Cellular Biophysics
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Viscosity

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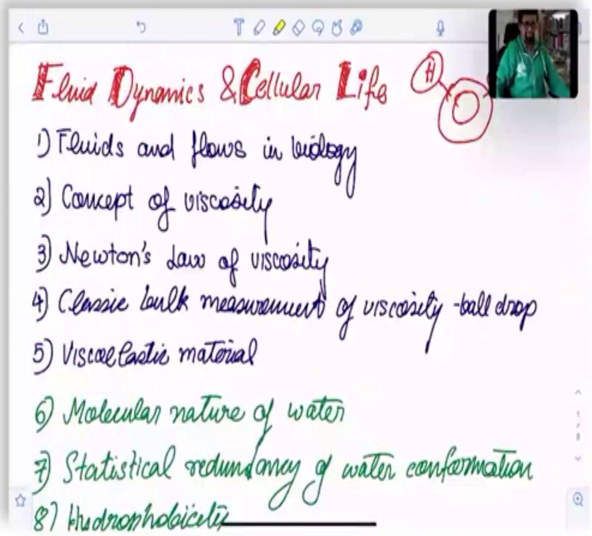

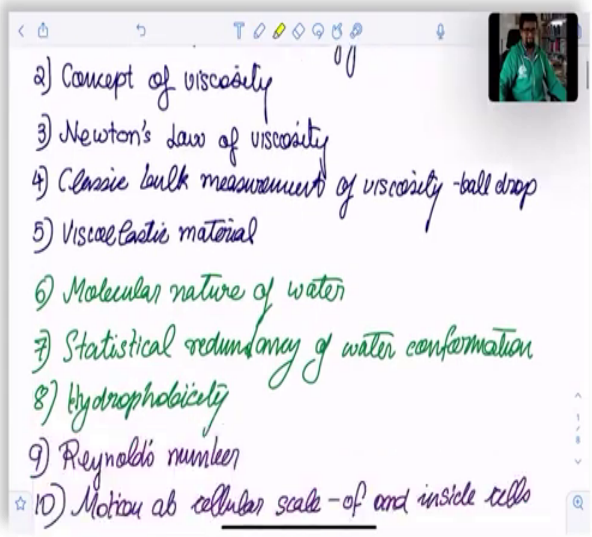

Hi, welcome back. We are going to talk in the coming few lectures about a whole bunch of exciting things relating to fluid dynamics and cellular life and we are going to start with the concept of viscosity. Already in the previous lecture, you heard about fluids and flows in the, in biology and their relevance.

And in the coming lectures we are talking about the concept of viscosity, Newton's law of viscosity and classic bulk measurements viscosity, I mentioned something called the ball drop experiment. We will end this segment with a brief discussion about viscoelastic materials and in future, I hope you will see some exciting demonstrations. So, let us get to it.

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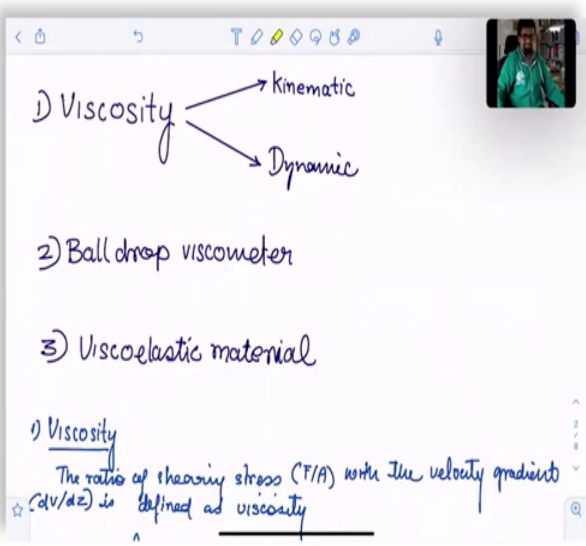

Viscosity as such can be considered in terms of kinematic and dynamic viscosity and the ball drop viscometer is a standard physical measurement that is used to measure bulk viscosity. And viscoelastic materials are a category of materials that we see very often in biology, so we are going to talk about them.

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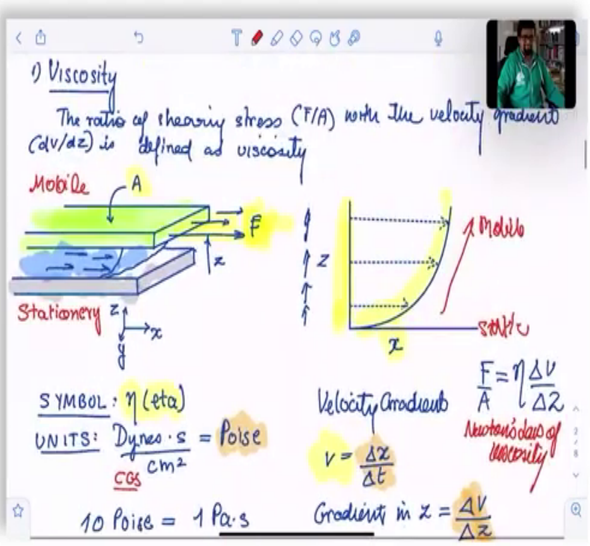

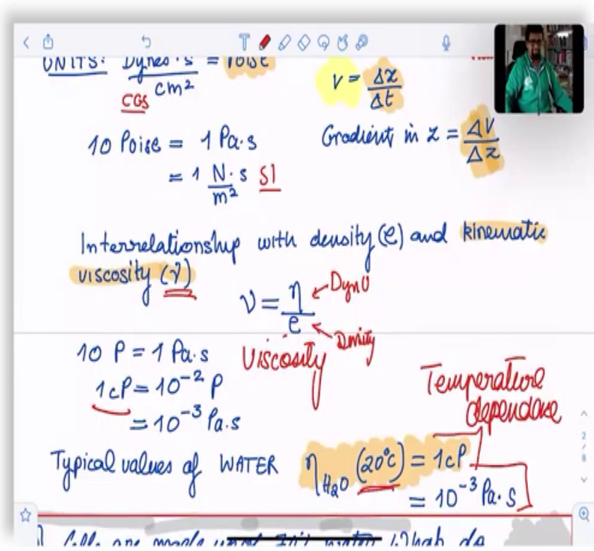

So as such, the viscosity itself is defined and we did as a colloquial definition last time if you remember, ‘as the ratio of sharing stress F by A with the velocity gradient dv by dz. If you remember this was idea of two plates, a parallel plate, one that is stationary and one that is moving. This one is stationary and this is mobile.

And the mobility is what creates the shear, it is like when you slide two plates one past the other you create a friction and if the fluid is in between those two plates then you create this kind of deformation. And we know from high school physics that our velocity as a, from the displacement and velocity as a function of z position will increase.

So, the further we are from the static plate faster the motion is, when we are closest to the moving plate, we are moving the fastest. So, this velocity gradient is given by this expression here

$$V = \frac{\Delta x}{\Delta t}$$

What is x, change in x position that is over here, and time is just your change in time. Now, v itself, meaning to say the velocity itself changes as we go upwards in this direction, away from the static to the mobile plate.

So, when we do that, then we are expecting that the velocity itself has a gradient in z and z being the position away from the static plate. The proportionality constant that connects the stress that is to say the force by unit area f by A, where F is the force driving the moving plate, this one here, and A is the area of the plate that is being moved, the mobile plate, then F by a is proportionally related to Δv by Δz by a proportionality constant, which is called viscosity. And this is nothing but Newton's law of velocity.

What are the units? It is a physical quantity so we must obviously define the units and the symbol. So, the symbol that is typically used in physics is eta, this is the Greek letter η, and the units can be in CGS units,

$$Poise = \frac{Dynes\,.\,s}{cm^2} = \frac{N\,.\,s}{m^2}$$

Dynes times seconds per centimeter square which is also defined as Poise in honor of a scientist who came up with many of the basic concepts of viscosity. But we also know that a Poise can be related to SI units through a factor of 10.

So, 10 Poise make 1 Pascal second, Pascal as you remember is newton per meter square, newton and meter are SI versions of the same units that we discussed earlier. These are CGS. Remember the difference between units and dimensions and we will return to this in a bit. But in addition, so what we are defining as η is nothing but the dynamic viscosity, η is the dynamic viscosity.

There is another term which is called kinematic viscosity represented by the symbol ν, which is here and kinematic viscosity is defined as

$$\nu = \frac{\eta}{\rho}$$

the dynamic viscosity divided by ρ, rho is nothing but density. And many of you may have studied some of these concepts earlier, but you will see in a little bit in the next few lecture modules that we use this term nu quite frequently.

The relationship between units in viscosity we said our Pascal second or 10 Poise, but the most frequently found number for a viscosity that we will be concerned with, because it relates to biological materials and remember we started with this motivation that biological materials are mostly made up of water is the viscosity of water. What is the viscosity of water? And this question we will try to address in a couple of other ways.

Suffice to say that 1 centipoise is considered to be a reasonable number, the fun part about viscosity is that there is a temperature dependence, which means that when we report viscosity we cannot just say the viscosity is 1 centipoise or 10^{-3} Pascal.second, we must also say at what temperature this was measured and this measurement of 1 centipoise or 10^{-3} Pascal.second is a value reported at 20 ℃

So, just to recap viscosity is the proportionality constant between the stress and the velocity gradient, and the units in CGS are Dynes centimeter, per centimeter square times second, which is also written as Poise and SI units are Pascal second. 10^{-3}, one thousandth of a Pascal second is the approximate, is the viscosity of water at 20 ℃ or 1 centipoise.

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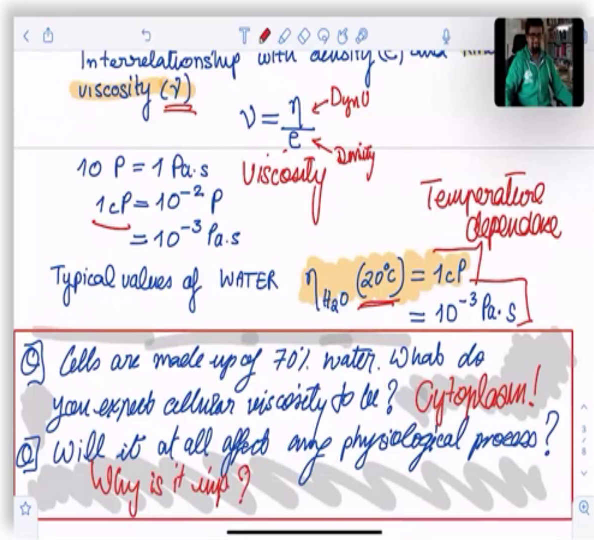

So, I have a question for you and I am going to return to this question at a later time, but the question is cells are made up of 70 percent water, what do we then expect the cellular viscosity to be, in other words the cytoplasm, what is the viscosity of the cytoplasm. Now, this may seem like a very physicist's approach to the question.

But you know the foundations of modern molecular biology were laid by Watson, Crick and Franklin; and of these three people Crick continued to do a lot of productive research in a slightly different area from what he was working on and he after he had elucidated the structure of DNA along with his co-workers.

And one of the questions he asked and answered was ‘what is the cytoplasmic viscosity’. And this is fascinating for me because in a way these are some slightly less known facts and more ignored facts about the foundations of modern biology. Now, the next question, once you have a measurement, because otherwise it is just a number, remember, will it at all affect any physiological process, does it help us?

Why is it important? Why is it important at all to know the viscosity of cytoplasm? And we will discuss some of these in the subsequent parts when we come to the part about macromolecular crowding. So, two questions, keep it in mind, cells are made of 70 percent, what do you expect cellular viscosity to be, please read, please try to find out, and what will it affect the physiological processes.

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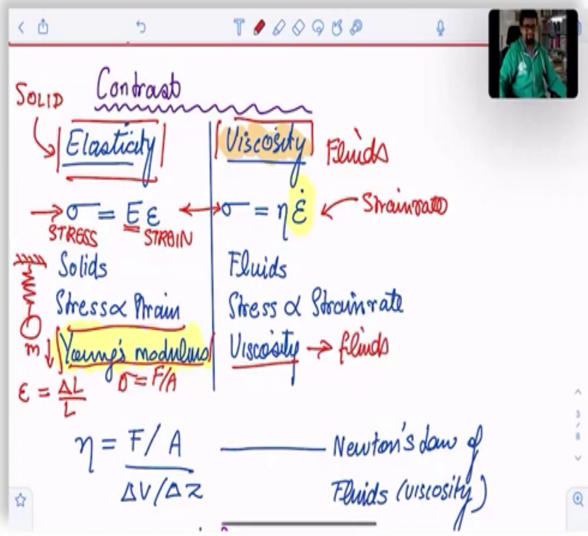

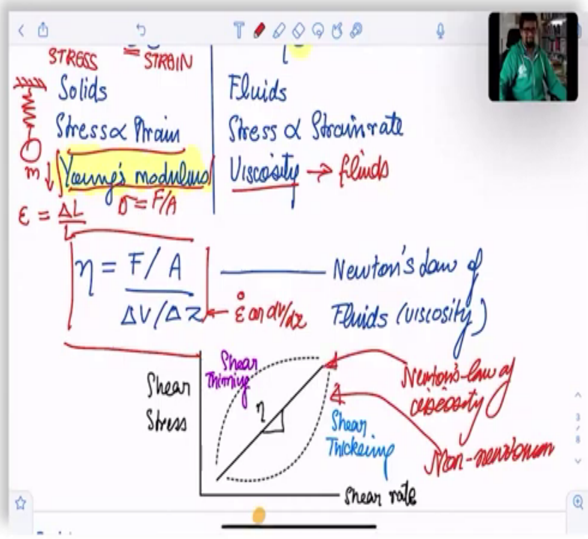

Now, when we talk about solids and fluids and I remember last time I mentioned to you in the previous lecture about solids being different from liquids. We can write down a simple equation which expresses this key difference. Now, for those of you remember high school physics, you remember that for solids we considered elasticity of simple solids to be a governing property, meaning to say if you deform them they change to a certain degree.

This relationship is exemplified by the expression of the stress, this is stress, it is not what you feel before exams, I think there is some person who talks about Shiksha, Pariksha, something coaching about how to do exams, this stress is mechanical stress and this is strain. Yes, strain is again not the strain you feel when you are, when you are asked a difficult question to answer in an exam, but this strain is mechanical strain, very precisely defined.

Those of you remember this strain is equivalent to relative deformation, in other words if I have a spring and a mass, and the mass is acting downwards then the strain is nothing but the change in length of the spring upon the resting length of the spring. So, that is what I meant by the proportionate deformation, and stress is nothing but force per unit area. We are aware of these definitions, it is always nice to remember them.

And spring mass system always gives us a very good way to handle these. They are related to each other by a proportionality constant, which you have come across called the Young's modulus, this one here. The Young's modulus allows us to characterize the material properties of a solid, in other words for a given solid the elastic behavior and the Young's modulus are characteristic of that solid.

Meaning to say for steel, for silk, for bones, for teeth, for cartilaginous tissue we can report a Young's modulus just like we can report it for wood, and for mud, and for concrete and so on and so forth, which is what an engineer would usually use. Engineering is nothing but applied physics. So, in terms of fluids however we come to a term called viscosity. Now, we said that this is a proportionality constant, but you should be excited to see that while we said that fluids and liquids are different, we also have a sense of how they are similar.

Because these two equations, I have put them side by side here, relate stress to something; in case of fluids the stress is related not to strain, but this strain dot over here, this is nothing but the strain rate. In other words the rate of change of relative deformation is what the strain rate expresses, and then the proportionality constant is not Young's modulus which is true of solids, but viscosity which is true only of fluids.

Which also means that viscosity is nothing but the ratio of the stress by the strain rate and the strain rate we are also expressed, like we have talked about earlier as the velocity gradient. Now, when we observe fluids that are occurring around us like water or oil or ethanol or any other simple liquid, we find that these laws hold true. But nature is not simple, in fact, biology is the most complex form that I think nature exists.

Because we are alive, we can try to understand our universe and so it is not surprising perhaps that the complexity of life shows up also in the complexity of the physics that applies to it. So, it turns out that the stress to strain rate of fluids which should be linearly proportional, you see this is what this equation is telling you that the ratio of the stress by strain rate should be a single value of constant slope of η, it appears to either undergo what is called shear thinning or shear thickening.

Now, this line represents Newton's law of viscosity, which also means that what is deviating from it is called correct Non-Newtonian. So, you must have heard this term called Non-Newtonian fluids or maybe you may have not heard it and now you are hearing it, but the basic reason for that is simply to say it deviates from the standard law, but just because it does not follow the standard law does not mean we cannot understand it, correct.

So, to understand it we must invoke a little bit more complex theory and that is the theory of viscoelastic materials, but before we do that I want to talk a little bit about the most simple experiment that you can do to measure viscosity itself.

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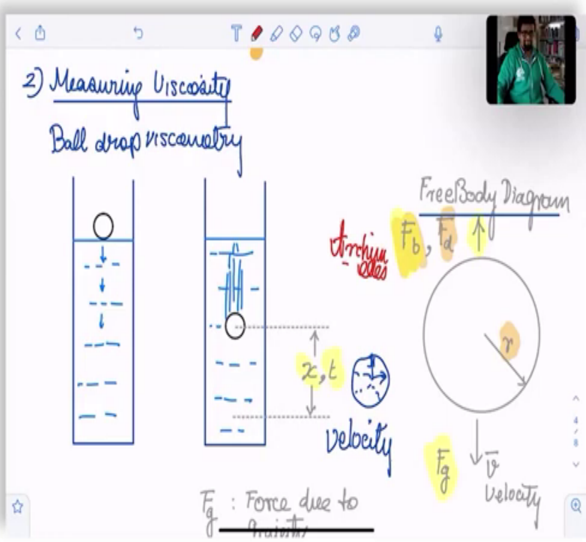

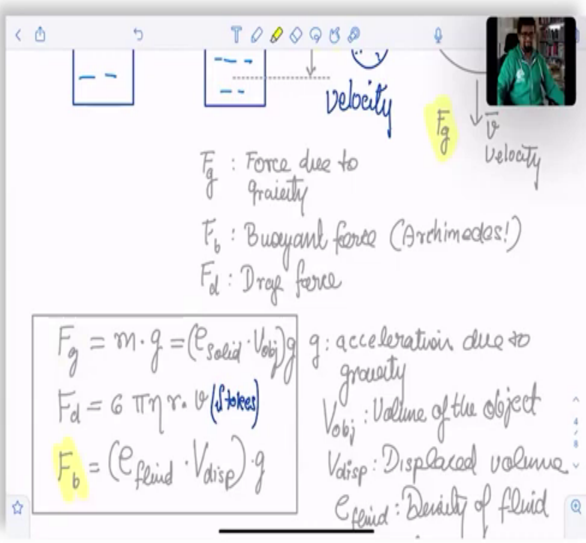

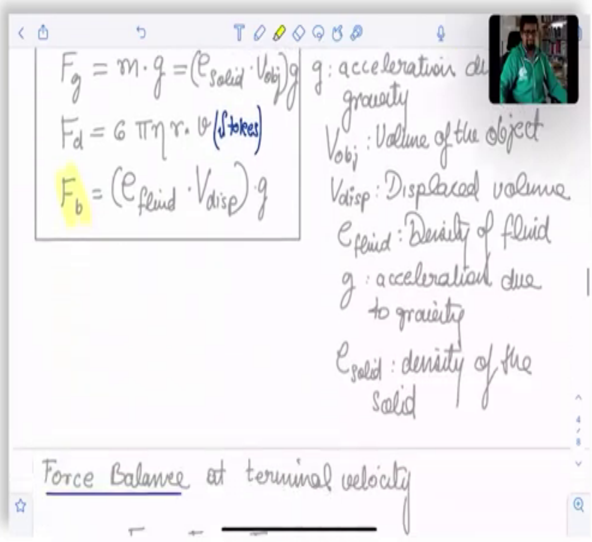

Now this measurement is based on what we call a bulk measurement. You remember the ball that I threw into a jar of water last time, you did not see it because it was very fast, but the fact is it went from the top and I released it with no other, no gap between the, I tried to maintain as little gap as possible between the ball and the top of the water surface and I released it and it rapidly went inside, it fell in.

And this calling in at some point just like most projectiles falling down, which you are familiar with from your high school physics of projectile motion, attain what is called a terminal velocity, meaning to say maximum velocity that they do not undergo any acceleration when all the forces are balanced. In such a case if we measure that velocity and we do that by measuring how much distance it travels, that is x, and how much time it takes to travel that and then x by t is your velocity.

Then we can actually measure the terminal velocity of a ball falling in a fluid. How does that help us? Good question. So, in order to make use of this information for measuring the viscosity, remember that is what we came here to do, we need a free body diagram. A free body diagram is nothing but one where we put a basic body and ask what are the forces acting on it, so we can argue that as the ball is falling through, it is falling through the water because we are on Earth.

Earth is exerting a gravitational force, that gravitational force is what we are referring to here as Fg, F underscore g, g being gravity. This was in terms of acceleration identified most clearly by Galileo and then in the following centuries refined and refined and refined. And even now you can find methods to make the measurement more precise.

And you are aware that in physics precision of measurement is important to the point that people spend entire lifetimes making instruments to make more precise measurements and sometimes they find funny things. So, this is a lesson I would like you to keep in mind that when we do quantitative biology, we may be limited by the instruments we have, but if we have better instruments we can make more precise measurements and we may find something new and that is what discovery is all about, about finding something new.

In a way it is a different way of finding something new, in the old days of biology we would find something new we would go to the jungle, look for a new animal, bacterium, plant, insect, maybe try to name it after our grandfather, our grandmother, our prime minister or the most famous scientist in the country and I think that is still valid because biology is still so underexplored.

But at the same time that should not prevent us from the systems that we do understand clearly from putting numbers to them, so to me this is an important lesson, but we will continue with viscosity, how do we measure it. So, we have F_d which is the drag which is imposed by the fluid, which is like a fluid friction, it just prevents it from falling very fast. You know this intuitively that when you fall through air versus vacuum there will be no friction in vacuum, in a true vacuum.

The second force that is acting upwards, this upward arrow, is the buoyant force. Now you remember again high school physics, Archimedes principle. He demonstrated that depending on the volume displaced by an object, the fluid will exert an upward force on it, and so now you have two upward forces, one downward force, and if they are equal, then the force due to gravity is equal to the summation of the buoyant force and the drag force.

We need to write out these equations, so F is, Fg which is your so called your standard gravitational force is nothing but mass into gravitational acceleration, remember that gravitational acceleration and quantity meters per second square. Mass itself is nothing but the density times volume, so rho solid times v object into g.

The drag coefficient, I am going to ask you to take this as a granted, but for a spherical object which is partly why we do a ball drop, ball because it is a spherical object, that drag force, the resistance of friction due to the fluid, even in the opposite direction for the direction of motion therefore the upward arrow, is given by 6 pi eta r into v.

$$F = 6\pi\eta r v$$

This is the Stokes drag force, v being the velocity, η being the viscosity, r being the radius of the sphere, 6π is a constant. So, this is what are drag force is.

Then we are left with the last force which is the buoyant force. Now you may not remember your Archimedes principle or some of you are very keyed up with what you learned in school, but that is simply the density of the fluid times the volume displaced into g, which gives you the weight, essentially the mass of the weight, the force of the fluid because it is mg, remember.

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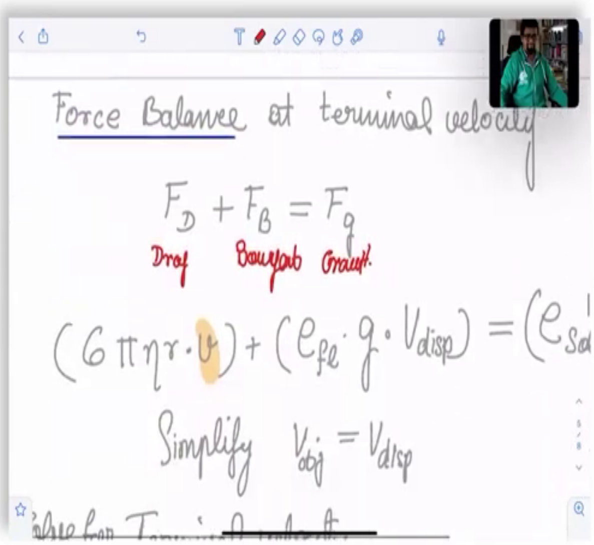

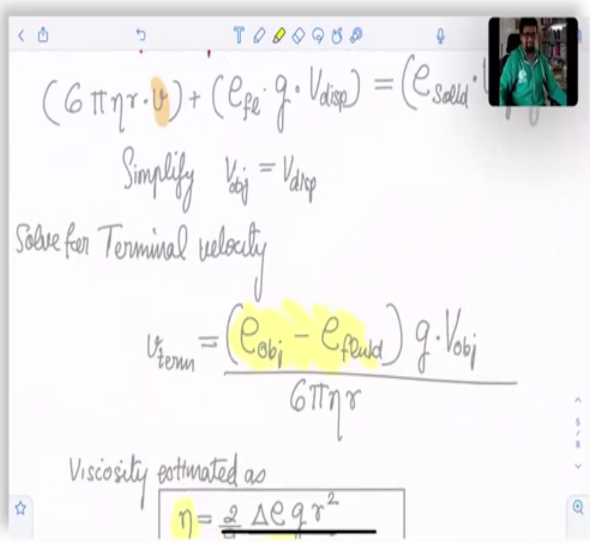

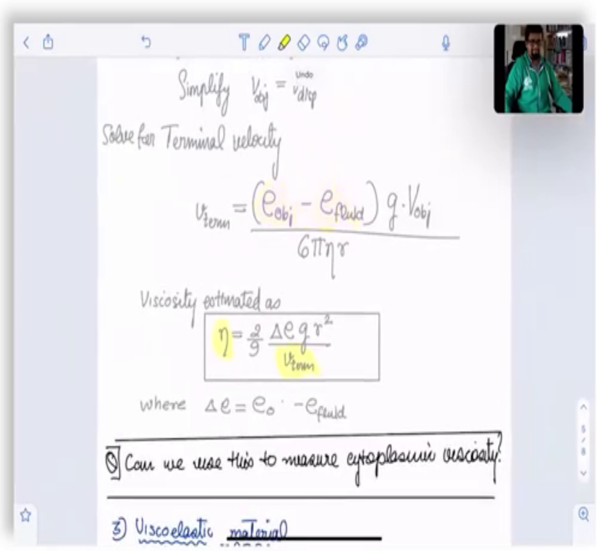

So, with all these symbols in hand we can write a force balance at terminal velocity. Remember for balance of forces you need to equate them, so we just equated them Fd, that is the drag force, plus Fb, the buoyant force, is equal to Fg, which is the gravitational force. So, let us write this, drag, buoyant and gravitational. Now, we substitute the terms, remember we wrote these here, so when we substitute them we get 6 π η r v plus ρ fl times g times, v displacement is equal to ρ solid times the object into g.

We assume that the volume of the object and the volume displaced are equal and therefore, when we solve for terminal velocity, we get v terminal is equal to object minus flow fluid into g times the object upon $6\pi\eta r$. eta remember is viscosity and so now this is nice because, viscosity can be estimated as η is equal to 2 by 9 into Δ ρ g into r^2 upon $v_{terminal}$.

Just let us think about this equation for a minute. This means that η, viscosity is inversely proportional to terminal velocity. What does that mean? It means that in a less viscous fluid velocity is more and in a more viscous fluid the velocity is less. This makes sense to you. If you are trying to move a ball through honey versus trying to move a ball through water, the honey ball will move slower, viscosity is higher, we know this intuitive.

Secondly, gravity is directly proportional, in other words experiment on the moon which has a weaker gravitational acceleration, you should see a value of terminal velocity that is lower. Yeah, I am shifting the terms around. For a larger ball the viscosity will be balanced by the velocity, in other words larger ball will have a higher terminal velocity quadratically and delta g is object density minus fluid density that is the definition of delta g.

So, if the difference is greater the velocity is greater. So, now the question becomes can we use this to measure cytoplasmic viscosity? What is cytoplasmic viscosity? It is the viscosity of the cytoplasm. Can we use a ball drop viscometer to measure it, if so then how, if not then how, why not, and if not and why not, then how should we measure it otherwise. And I will have these discussions in a demonstration that I will do for you subsequently.

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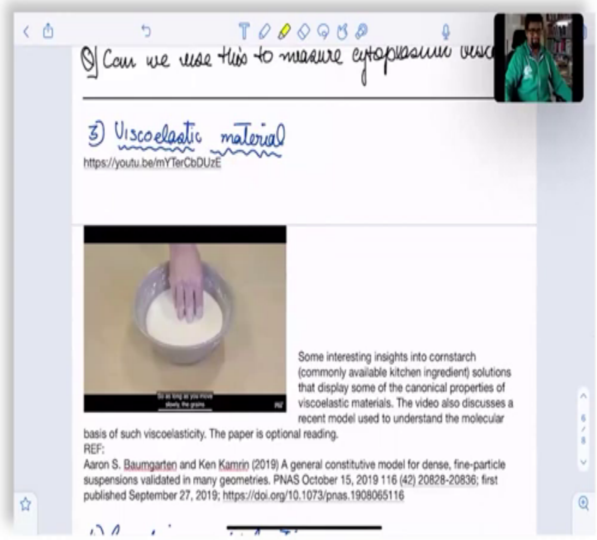

But for now we will go to the last part of the section that I wanted to discuss which is regarding viscoelastic materials. Now, there is a YouTube link here, demonstration made by folks who mixed corn flour, a kitchen ingredient, with water and described it in a research paper in Proceedings of National Academy of Sciences of USA about a general constitutive model for a dense fine particle suspension validating many geometries.

This material is something you can make in your kitchen because cornstarch, remember, is what we use in Gobi Manchurian, so your Gobi is coated with corn flour, ('makke ka atta' in Hindi). So, making a solution of 'makke ka atta' you can demonstrate that a material can behave like a fluid at times and like a solid at times. This is magical, this is like saying that is something a solid or a liquid, I mean, if I see a glass of water it is not a doubt whether it is a liquid or solid, it is liquid.

If I see a block of wood it is not a doubt whether it is a liquid or a solid, it is a solid, if I see a bar of steel it is a solid. But there are some materials that exist in both states and it depends and we are going to discuss these in a demonstration. So, that is it for this module and more will be discussed later.