Bioreactor Design and Analysis
Prof. Dr. Smita Srivastava
Department of Biotechnology
Indian Institute of Technology - Madras

Lecture – 22
Rheology of Fluids

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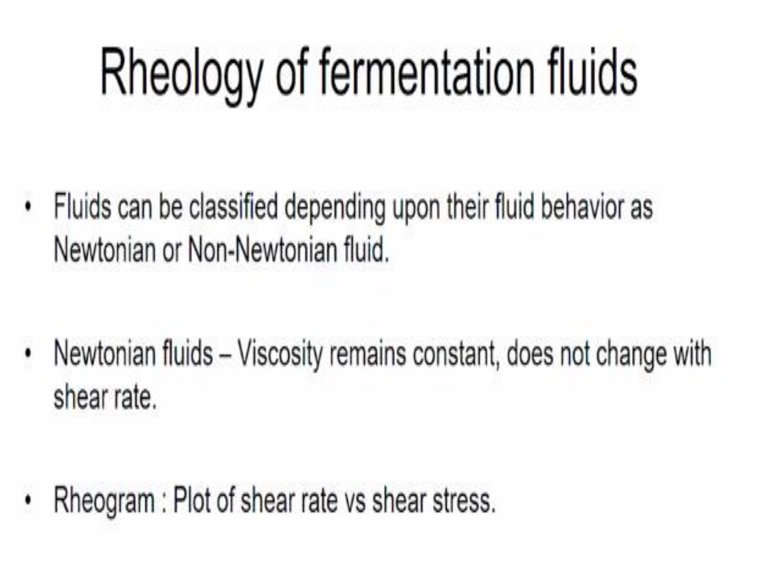

So, let us talk about rheology of fermentation fluids. Now fluids are classified depending on their fluid behavior into either Newtonian types or non-Newtonian type of fluids. Generally, most of the fermentation broths these are aqueous solutions and because they are homogeneous, so we assume that they continue to behave as Newtonian fluids till the end of the fermentation.

However, depending on the production platforms which we use like plant cells or tissue cultures which tend to aggregate with high cell densities may not be homogeneous and therefore they tend to deviate from the Newtonian assumption and they behave like non-Newtonian fluids.

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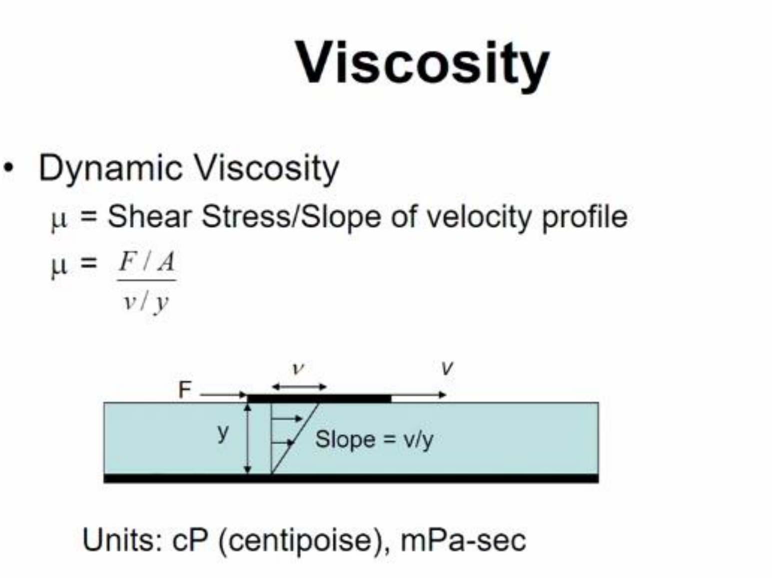

So, let us just revise what we earlier have known about the Newtonian and Non-Newtonian fluid behavior.

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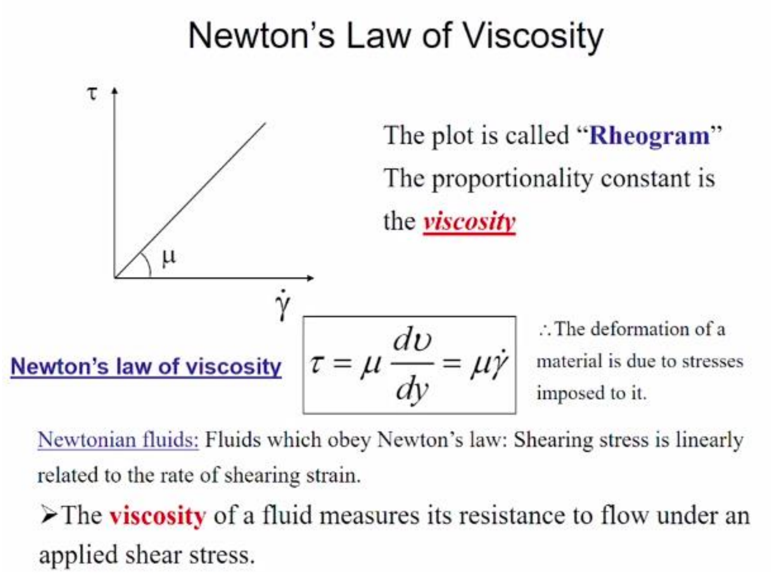

So now for Newtonian fluids, we know they follow Newton's law of viscosity where the viscosity is said to be a function of shear stress to shear strain. Now this proportionality constant of shear stress versus shear strain plot is what we know as absolute viscosity. So, any deformation which might happen in a fluid will be due to the stress which will be imposed on it.

So Newtonian fluids they follow Newton's law and shear stress is linearly related to the rate of shear strain. And viscosity to define of a fluid measures its resistance to flow under the applied shear stress.

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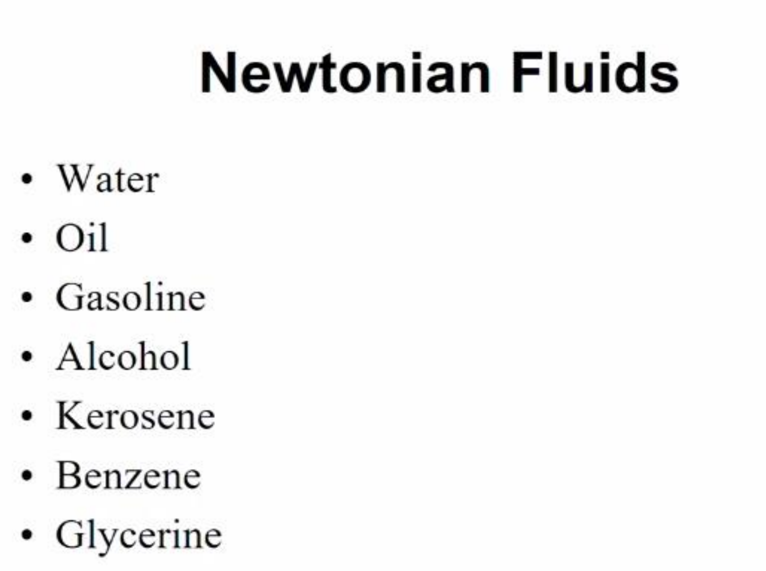

Some examples of the Newtonian fluids are like water, oil gasoline, alcohol, kerosene, benzene and glycerin.

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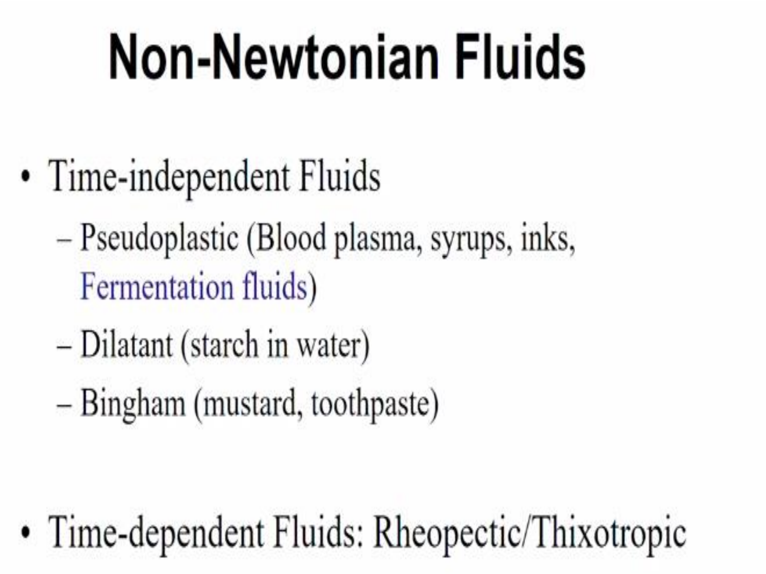

Now what are non-Newtonian fluids? Non-Newtonian fluids can further be differentiated into different forms like pseudoplastic where example is blood plasma or syrups which we drink or ink, fermentation fluids come under this class. Now dilatant behavior it is like starch in water or Bingham plastic is like mustard or toothpaste. Now there are another kind.

So, these all come under time dependent independent fluids which means their viscosity is time independent, but there are certain Non-Newtonian fluids whose viscosity is time dependent. These can be further classed into being rheopectic or thixotropic.

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Non-Newtonian fluids

Fluids which do not obey Newton's law: Shearing stress is not linearly related to the shear rate. (μ not constant – depends also on shear rate)-Apparent viscosity

- **Bingham plastics**
- **Shear thinning (pseudoplastic)**
- **Shear thickening (dilatant)**

So, fluids which do not obey Newton's law which is nothing but shear stress is not linearly related to the shear rate, then the viscosity which is mu is no more constant and it depends on the shear rate. Now this is called as apparent viscosity. So, the examples as I said the Bingham plastic. Shear thinning liquids is what is pseudoplastic where fermentation fluids are classed and shear thickening is dilatant fluids.

So, the impeller if you remember it helps in creating more shear and also therefore in reducing the viscosity.

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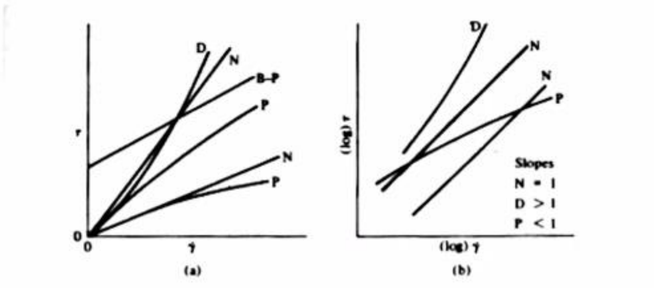

Figure 15.2 Types of flow curves: (*a*) arithmetic; (*b*) logarithmic. N, Newtonian; P, pseudoplastic; B–P, Bingham plastic (infinitely pseudoplastic); D, dilatant.

In the general case: Viscosity = Shear stress/Shear rate

$$\eta = \frac{\tau}{\dot{\gamma}} \Rightarrow \eta \text{ is a function of } \dot{\gamma}$$

Generalized Newtonian Fluid

Now in general case we know that viscosity is equal to shear stress to shear strain. In non-Newtonian fluids your viscosity which is called as apparent viscosity is then dependent on the shear strain as well.

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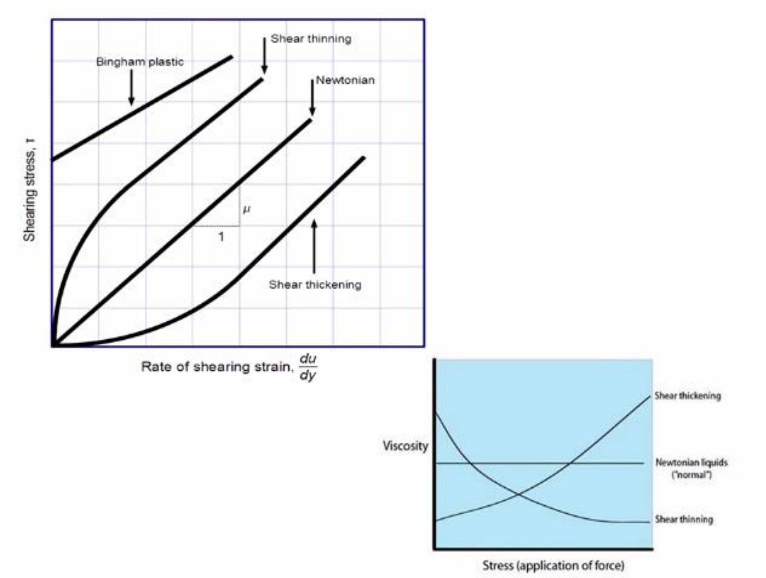

So, if you see the plot on the slide you can clearly see the incline straight line in the center passing through the origin this shows a Newtonian fluid behavior where the plot is between the shear stress and shear strain. Shear thinning are your pseudoplastic fluids and shear thickening are your dilatant fluids. So, in order to understand what the shear thinning or thickening means if you make a plot of viscosity versus the applied force which is your shear stress.

You can find that in shear thinning liquids the viscosity will go down as the stress keeps on increasing. Similarly, in shear thickening the viscosity will keep on increasing as the shear stress is increased. Whereas for Newtonian fluids in the same plot of viscosity versus stress the viscosity would be a straight line parallel to the x axis which is the shear stress.

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Power Law model

$$\tau = K \dot{\gamma}^n$$

K – Consistancy index, n= Power law index (Flow index)

Power Law Index (or Flow Index) n: is a measure of non-Newtonian-ness.

Newtonian fluid Power Law Index = 1;

For a shear-thinning fluid (pseudo plastic)it is between 0 and 1

For a shear thickening fluid (dilatant) it is greater than 1.

Consistency K: It is the viscosity (or stress) at a shear rate of $1s^{-1}$.

So, your power law model is used to define the non-Newtonian fluids. So, power law index as shown on the slide is defined as n which is a measure of a non-Newtonian-ness of a fluid and if that n becomes 1, then this is the Newtonian fluid. So, for shear thinning fluid which are pseudoplastic it is between 0 and 1 and for shear thickening fluid which are called as dilatant fluids the n value becomes greater than 1.

Your K is called as proportionality constant which is called as consistency index. It is the viscosity at a shear rate of one second inverse.

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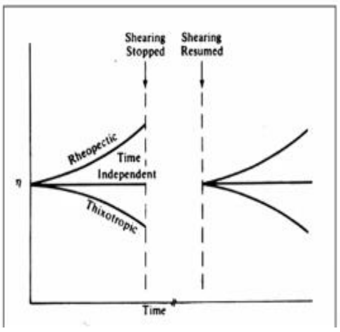
Time-Dependent Behavior

Apart from shear dependency, some fluids also exhibit reversible time-dependent properties. The viscosity of a “thixotropic” fluid decreases with time, implying a progressive breakdown of structure. The opposite behavior is observed for a “rheopectic” fluid.



If you see time dependent behavior in a plot of viscosity versus time, you can see that so apart from shear dependency there are some fluids which also exhibit reversible time dependent properties. The viscosity for example of a thixotropic fluid it decreases with time and implies a progressive breakdown of structure. So, you can think of an example where with time there is a progressive breakdown of the structure of the molecules in the fluid which cause the viscosity to reduce.

The opposite of this is a behavior which is observed in thixotropic fluids where with time it becomes thicker and thicker. Can you think of an example? So, if you make a plot between viscosity versus time, so then you can see on the plot once the shear is stopped then for rheopectic fluids the viscosity increases with time and for thixotropic fluids the viscosity will decrease with time.

And the in between line which is parallel to time which means that viscosity is constant, it is not dependent on time. So, these are time independent fluids.

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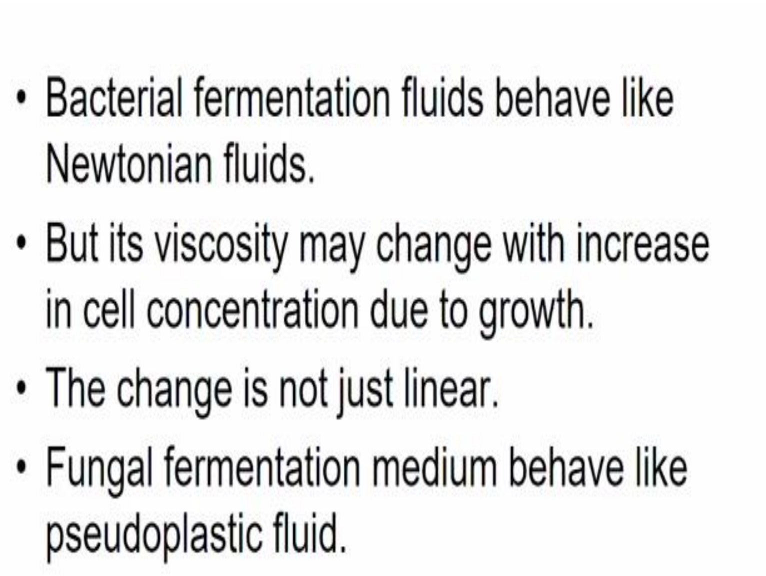

So where do fermentation fluids lie? Bacterial fermentation fluids they behave like Newtonian fluids because they can be assumed as very homogeneous uniformly suspended single cells. But its viscosity may change if the cell concentration increases and it becomes a very high cell density process like in case of perfusion reactors continuous reactors with cell recycle.

So there with time you may observe that the behavior may deviate from Newtonian fluid to a non-Newtonian fluid. So, the change which you will observe may not be a linear change. Another example is fungal fermentation medium which behaves like pseudoplastic fluids which are called as shear thinning fluids.