always a some thread of maximum viscosity and minimum viscosity and we need to choose a proper lubricant which it gives a desirable results from load point of view as well as the friction point of view. And of course, we want wear to be 0. We never attempt to collide surface or contacting two surfaces. We do not want that this film thickness turn out to be 0 at any point.

That is why we say that in ideal case. I am using the word ideal case because whatever we do is still there is a possibility of 1 percent or 2 percent metal contact may be transient condition is start and stop condition, but in ideal case. There should not be any wear of removing parts. If we are planning to go ahead with a hydrodynamic lubrication mechanism.

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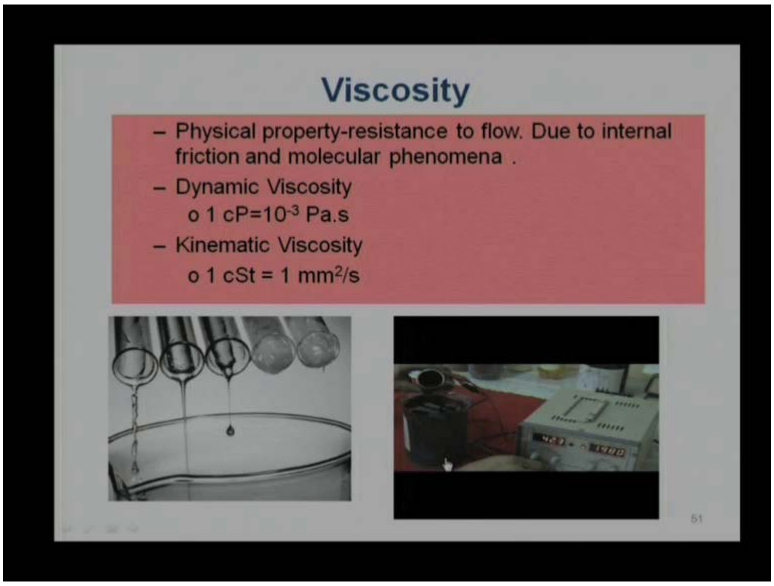

Viscosity

- Physical property-resistance to flow. Due to internal friction and molecular phenomena .
- Dynamic Viscosity
  - 1 cP=10^{-3} Pa.s
- Kinematic Viscosity
  - 1 cSt = 1 mm^2/s

As more and more emphasis was given on viscosity there is a point to give few slides on the viscosity. So, that it is a physical property of the liquid. It is not a metal property, but, we say that there is a physical property of the liquid to which can be measured by finding their molecular attraction. We have some resistance against flow.

And if we are able to observe that will give us viscosity. We have 2 units of the viscosity or commonly we use a 2 viscosity terms with what we call as a dynamic viscosity and kinematic viscosity. In kinematic viscosity we do experiment with the influence of the gravity force. And that is gravity does not come into picture over here and common unit to which we use for the kinematic viscosity is a centistokes and metric unit. It can be expressed as a millimeter square per second. Once a dynamic viscosity is generally expressed in a centipoises and if we use S I unit it will be a pascal second or often it is expressed under millipascal second.

So, for most of the our theoretical calculation or when we do computational work or when we do the modeling of tribo surfaces we may require dynamic viscosity. While when we do experiments most often we use major dynamic viscosity expect the few experimental set up whether rotation is movement is used and we do not use gravity force.

To just give a feel of the viscosity this diagram shows some drops. You can see the first figure or the over the first part of the figure, which shows that liquid is dripping and the liquid molecule or the drop size is very big. Compared to drop size of this we can see the flow is slightly lesser and this case flow is more, but, we can find here all are tilting angle is same. Tilting angle for the all arrangement is remain same.

Here, liquid is flowing with more mass flow rate, less for mass flow rate almost negligible mass flow rate. Here it is taking time to flow and here almost stick. So, it is more like a gel character because the gel will be having higher viscosity. I have a some video to show what is this viscosity flow?

Let us play this can see (No Audio Time: 26:22 to 26:32) when we are switching off current then liquid is start flowing. When we switch on current which is getting displayed in this power supply. That is supplying the current to the lacto magnitude here that generate magnetic field and causes restriction of the flow or in other word using this kind of arrangement we are changing online viscosity.

Low viscosity to high viscosity just by changing supplying some current to that arrangement. This kind of liquids are known as a magnitude rheological liquid and they are known for change in viscosity or their behavior is known for the liquid to the solid to liquid to semi solid to the solid.

Their strength or shear strength changes from the 0 pascal to maybe say 100 kilo pascal. Then substantial change happens in just fraction of second. That is why we can say viscosity plays a important role and this kind of fluid we are changing the online viscosity. What does the viscosity we require it can be made according to that.

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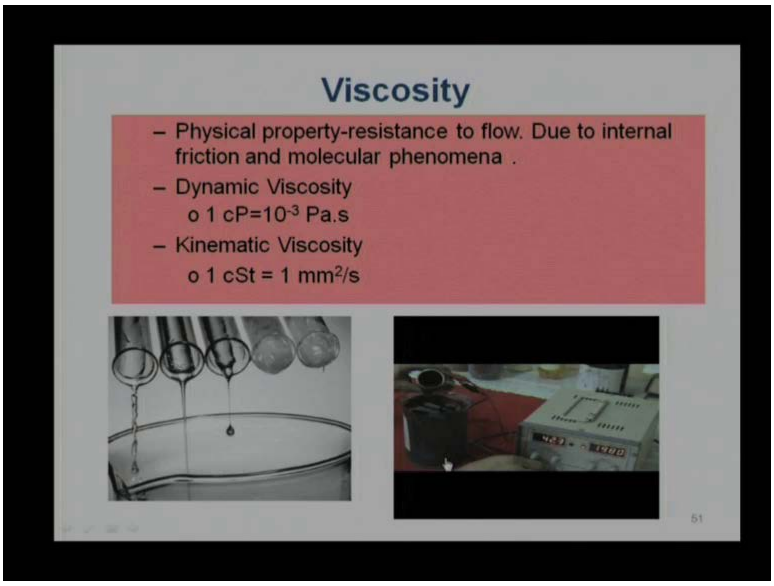

Viscosity

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  - o 1 cSt = 1 mm^2/s

They are this table show that some typical of viscosity values, which have been utilized in a number of arrangements. We can conclude from this arrangement is that if the load is increasing viscosity need to be increased. Take an example of instruments or the clock and we know very well the load is almost negligible on those arrangements, but take an example of the warm wear. Load is very high contact will be very very high or contact area need to be larger in this case because of the applied load is very high.

You can see the viscosity change the kinematic viscosity we were using 5 to 20 centistokes in that here we are using 200 plus. So, increase in load is increase require the higher viscosity. Even though we say that hypoid gear and worm gear they do not work in a hydrodynamic lubrication. They generally work in mixed lubrication, but major part of the mixed lubrication is hydrodynamic lubrication. That why we are using the viscosity values for that.

Take an example of the roller bearing. Generally they work in a elastohydrodynamic lubrication, but again the elastohydrodynamic lubrication major part is a hydrodynamic lubrication the viscosity matters in this case.

So, depending on the kind of the load arrangement viscosity need to be selected properly, if the lower load arrangement or the apply load is lesser. Then we can a low viscosity if apply load is very high and we know that there is a more chance of liquid is squeezing out. Then we require thick oil we require high viscosity of the oil or some additional polymers, which are really making apparent viscosity. If I am using the word apparent viscosity not necessary every time viscosity need to be defined. Many times solid molecular layers are formed in a surface, which are very difficult to squeeze out.

But in that case we need to use a word apparent because viscosity because liquid is there and that is making molecular layer on the surface and finding how it can sustain more load. So, when we use word mixed lubrication it has to be done with some apparent viscosity term.

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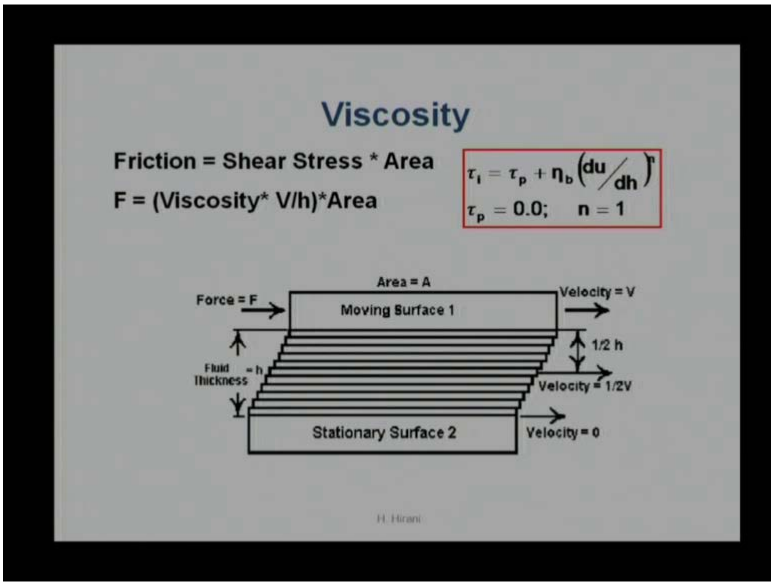

Viscosity

Friction = Shear Stress * Area

F = (Viscosity* V/h)*Area

$$\tau_i = \tau_p + \eta_b \left(du/dh \right)^n$$

$$\tau_p = 0.0; \quad n = 1$$

This slide shows the some fundamental arrangement how and why viscosity instrument is mentioned? We can see the moving surface, stationary surface gap is some film thickness is equal to h and we are because of the viscosity. Generally, they will remove or they move layer value here as more like a laminar flow because of the viscosity.

And if we take this kind of assumption it will be very simple for us to find out what will be the friction force? Friction force is generally in that case will be shear stress into area and in on the shear stress. For newtonian fluid can be as a viscosity velocity per unit gap or we say the viscosity into velocity gradient. Viscosity is generally given in a pascal second and velocity is gradient is in express per unit second. So, second second will be cancelled out this will turn out to be pascal. Pascal into area it is new term.

So, friction force can be measured using this kind of arrangement. However, there is a possibility of some modified arrangement or modified relation for that. We say that this is a for valid only for newtonian fluid. What is the meaning of newtonian fluid? Where they say that initially the top heat term is equal to 0 and n is equal to 1 .Otherwise if it is a non newtonian fluid or we say if the fluid is a newtonian, then we should express tangential stress or shear stress of the liquid in terms of topping. At initial stress which is required to start flow.

Then the viscosity and then velocity gradient that there is constant of exponential constant that is n which may be lesser than 1, greater than 1 or equal to 1. For newtonian fluid it is equal to1.

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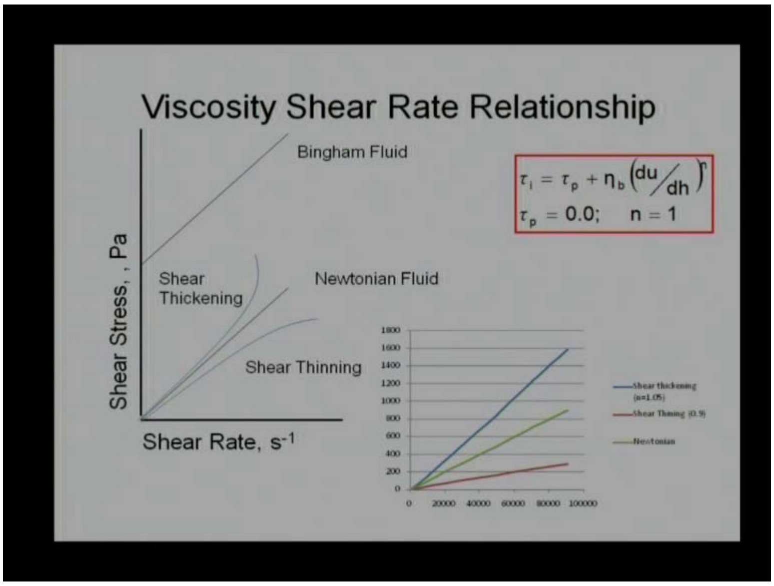

Viscosity Shear Rate Relationship

$$\tau_i = \tau_p + \eta_b \left(\frac{du}{dh}\right)^n$$

$$\tau_p = 0.0; \quad n = 1$$

Now, this slide gives a more elaboration on this Newtonian and non Newtonian fluid behavior. We say that Newtonian fluid can be expressed in a terms of viscosity and shear rate relationship. Would is a shear rate relationship with viscosity? If that is defined then we say whether fluid is in non newtonian or newtonian. For newtonian fluid shear rate and shear stress they are in proportion. As a shear stress increases, shear rate increases or an otherwise we say the shear rate increases the shear stress increases.

So, shear rate n equal to 1 top is equal to 0, but if n is not equal to 1 is a lesser or greater than 1. In this case example is given when this is a lesser than 1. When the n is lesser than 1, what we call as a instead of newtonian fluid we call as a shear thinning liquid. As a velocity increase shear rate is causing lesser and lesser shear stress. That is known as a shear thinning liquid.

Similarly, there is another possibility of shear thickening fluid. As velocity or velocity gradient increases that surface is getting more and more thicker. And take a example of a corn starch. When we use a corn powder and use a water and mix this together. Corn may be in some of the size then corn powder may be in smaller size and it will turn out to be a liquid which can easily flow, but, if we start rotating that fluid has a high speed and we can find out a very solid surface from that corn starch.

And that is why many times we use this kind of shear thickening liquid in armors cloths. We say that and bullet proof jackets. The bullet proof jacket is generally in based on the shear thickening liquid. There is no velocity then it can be the liquid. When bullet comes with very very high velocity. There will be shear thickening in fact and it can act as a solid and it can act as a surface which cannot be easily penetrated.

So, that kind of liquids have also utility, but what we are thinking much or about the liquid lubricant where the shear thinning behavior are is observed dominantly. Any example of liquid which liquid lubricant generally, it will be a shear thinning behavior. Take an example of a M R fluid also magnitude rheological liquid. They show also a significant shear thinning effect. They are very effective at the velocity, but they turn out to be not that much effective at the high velocity.

There is another kind of the liquid we call as a Bingham fluid or Bingham liquid. That shows that initially the some shear stress is required to start the flow of liquid. Take an example of the grease, grease is Bingham fluid or take an example of a magnetic rheological fluid. They are Bingham fluid depends on current supplied. The current supplied to the magnetic or we say magnetic field supplied to the M R fluid is almost negligible as 0.

Then it will act as a Newtonian fluid while if the current is supplied magnetic field is supplied. Then it will develop some sort of shear strength or we say that in the top you will be having some finite value and then finite value is generally greater than the second term. That is why we say that apparent viscosity which can be calculated based on this summation itself. Apparent viscosity of magnitude rheological fluid can be increased by the 100 times by exchanging this parameter top.

May be initially a low value then high value it can be in pascal it can be in kilo pascal also. So, some results are shown in the this figure we can say that on x axis there is a shear rate on y axis there is a shear stress. That in a pascal, this is an per unit second. For Newtonian fluid we are able to show results for the same shear rate. We can see for shear thinning liquid shear stress will be lesser. That means, if a magnitude rheological liquid which should be used is a grading shear thin. Then it will not be able to sustain that much load or it will not be able to generate that much stock.

So, if you are trying to use magnetic rheological liquid for some special application, where the relative velocity is high. Then arrangement need to be met in such a manner the shear thinning behavior is not very dominant in behavior. In the same arrangement it is shown that the same shear rate maximum shear resistance comes from the shear thickening liquid.

We are saying here the n here is only 1.05 and we can see the significant change because the shear rate is very high. Significant change just by changing by 5 percent while in this case shear thinning effect also is significant by just changing the 10 percent value of that.

So, they are very sensitive and we need to really design liquid accordingly. Many times we add liquid lubricant to the liquid. Even though liquid in original condition remain as a newtonian liquid, but when we add some additives then there is a possibility. It can gain shear thinning or shear thickening behavior and that need to be noted.

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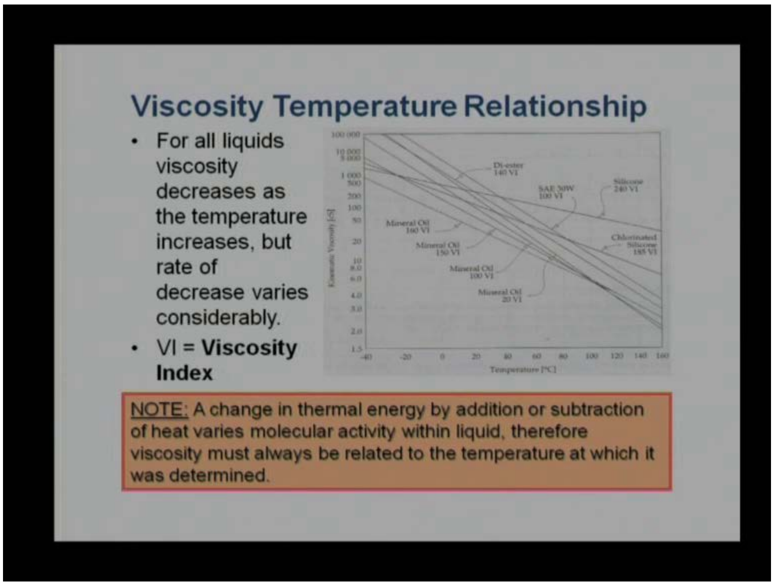

Viscosity Temperature Relationship

- For all liquids viscosity decreases as the temperature increases, but rate of decrease varies considerably.
- VI = **Viscosity Index**

NOTE: A change in thermal energy by addition or subtraction of heat varies molecular activity within liquid, therefore viscosity must always be related to the temperature at which it was determined.

Then we have discussed in the previous slide about the viscosity and shear rate relation. Now, in this slide we are going to discuss about this viscosity and the temperature relationship.

This is the more important from thinking what the towers did? Tower express that, the friction force reduces with increase in the temperature. So, there is always some relation between viscosity and temperature (( )) as the temperature increases viscosity will decrease. Reason generally is given the molecule they remain in closeness initially as the temperature increases.

They get a more energy and then they try to get separated from each other and that is why the viscosity goes down or reduces with increase in the temperature. That is why we are writing that for all the liquid viscosity decreases as the temperature increase, but rate of decrease varies considerably.

We are not arguing that there will not be any decrease in viscosity, but we are trying to discuss how fast they are reducing? If the liquid is a very stable even though there is decrease, but that not very dominating factor. It is gradually decreasing than that kind of liquid will be good for the application or that can give more robust behavior.

Often, viscosity temperature relation is expressed in terms of viscosity index. If not like a parameter says that higher the value lower will be the effect of temperature and viscosity and there is a chart shown over here. It is figure shown over here different V I for the different oil. Take an example of the mineral oil here mineral oil has a one 60 VI some number.

So, and mineral another mineral oil has a 150 V I other mineral oil has a 100 V I. That means, when we talk about the mineral oil it is not a single value or it is not a single substance. Mineral oil have a number of variations I mean say number of classes in mineral oil itself. As we cannot call as paraffinic oil, naphthenic oil and based on different proportion mineral oil will be changed, but they are generally made from the same source from the petroleum crude oils. That is why they are known as a mineral oil.

So, mineral oil work is not very good as such for all the liquid lubricant. It should be specifying what which mineral oil or at least we should a specify what is the viscosity grade of that oil? That is why in this chart we are able to see mineral oil. Even the 20 V I because may be bad viscosity index. Is as I mentioned more and more viscosity index better and better lubricant from temperature point of view. We are not discussing about any other point of view in this slide we are expressing with the temperature relationship.

There are some oils which are showing viscosity index is high as a 240. Can say silicon oil this kind of the oils are the synthetic oils. They are manufactured or they are fabricated or they are planned in a lab. How one molecule should act with other molecule? That is why they are synthetic. They are synthesize as per the wish. We can say what was earlier concluded from here? A chain in thermal energy by adding or subtracting heat. Viscosity will be changed and that is why whenever we code viscosity, viscosity of the liquid which should always come with the temperature.

Viscosity of the 40 degree centigrade, viscosity of the 100 degree centigrade, viscosity of the 70 degree centigrade. We cannot use we are using a liquid which has a 160 viscosity. That will be wrong interpretation with we will not be knowing whether we are talking about 20 degree centigrade, we are talking about the 40 degree centigrade, we are talking about the 100 degree centigrade or what is the operating temperature at which we are (( )) of the viscosity?

So, I will we will be that when we do calculations find out what viscosity is required and then compare available viscosities. Viscosity of the oils in terms of either 40 degree centigrade or 20 degree centigrade. Generally, when we purchase oil from the market they mention viscosity of oil at some particular temperature. It may be 37.8 degree centigrade it can be 40 degree centigrade also.

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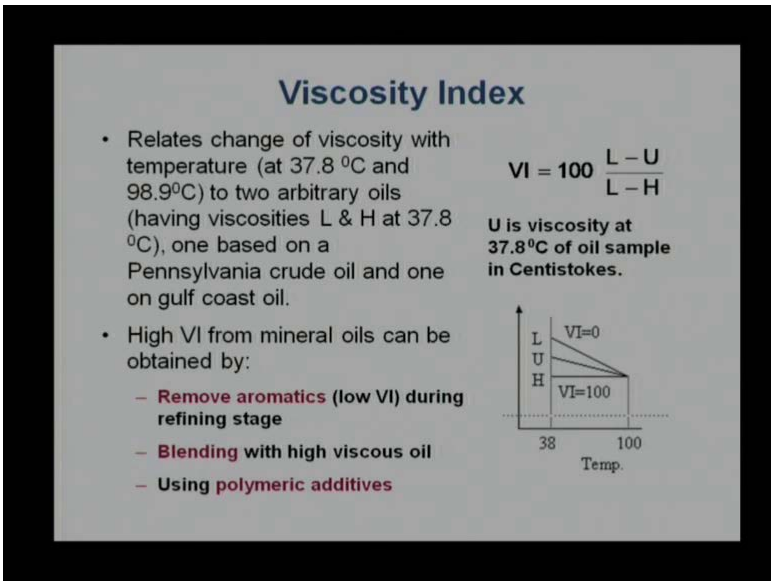

Viscosity Index

- Relates change of viscosity with temperature (at 37.8 ^{0}C and 98.9^{0}C) to two arbitrary oils (having viscosities L & H at 37.8 ^{0}C), one based on a Pennsylvania crude oil and one on gulf coast oil.
- High VI from mineral oils can be obtained by:
  - **Remove aromatics (low VI) during refining stage**
  - **Blending with high viscous oil**
  - **Using polymeric additives**

$$\mathbf{VI = 100\ \frac{L-U}{L-H}}$$

U is viscosity at 37.8^{0}C of oil sample in Centistokes.

To give more emphasis on viscosity index, because it is one of the very important parameter. Generally we say that viscosity index is different, but this relation V I is equal to 100 ratio L minus U divided by N minus H. L is unknown liquid or liquid which we want to find out what is the viscosity index of that. At is the viscosity index of the liquid which is very good viscosity index or liquid is a good from temperature stability point of view. L is having a lowest viscosity index lubricant. Of course, everything is expressed in terms of viscosity.

That this can be explained in simple relation by referring this figure. We are saying that all the liquid whatever the liquid we are choosing liquid corresponding to L, liquid corresponding to U, liquid corresponding to H. They have same viscosity at the 100 degree centigrade. Using the word 100 degree centigrade many times is a confusing because it is generally expressed in fraction which say that 98.9 degree centigrade.

So, these all three liquids have a same viscosity at a 98.9 centigrade temperature, but they have a different viscosity at the lower degree temperature. Here it is written 38, but again that is not right is a fraction is 37.8 degree centigrade. So, here is a U comes somewhere in between L has a lowest viscosity. That is why you can see the more slow power here or the viscosity is changing rapidly with increase in temperature.

Here it is shown the viscosity index equal to 100 for H and the almost the flat line which is also just the hypothetical concept. We know even for viscosity equal to a viscosity index equal to 300. This line will never turn out to be horizontal there will be always some strength.

Just to explain with this concept of the viscosity index we are using the good viscosity H as a viscosity index equal to 100 and that is the flat line or this relation is valid for the viscosity index up to 100. That is started initially, but now we have got a number of lubricants which have very high viscosity index compared to 100.

And this L and H generally referred with two oils, one is bad oil one is a; other one is a good pennsylvania crude oil and a golf crust oil. Generally referred, but every company has its own norms to define when they market they have a different nomenclature. And this a point comes how to get this I V I lubricants?

Say high V I lubricant can be the h c or the we can find using some filtration process or refining process by removing the aromatic component of the from the mineral oils. If we remove aromatic component from the mineral oil will be a getting high V I lubricant. Aromatic generally have more temperature is sensitive that is why we want to; If we remove those additives then it will give very good V I of the mineral oil.

Another thing is that some time we use a blending of the oils, one is having a low viscosity oil or there is a high viscosity oil. At the low temperature or the low viscosity is dominating at the high temperature more viscosity oil will turn out to be thinner. And then it will overall give a more temperature stability or resistance compared to just a low viscosity oil. And finally come at the polymer additives we say that this kind of arrangement is used to find out the multi grade oil. Multi grade oil will be discussed in a few slide after this slide.

So, that if we use the polymer additives which are initially coiled up which are not active which remain inactive at the low temperature. Then it will these additives are not going to increase viscosity of the lubricant.

But as the temperature increases coiled structure turn out to be uncoiled structure and slowly slowly they turn out to be straight lines or we say that they straighten up themselves. What will happen? In that situation surface area will increase. As the surface area is increasing which is going down going to show and more and more resistance towards the flow. That means more and more viscosity of the liquid at why one and mineral oil are losing viscosity other n polymers are adding viscosity. That is why we get more and more stability to all those liquids.

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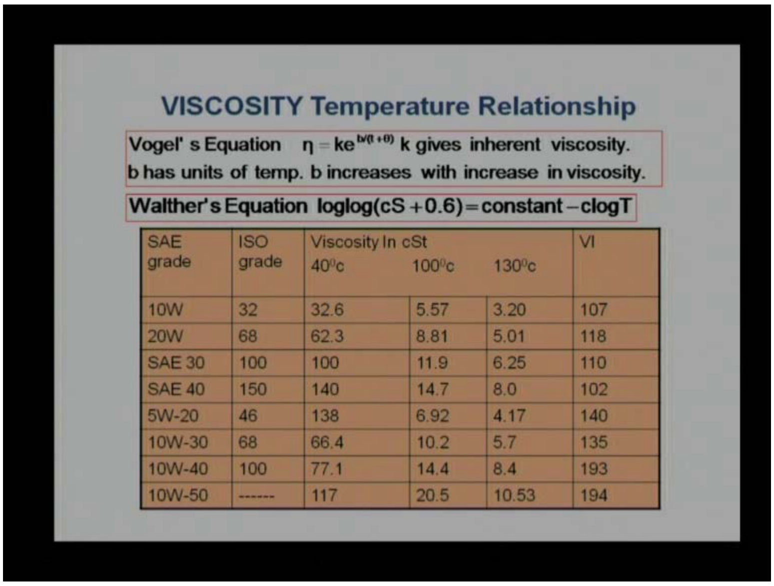

VISCOSITY Temperature Relationship

Vogel' s Equation $\eta = ke^{b/(t+\theta)}$ k gives inherent viscosity.
b has units of temp. b increases with increase in viscosity.

Walther's Equation $\log\log(cS + 0.6) = \text{constant} - c\log T$

SAE grade	ISO grade	Viscosity In cSt 40⁰c	100⁰c	130⁰c	VI
10W	32	32.6	5.57	3.20	107
20W	68	62.3	8.81	5.01	118
SAE 30	100	100	11.9	6.25	110
SAE 40	150	140	14.7	8.0	102
5W-20	46	138	6.92	4.17	140
10W-30	68	66.4	10.2	5.7	135
10W-40	100	77.1	14.4	8.4	193
10W-50	------	117	20.5	10.53	194

And when we try to express his mathematical viscosity and temperature. Two popular relations are available while proven relation what we call the vogels relation, vogels equation. We can say here the dynamic viscosity is given as a eta. Eta is expressed from this in pascal second or millipascal second. There is a constant key and is exponential relation, there is another constant b and constant t. So, either constant t or theta in this we can express one relation in terms of temperature. So, we can say if I assume that t is a temperature when theta is constant.

So, theta is a constant beta is a b is constant, k is constant. They are three constants available in the set this relation and this is a kinematic viscosity relation is a dynamic viscosity relation. While coming to the second relation, what we call as a vogels relation, but before that there is a table shown that if we require to evaluate three constants k b and theta use this kind of table. Viscosity has a 40 degree centigrade is defined, viscosity 100 degree centigrade is defined, viscosity at the 130 degree is defined.

So, we have a three viscosity at three different temperatures. We substitute we will be able to get k, we will be able to get b, we will be able to get theta. Once we know all this three parameter then viscosity between 40 to 130 degree centigrade for any temperature it can be defined by this relation. As I mentioned other relation is walthers relation, which is more popular relation because of the kinematic viscosity and generally viscosity is measured in centistokes and given in a centistokes.

Of course, kinematic viscosity can be converted dynamic viscosity by using density term. To when the viscosity walthers equation is used we can directly use this kind of a parameters.

We say that in the when we want to find out what will be a viscosity of certain temperature? Then we can find out constant, this constant and another constant see here. I can say constant a constant B also. Here can find out the capital t that means it has been expressed in the Kelvin. So, whatever the temperature need to be added with the 273. In this case I if I want to define the viscosity 40 degree centigrade T will be 273 plus 40 degree centigrade and this is centistokes viscosity can be directly substituted.

So, centistokes plus 0.6 some time as relation 0.7 is also used constant A and constant B. So, that means I required in this case only two temperatures and by enlarge in literature we find only two temperature coated by the company. By large it is a 40 degree centigrade and 100 degree centigrade or we say the 100 Fahrenheit and 212 Fahrenheit.

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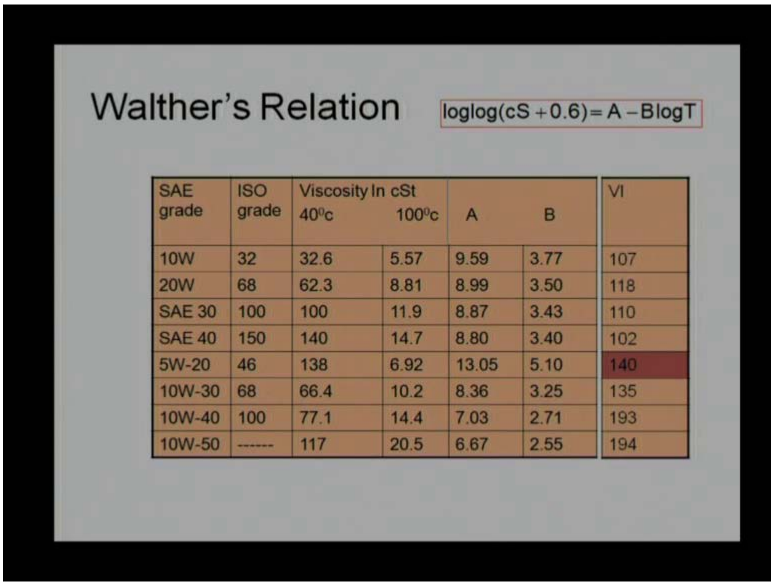

Walther's Relation

$\log\log(cS + 0.6) = A - B\log T$

SAE grade	ISO grade	Viscosity In cSt 40⁰c	100⁰c	A	B	VI
10W	32	32.6	5.57	9.59	3.77	107
20W	68	62.3	8.81	8.99	3.50	118
SAE 30	100	100	11.9	8.87	3.43	110
SAE 40	150	140	14.7	8.80	3.40	102
5W-20	46	138	6.92	13.05	5.10	140
10W-30	68	66.4	10.2	8.36	3.25	135
10W-40	100	77.1	14.4	7.03	2.71	193
10W-50	------	117	20.5	6.67	2.55	194

We use that kind of a relation. We can find out what is the overall gain from this solution. We say this is a relation we are using this case I am assuming constant A and constant B. And for the different oils I am trying to find out what is the value of A and B? Can see a where it can be determined because viscosity at the 40 degree centigrade is defined, viscosity 100 degree centigrade is defined. We substitute here we can evaluate A and B constant.

A constant for the 10 W oil is turning out to be 9.59 while B is 3.77. For 20 W this is a 8.99 and B is a 3.5. We go ahead and find out all the parameters. Then what we can get the result wherever the B value is high. That will be having more temperature sensitivity. That is clear if the value of B is high temperature is given over here. Overall reduction in viscosity will be substantial lesser the value of the B better the results.

So, this is the importance of the walthers relation. We can find out the B and we say or this is the liquid is not showing very good results we should chose a different liquid which has a lesser value of the B. This can be also related with V I index which is generally expressed in this term. We say as the B value is lower, viscosity is index is high we say the 2.55 viscosity and it is 194. 2.71 slightly more than this value viscosity index is reduced. Then higher value this is reduced.

However, the one value it is says 140 and B value is 5.0. This clearly indicate the whatever the data quoted are wrong. I can compare any of these two data let us a example of viscosity index 102 that the viscosity of 40 degree centigrade is defined as a 140 and viscosity of the 5 W 20 is defined 138 not very much variation. That is in tolerance range. However, variation comes over here 100 degree centigrade with the viscosity of the S A E 40 it is turning out to be 14.7 high viscosity. While for 5 W 20 it is turning out to be 6.92. There is a substantial decrease.

This viscosity is lesser than half of this viscosity. So, that is a wrong data we say that this viscosity index is need to be higher compared to this viscosity index. So, when we do this kind of a calculation we figure out yes something is wrong over here B is 5.10 substantially high and this is just 3.4. And still we are saying that this has a viscosity index of 140. That means, some sort of miss misprint is coming or some mistake is been made when the data work quoted.

So, this is what utility of the walthers relation will continue with viscosity discussion in our next lecture. Thanks for your attention.