Chemical Process Instrumentation
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Lecture – 54
Miscellaneous Measurements: Composition (Contd.)

Welcome to lecture 54, this week we are talking about Miscellaneous Measurements. In today's lecture we will talk about measurement of viscosity, viscosity is an important fluid property it plays a major role in fluid flow phenomena, we associate viscosity with a fluids internal resistance to flow, let us say we talk about fluids such as water, air, kerosene, we know from our everyday experience that these fluids are easy flowing fluids.

So, they have less internal resistance to flow, their viscosity is low, we call this fluids as thin fluid commonly. On the other hand let us consider about honey, it offers more internal resistance to flow is viscosity is high we call it thick fluid. So, the viscosity is associated with fluids internal resistance to flow, in today's lecture, we will learn certain measurement procedure to measure viscosity of fluids.

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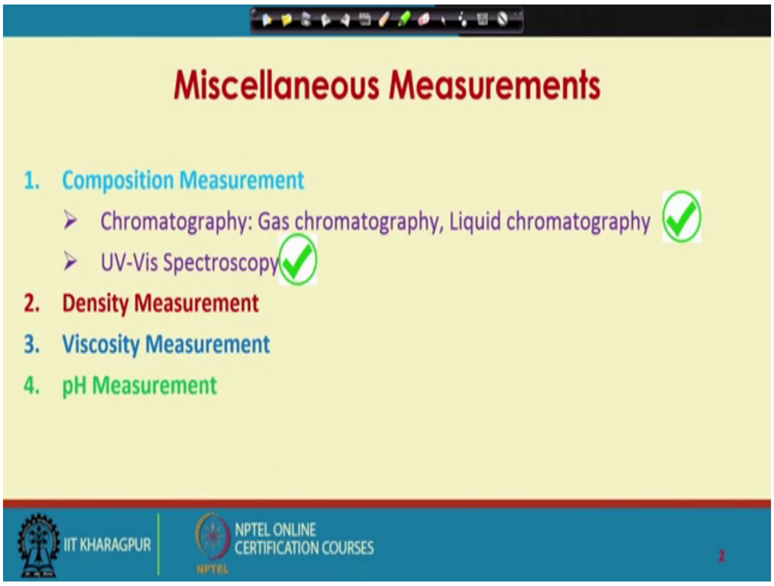

We have already talked about composition measurement by chromatography an UV Vis spectrophotometer.

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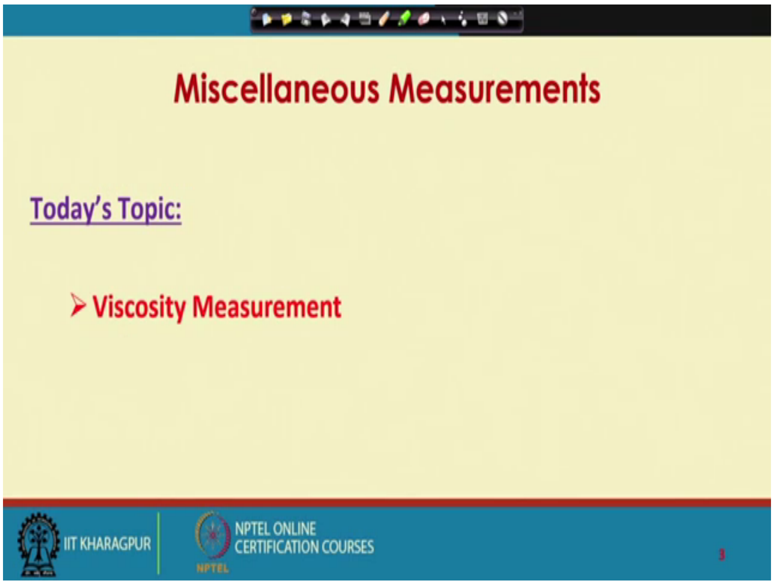

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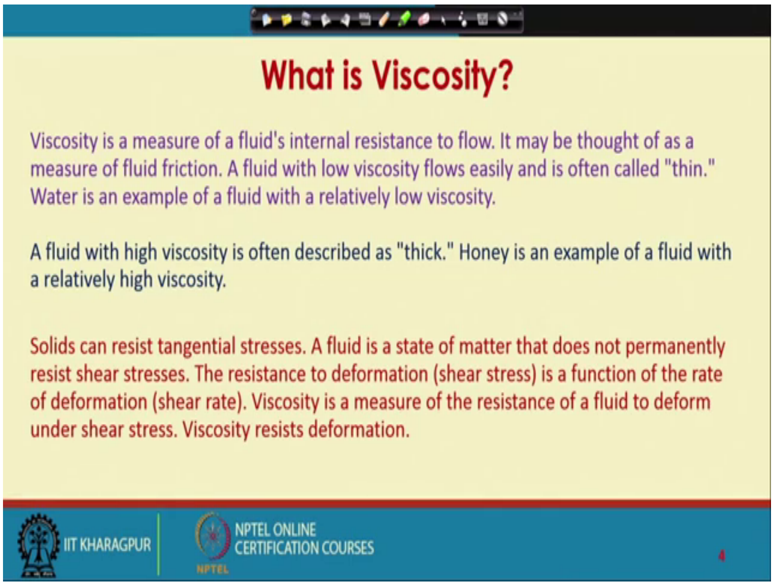

So, today we talk about viscosity measurement; solids can resist tangential stresses, but a fluid is a state of matter that does not permanently resist shear stresses. So, this is an example between solid and fluids, solids will offer resistance to tangential stresses, but fluids does not permanently resist shear stresses, there will be deformation of the fluid, when you apply shear stresses and the fluid will flow. The resistance to deformation or shear stress is the function of the rate of deformation, or shear rate viscosity is the measure of the resistance of a fluid to deform under shear stress, viscosity resist deformation.

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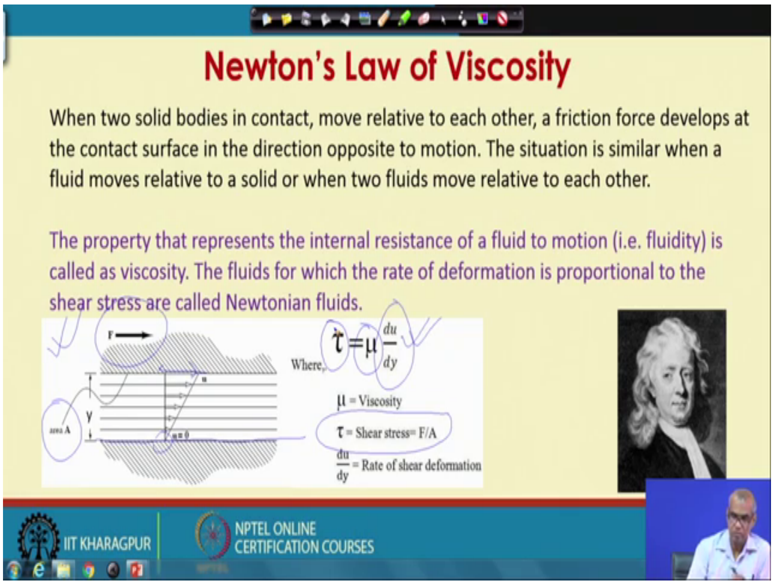

When two solid bodies are in contact and they move relative to each other a friction force develops at the contact surface in the direction opposite to motion the situation is similar, when a fluid moves relative to a solid or when two fluids move relative to each other suppose two fluids move in relative to each other or one fluid is moving on a stationary plate.

The property that presence the internal resistance of a fluid to a motion that is fluidity is called as viscosity. The fluids for which the rate of deformation is proportional to the shear stress are called Newtonian fluids. So, the Newtonian fluids are those fluids for which the rate of deformation is proportional to the shear stress, if you look at the figure a fluid flows, let us say over this plate. The velocity of the fluid elements that is in contact with this plate here is 0 and the fluid velocity in physics as we go up in the y direction and it becomes let us say u here. So, the velocity gradients is du dy. The shear stress is f by a where f is the force applied and A is the area. So, the shear stress is proportional to the velocity gradient, if the fluid is Newtonian fluid and the proportionality constant is the viscosity new.

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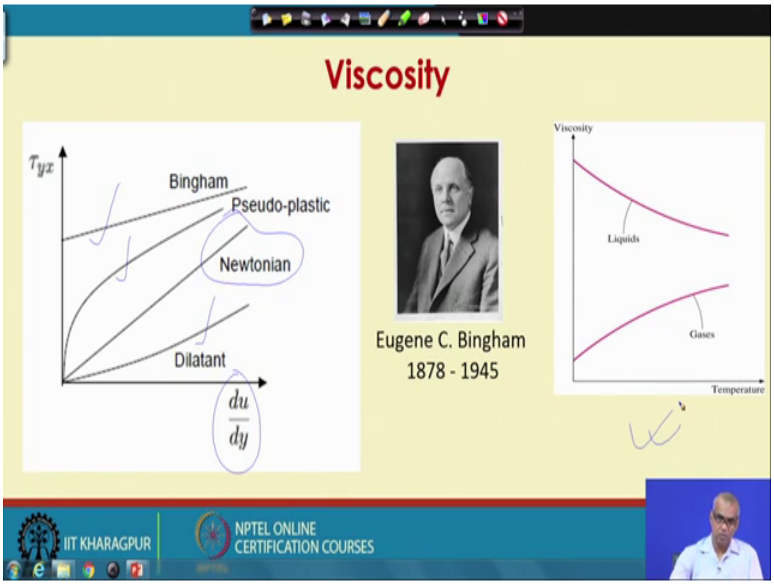

Here you can see how shear stress, changes with velocity gradient for different types of fluids, as we have just seen in our previous slide, that shear stress is proportional to the velocity gradient, or rate of shear deformation, we will accept that we will obtain a straight line, if I plot shear stress verses du dy, or rate of shear deformation or velocity gradient. So, this is what we get for Newtonian fluid shear stress and du dy as a linear relationship, this type of relationship is known as dilatants fluid this is known as Pseudo plastic, they are non Newtonian fluids and, this is Bingham fluids this figure shows you how viscosity changes with temperature for liquids and gases. From our common experience we know that viscosity of a liquid decreases if you increase temperature, but the viscosity of the gases generally increases with increase in temperature.

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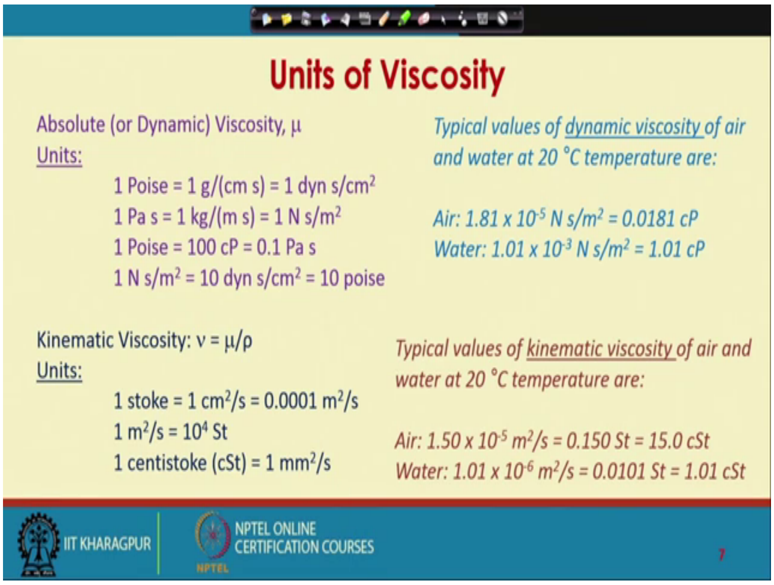

The absolute or the dynamic viscosity which is commonly represented by the symbol mu has the following units, poise Pascal seconds Newton seconds per meter square. The relationships are given 1 poise equal to 1 gram per centimeter second equal to 1 dyn seconds per centimeter square, 1 Pascal second is 1 kg per meter second is equal to 1 Newton second per meter square, 1 poise is equal to 100 centipoise or 0.1 Pascal second, 1 Newton second per meter square is 10 dyn second per centimeter square equal to 10 poise, there is another term known as kinematic viscosity which is nothing, but dynamic viscosity of the fluid divided by density of the fluid.

So, it is commonly represented by the symbol nu. So, nu equal to mu by row. The units for the kinematic viscosities are stoke meter square per second centistokes etcetera, 1 stoke is 1 centimeter square per second which is 0.0001 meter square per second, 1 meter square per second is 10 to the power 4 1 centistokes is 1 millimeter square per second.

Here we report some typical values of dynamic viscosities and, we have taken example of air and water at 20 degree Celsius temperature. The dynamic viscosity of air at 20 degree Celsius is about 1.81 into 10 to the power minus 5 Newton second per meter square, which is 0.0181 centipoises for water dynamic viscosity 1.01 into 10 to the power minus 3 Newton second per meter square, which is same as 1.01 centipoises. The typical values of kinematic viscosity of air at 20 degree Celsius is 1.50 into 10 to the power minus 5 meter square per second, which is same as 0.150 stokes, which same as 15 centi stokes. For water the kinematic viscosity at 20 degree Celsius is about 1.01 into

10 to the power minus 6 meter square per second, which is equal to 0.0101 stokes which is same as 1.01 centi stokes.

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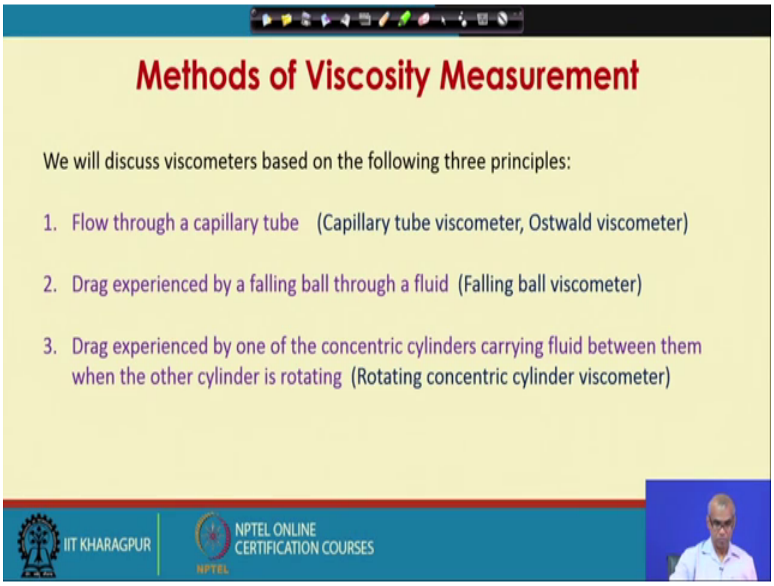

Now in today's lecture we will discuss viscosity measurements based on three different principles. The instruments that are used for measurement of viscosity can be commonly said as viscometers. So, we will talk about three different types of viscometers, which are based on the following principle. First flow through a capillary tube, viscosity can be measured by doing an experiment, where you make the liquid flow through a capillary, then from pressure drop measurement we will be able to calculate viscosity by making use of Hagen Poiseuille equation.

We will talk about capillarity of viscometer and also always committed under this category. Viscosity can also be measured by doing an experiment, where the drag is experienced by a falling ball through a fluid and, we will talk about falling ball viscometer under this category finally, viscosity can also be measured by doing an experiment, where drag is experienced by one of the concentric cylinders carrying fluid between them when the other cylinder is rotating.

So, there will be two concentric cylinders and, the fluid is viscosity will be measured will be taken in between one cylinder will be stationary other will be rotating and, the drag experienced by one of the cylinders can be used to compute viscosity. We will talk about rotating concentric cylinder viscometer.

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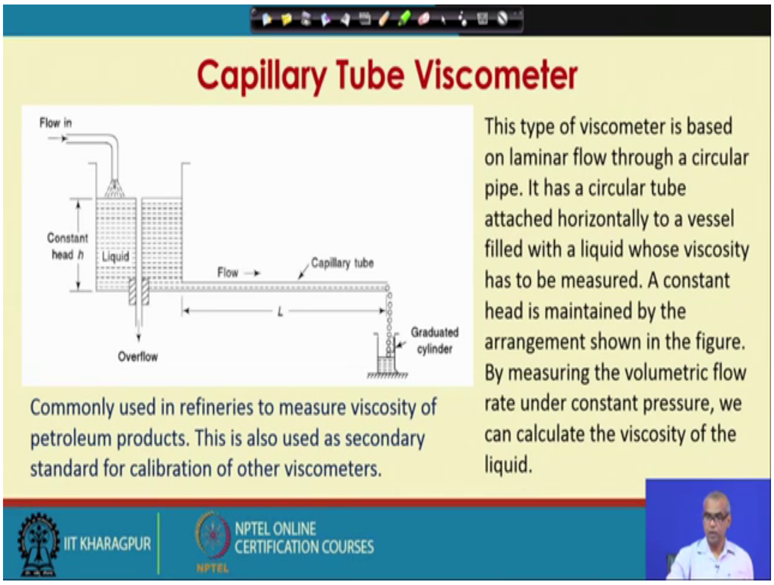

Let us first talk about capillary tube viscometer. The capillary tube viscometer is commonly used in refineries to measure viscosity of petroleum products. This is also used as secondary standard for calibration of other viscometers.

Capillary viscometer is a very simplified method of computing viscosity or calculating viscosity, the experimental setup is very simple and, it can be easily set up in the laboratory. So, it basically consists of a tank, or a container where you take the liquid whose viscosity needs to be measured, you have to maintain a constant head and you can see in the diagram how the constant head is being measured.

So, we have flow in here and the overflow goes out from here. So, this head is always maintained constant, a capillary tube is attached here the length of the capillary tube and the diameter is known. And the liquid flows through the capillary tube and, I can measure the volumetric flow rate here, it can be done easily with help of a graduated cylinder. So, we collect the amount of fluid for a given amount of time and then you can compute the volumetric flow rate.

Once you have this information about the volumetric flow rate, the length of the capillary tube, the diameter of the capillary tube, as well as the pressure constant head, you can compute viscosity using again Poiseuille equation. So, capillary viscometer is based on laminar flow through a circular pipe, it has a circular tube attached horizontally to a vessel filled with a liquid whose viscosity has to be measured. A constant head is maintained by the arrangement shown in the figure, by measuring the volumetric flow rate under constant pressure, we can calculate the viscosity of the liquid.

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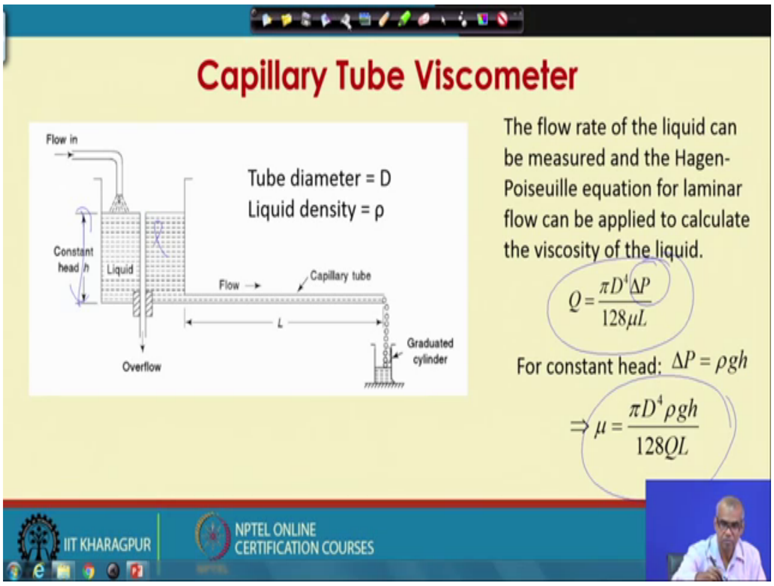

Let us consider the tube diameter is D and the liquid density is rho, the length of the capillary tube is L. The flow rate of the liquid can be measured and the Hagen Poiseuille equation for laminar flow can be applied to calculate viscosity of the liquid. If you recollect the Hagen Poiseuille equation is Q which is volumetric flow rate equal to pi D to the power 4 into delta P, which is pressure drop divided by 128 mu into l where mu is the viscosity.

We are maintaining constant height in our experiments. So, delta P is rho g h, where rho is the density of this liquid g is the acceleration due to gravity. And h is this constant head. So, delta P is rho g h. So, put delta P equal to rho g h in this expression and, then rearrange you will get the expression of viscosity as mu equal to pi D to the power 4 rho gh divided by 128 Q into L please be consistent with the units in the expression.

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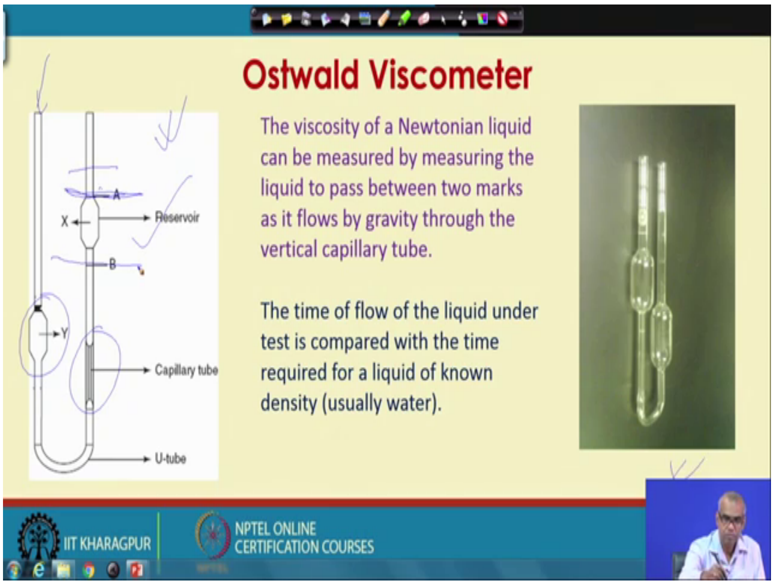

Next we talk about Ostwald viscometer. This is a schematic of an Ostwald viscometer and, this is a real image a photograph of Ostwald viscometer. The viscosity of a Newtonian liquid can be measured by measuring the liquid to pass between 2 marks as it flows by gravity through the vertical capillary tube. So, basically the all viscometer consists of a reservoir, it consists of a capillary tube, it also consists of another bulb layer which can access reservoir.

So, what you do is you take liquid whose viscosity needs to be measured and, you can suck the liquid so, that it comes above the mark a let us say it comes here, then you allow the liquid to pass through this capillary under gravity, when it comes here when the liquid level comes here at the mark A, you start counting the time. So, let us start a stopwatch, when the liquid comes at mark A and you stop the stopwatch, when liquid reaches the mark B and determine the time the fluid takes to pass through between mark A and mark B.

From the time the liquid takes to flow through this capillary, we can compute the viscosity.

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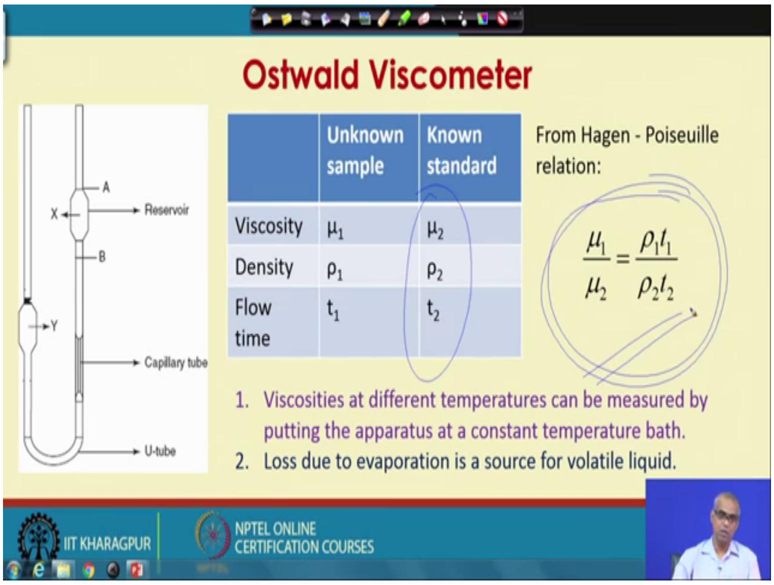

What we do is we will first do an experiment with a known standard; that means, the liquid whose viscosity is known, then by comparing the results for an unknown sample we can compute the viscosity. If we use Hagen Poiseuille equation, you can write down this expression, where I take say an unknown sample whose viscosity is mu 1 density is rho 1 and the time required to flow between mark A and mark B is t 1.

Now, I take another sample whose density whose viscosity is known; let us say I take water. So, I know is this density I know it is viscosity let us say these values are mu 2 rho 2. And let us say the standard takes time t 2, for flowing between mark A and mark B, then I can write mu 1 by mu 2 equal to rho 1 t 1 by rho 2 t 2. So, since I know these quantities for the standard, if I know the density of the liquid whose viscosity I am measuring I can compute the viscosity.

Also the kinematic viscosity can also be obtained directly because, mu 1 by rho 1 is kinematic viscosity. So, viscosity is at different temperatures can be measured by putting the apparatus at a constant temperature bath, it is possible to measure the viscosity is a different temperatures by putting the apparatus at constant temperature, but there may be one source of error due to loss of evaporation, due to loss of liquid due to evaporation.

So, you have to be careful while measuring the viscosity of a liquid which is highly volatile, it should be actually avoided because, it may take some time for the liquid to pass through mark between mark A and mark B.

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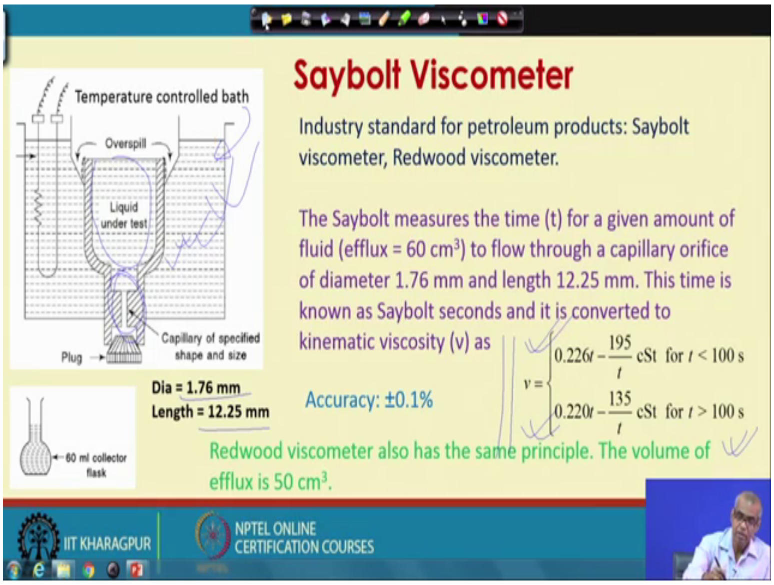

Next let us talk about say bolt viscometer. In fact, say bolt viscometer is an industry standard for petroleum products. Similar to say bolt viscometer there is another viscometer known as redwood viscometer.

Basically both were using the same principle, the say bolt measures the time t for a given amount of fluid to flow through a capillary orifice of diameter 1.76 millimeter and length 12.25 millimeter, this time is known as say bolt seconds and, it is converted to kinetic viscosity using certain empirical equations. So, look at the schematic for a say bolt viscometer. So, it basically consists of a liquid holder.

So, you have the liquid here and you have a capillary of specific shape and size meaning, you have a capillary of specific length and specific diameter, a known amount of liquid will be allowed to flow through this capillary and, the time required for this flow will be noted this time is known as say bolt time. Then this say bolt time which is expressed as say bolt seconds, time is noted in seconds and this is known this time is known as say bolt seconds, this say bolt seconds is converted to kinematic viscosity using certain empirical equations.

For say bolt viscometer the given amount of fluid that we are talking about which is known as a efflux is 60 centimeter cube. So, for several visco meter a 60 centimeter cube of liquid is allowed to flow, through this through a capillary which has length 12.25 millimeter and diameter 1.76 millimeter. And you note down the time required for the flow, this is known as say bolt seconds and then say bolt seconds is converted to kinematic viscosity in the units of centi strokes using this equation or this equation.

You use the first equation; that means, mu equal to 0.2 to 60 by 195 by t centistokes, if time t is less than 100 seconds and, if it is more than that you use the second equation, the say bolt viscometer accuracy is quite high plus minus 0.1 percent, the red wood viscometer also uses the same principle, instead of 60 centimeter cube liquid here the efflux is 50 centimeter cube.

So, in case of redwood viscometer 50 centimeter cube of liquid will be allowed to pass through the capillary, and you again measure the time of flow, note how the say bolt viscometer can be used to measure viscosity at different temperatures, by putting the viscometer in a constant temperature, but. So, this is this is a temperature control, but whose temperature can be measured accurately and controlled accurately. So, you put the say bolt viscometer in this water berg and, you can measure the viscosity of the liquid at different temperatures.

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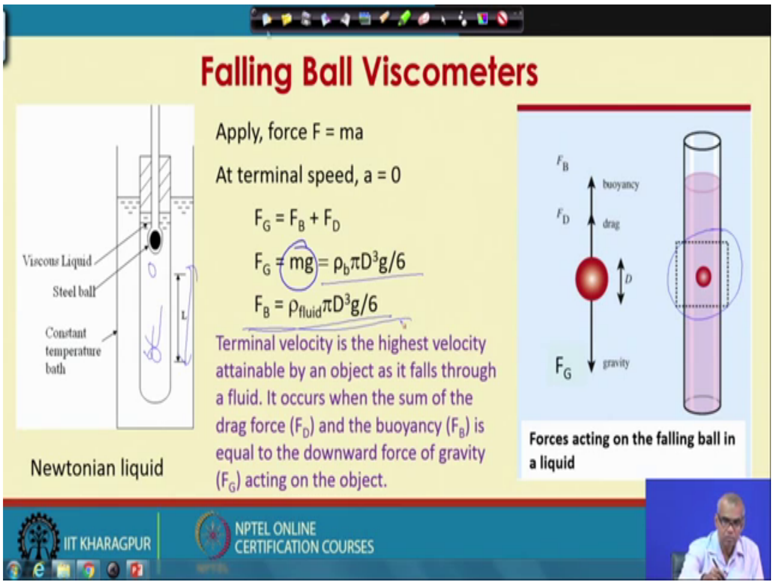

Next, let us talk about falling ball viscometers, falling ball viscometers is another simple setup for measuring viscosity, we are measuring viscosity of Newtonian liquid, here what you do is, you have taken liquid let us say in this tube. Let us consider you have taken a ball let us say made of steel in this liquid you have taken a tube, you have to and you have taken the liquid whose viscosity, you want to measure in this liquid in this tube, this tube can be put in a constant temperature bath.

So, that you are measuring viscosity at a specific temperature, then a steel ball or a ball metal ball is put into this liquid content in the tube. Now when the ball which is falling due to gravity, will attain terminal speed, I will measure the time taken by the ball to cover a specific distance let us say this distance is L. So, let us say when the ball comes here it attains terminal velocity and, I will consider the fall of this ball over this distance length and measure the time taken by the ball to cover this distance from that I will be able to compute the viscosity.

So, consider the ball which is falling with terminal velocity. Now let us look at all the look at all the forces that are acting on the ball, you know force f equal to mass into acceleration, when the ball reaches terminal speed acceleration equal to 0, the forces that are acting on the ball, the gravitational force which is acting downward, the buoyancy force which is acting upward and the drag force which is again acting upward.

The gravitational force is nothing, but the mass of the ball. So, which can be written as rho being pi D cube g by 6, where D is the diameter of the ball and rho B is the density of the material of the ball buoyancy force can be computed as density of the fluid into pi D cube g by 6. So, mass of the liquid displaced by the ball, which is basically equivalent to the volume of the same volume of the liquid so, volume of the ball that much of volume of liquid will be displaced. So, weight of that much of the liquid from that you can compute the buoyancy force.

The terminal velocity is the highest velocity attainable by an object as it falls through a fluid, it occurs when the sum of the drag force and, the buoyancy force is equal to the downward force of gravity acting on the object. So, we have seen expression for gravitational force and buoyancy force.

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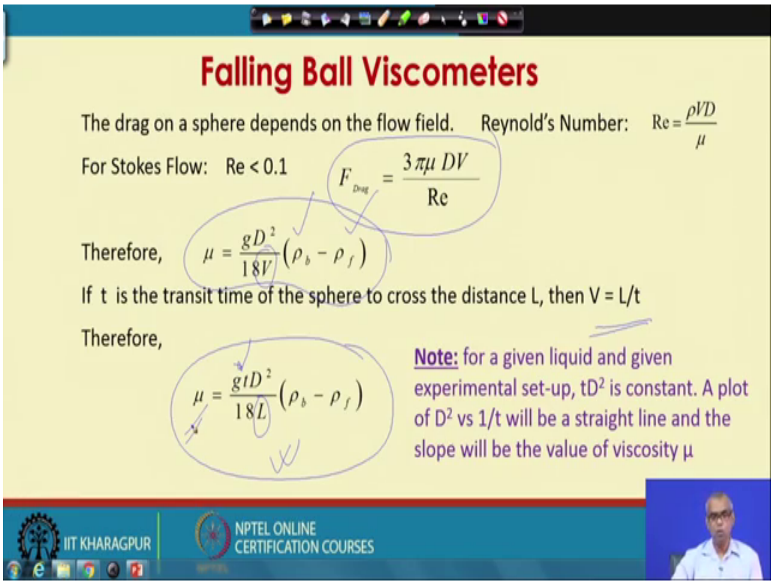

Now let us look at the drag force. The drag force on a sphere will depend on the flow field. So, it depends on the Reynolds number Reynolds number you know, it is DV rho by mu for stokes low Reynolds number is less than point 1 and the drag force can be written as 3 pi mu DV divided by Reynolds number, where mu is the viscosity of the fluid D is the diameter of the ball and V is the velocity of the ball.

So, now comparing combining all this drag force buoyancy force and the gravitational force, I can compute viscosity as g D square divided by 18 V into density of the ball minus density of the fluid. So, this is density of the ball this is density of the fluid. So, this you can obtain once you combine 3 expression for the 3 forces buoyancy force drag force and gravitational force. If the time taken by the sphere to cross the distance L is t then the velocity V is L by t.

So, I can put V equal to L by t and if I do that I get the final expression for viscosity mu as g t D square divided by 18 L into density of ball minus density of fluid. So, by measuring the time taken by the ball to cover a distance , when the ball reaches terminal velocity I can compute viscosity of course, I should know the density of the ball and density of the fluid. So, for a given liquid and given experimental setup t into D square is constant according to this expression. So, a plot of D square by 1 by t will in a straight line and the slope will give you the value of the viscosity.

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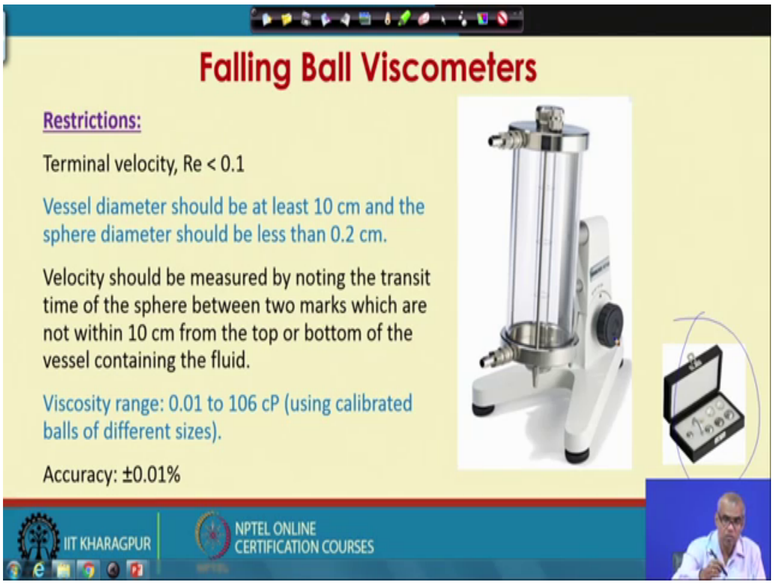

So, there is commercially available falling ball viscometers an image is shown different types of balls are available. So, that will change the ray scan, we must do the experiment when the ball reaches terminal velocity Reynolds number less than 0.1 vessel diameter should be at least 10 centimeter and, the sphere diameter should be less than 0.2 centimeter velocity, should be measured by noting the transit time of the sphere between two marks which are not within 10 centimeter from the top or bottom of the vessel containing the fluid. Viscosity range is 0.01 to 106 centipoise using calibrated balls of different sizes, accuracy is quite high 0.01 percent.

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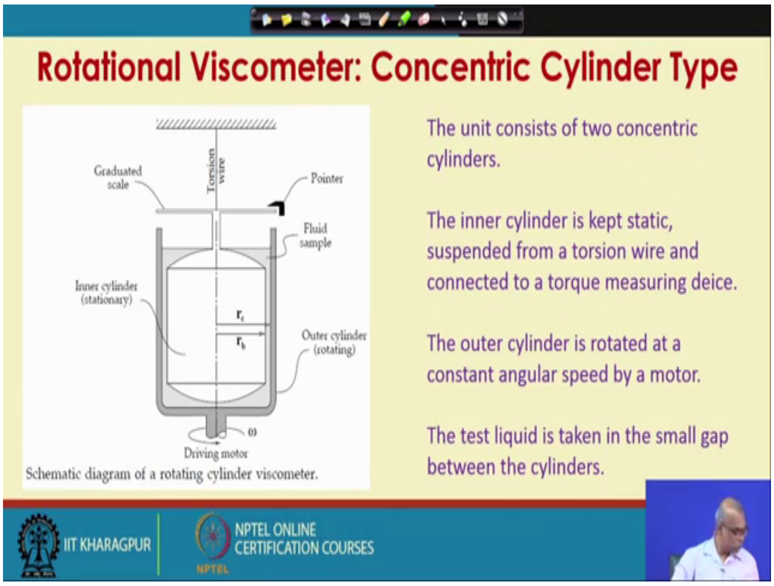

Next let us quickly look at rotational viscometers; we will talk about two one is concentric cylinder type. As the figure shows the concentric cylinder type is viscometer consists of two concentric cylinders, the inner cylinder is kept static suspended from a torsion where and connected to a top measuring device, the outer cylinder is rotated at a constant angular speed by a motor the test liquid is taken in the small gap between the cylinders. So, inner cylinder is stationary connected to a torsion wire and a torsion measuring device the outer cylinder will be rotating. And, it is rotated by a motor and the test sample test liquid whose viscosity, I am measuring is taken in the gap between these two cylinders.

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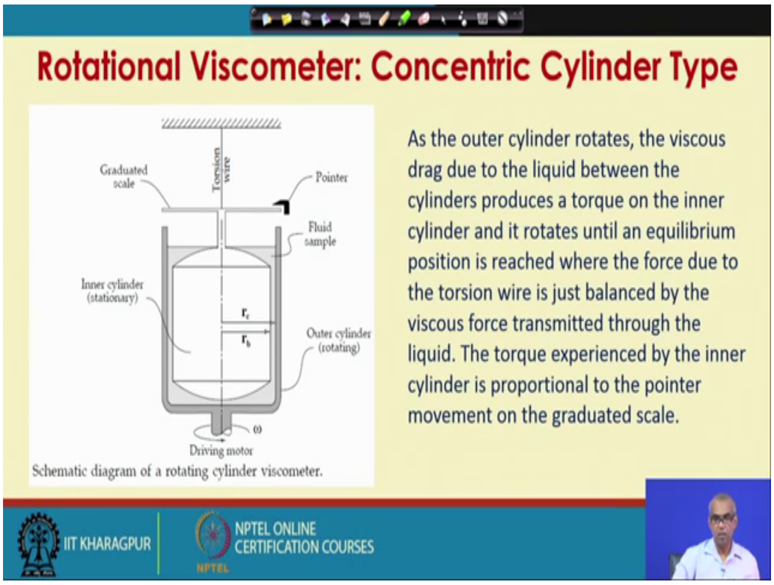

As the outer cylinder rotates the viscous drag due to the liquid between the cylinders produces a torque on the inner cylinder and, it rotates until an equilibrium position is reached, when the force due to the torsion where is just balanced by the viscous force transmitted through the liquid.

The torque experienced by the inner cylinder is proportional to the pointer movement on the graduated scale. So, as the outer cylinder rotates the inner cylinder experience a torque that is proportional to the viscosity of the liquid.

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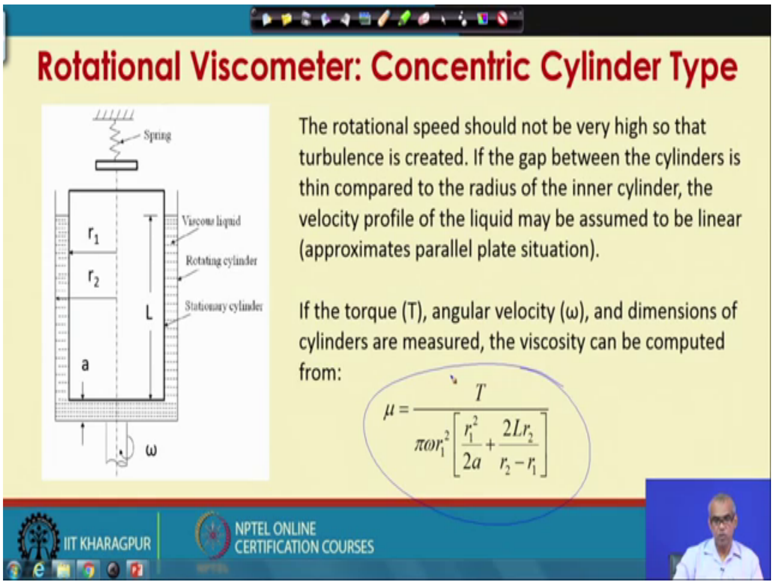

The rotational speed should not be very high. So, that turbulence is created if the gap between the cylinders is thin compared to the radius of the inner cylinder, the velocity profile of the liquid may be assumed to be linear basically it approximates parallel plate situation.

Under such circumstances if the torque is T the angular velocity is omega and the dimensions of the cylinders are measured the viscosity can be computed as this. So, viscosity is proportional to torque here r 1 is the radius of the inner cylinder r 1 is the radius of the outer cylinder, a is this gap between the inner cylinder and the outer cylinder and L is this length here, you have the test liquid is viscosity we are measuring.

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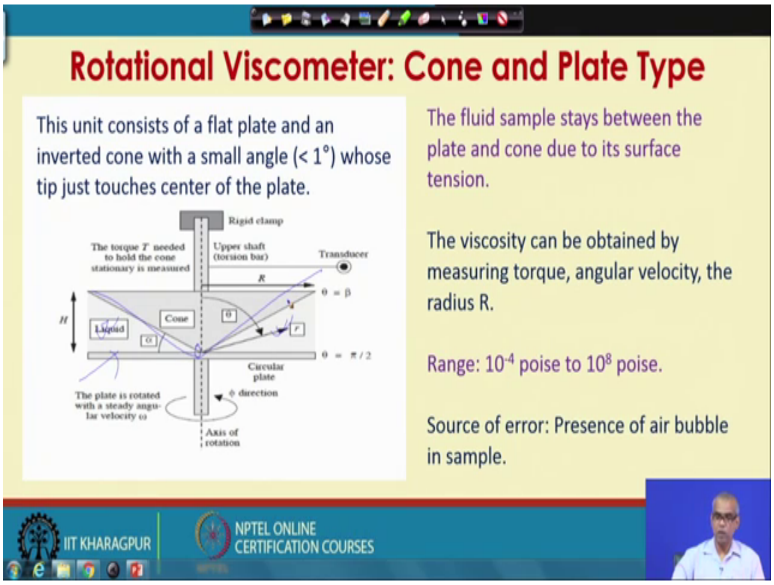

Finally, we will talk about rotational viscometer cone and plate type, cone and plate type rotational viscometer. This unit consists of a flat plate and an inverted cone with a small angle less than 1 degree who steep just touches center of the plate. So, you have a flat plate, you have a flat plate and you have an inverted cone whose tip just touches the center of the plate. The fluid sample is taken here between the flat plate and the inverted cone, the fluid sample stays there between this plate and the cone due to it is surface tension.

The viscosity can be obtained by measuring torque, angular velocity and the radius R. So, again the viscosity can be obtained by measuring torque and of course, it also requires the knowledge of angular velocity and the dimension of the cone that is the radius of the arc. The range of the viscosity that can be covered is 10 to the power minus 4 poise to 10 to the power 8 poise; there is a source of error presence of air bubble in the sample. So, this completes our discussion on viscosity measurement.