

Introduction to Fluid Mechanics
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Lecture – 02
Macroscopic and microscopic point of views

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Painless Needle mimics a Mosquito's Bite

<http://technology.newscientist.com/article/dn14348>

- A female mosquito sucks blood by flexing and relaxing certain muscles in its proboscis. This creates suction (or negative pressure) that draws blood into its mouthparts.
- Mimicking above, the sucking action in our invented microneedle is provided by a microelectromechanical pump, which works using a piezoelectric actuator attached to the needle.
- The new needle has an inner diameter of around $25\ \mu\text{m}$ and an external diameter of $60\ \mu\text{m}$, which is about the same size as a mosquito's mouthpart. Its size and the fact that it works by suction, makes it painless.
- The microneedle may be used to draw blood, inject drugs, and act as a smart glucose-level monitor for diabetics.

Ref: S. Chakraborty and K. Tsuchiya, Journal of Applied Physics, vol. 103, pp. 114701 (1-9), 2008

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I will come to another very fascinating example just to illustrate the kind of importance that fluid dynamics may have not just in medical diagnostics, but also in medical treatment or in a combined package of diagnostics and treatment.

So, we can think of like an injection for sucking blood, for testing the blood sample. For example, maybe for testing for sugar level in a diabetes patient and then transferring insulin to the same person based on the prevailing level of blood sugar. So, this is a very common procedure that many patients have to undergo throughout their life and it is not a very comfortable process.

So, one of the alternatives that one can think of is instead of a traditional needle one can think of a micro needle; very small needle and the typical micro needle may be designed by mimicking the act of a mosquito's bite this is called as biomimetics. This biomimetics, it does not mean that, we just copy what is there in nature. It is impossible to copy what is there in nature but, we can get some lessons out of it. For example, when a mosquito sucks blood it typically creates a suction pressure or negative pressure, that draws blood into it into it is mouth

parts.

So, you mimicking the above the sucking action in a microneedle may be provided by a microelectromechanical pump and it can draw the blood; very small volume of blood O then there can be a testing of the blood in a let us for example, say a metal oxide based semiconductor or MOSFET not a metal oxide semiconductor, but a MOSFET based blood glucose sensor and then based on that we can immediately get a result that whether what is the amount of glucose that is there in the blood sample. So, that the MOSFET based sensor gives that answer.

And then based on that there can be a smart insulin delivery system and this entire process can be built in a package which looks like a wristwatch which is shown in this view graph. So, this is just to say that one can have small needle and the needle really can make sure that you can have a very smart painless testing of blood sample to get the amount of glucose and deliver the insulin accordingly.

How does it work? One of course, is the like creation of the suction pressure, but the design of the microneedle is based on the fact that in the micro scale. In fact, mosquito's labium is also of micrometer scale like typical 25-micron to 50-micron diameter and in the typical micrometer scale surface tension works beautifully there are certain forces which are not that important in the large scale, but may be important in the small scale and surface tension is one such force.

So, because of the surface tension working beautifully the droplet of blood which is sucked from the bottom of the scheme can be transmitted is easily with a very little indentation force and that makes the device to work in a painless manner.

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Fluid Mechanics is often Amazing: Many times it Contradicts Common Intuition

- Rough surfaces may reduce frictional resistances against fluid flow instead of acting as hindrances
- Without friction birds cannot fly and fish cannot swim
- Symmetric problems may have asymmetric solutions
- Presence of particulate inclusions in a flow may reduce effective viscous nature of the fluid
- A highly viscous flow may be a good simulator of ideal flows with zero viscosity
- Time-dependence of a flow depends on the choice of reference frame
- Shear force may vanish although shear stress may exist
-and many more

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Fluid mechanics is often amazing. So, I can go on giving you examples, but I just do not want to like overburden you with examples. I just want to let you make you feel that fluid dynamics is not just the traditional automobiles or aircrafts or power plants or process plants that we can think off, but fluid dynamics is just in all aspects of modern science and technology and it is often amazing because many times it contradicts common intuition like rough surfaces may reduce frictional resistance against fluid flow instead of acting as hindrances.

Without friction birds cannot fly and fish cannot swim. Symmetric problems may have asymmetric solutions. Presence of particulate inclusions in a flow may reduce effective viscous nature of the fluid. A highly viscous flow may be a good simulator of ideal flows with zero viscosity. And, time dependence of a flow depends on the choice of reference frame like you cannot say whether the flow is steady or unsteady until and unless you specify a reference frame. Shear force may vanish all the shear stress may exist.

So, these are certainly very interesting phenomena and many more which contradict common intuition and this is what is important like from my perspective what I can share my own perspective or philosophy with you, that all of us are born with certain intuitions like even if you put even if there is a very little child who puts his or her finger in fire he or she knows that it will burn. So, this is something which is intuitive and this intuition is correct. But while going through experience in life one understands that there are many natural and physical phenomena which do not go by intuition and then to get an explanation to that to me that is the proper


learning of science.

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Taste a Non-intuitive Example: The Rough Makes it Smooth!

- confining rough surfaces made of water-disliking materials may trigger the formation of tiny bubbles adhering to the walls of narrow channels.
- This incipient vapor layer acts as an effective smoothing blanket, by disallowing the liquid on the top of it to be directly exposed to the rough surface asperities.
- In such cases, the liquid is not likely to feel the presence of the wall directly and instead may smoothly sail over the intervening vapor layer shield. Thus, instead of 'sticking' to a rough channel surface, the liquid may effectively 'slip' on the same.

Ref: S. Chakraborty, Physical Review Letters, vol. 99, pp. 094504(1-4), 2007



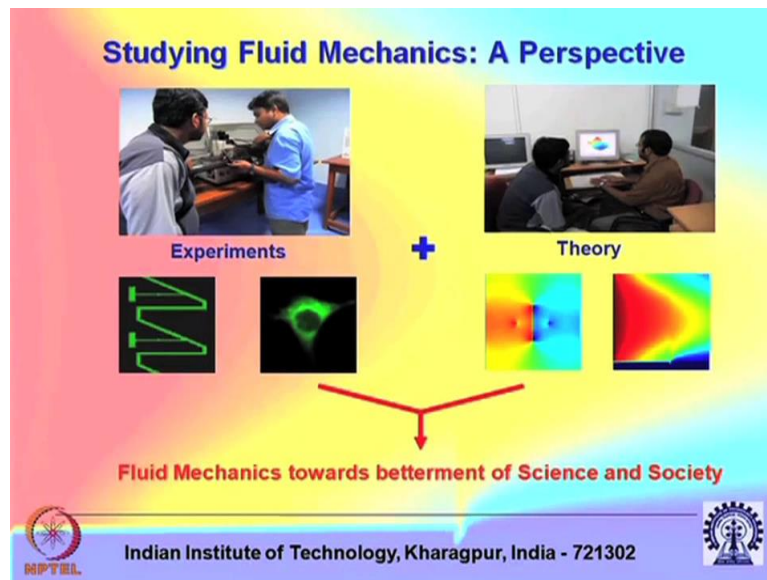
The slide features a 2D schematic of a channel with a rough bottom surface. The top surface is labeled 'Flow Direction' with an arrow pointing right. The bottom surface is labeled 'Nanobubble covered surface' and 'Wall'. The vertical axis is labeled 'z' and ranges from 0.0 to 0.12. The horizontal axis is labeled 'x' and ranges from 0.0 to 20.0. Below the schematic is a 3D surface plot of the rough surface, showing a highly textured, orange and red surface.

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So, I can give you a non-intuitive example that if we have rough surfaces, the rough surface is supposed to create more hindrance against fluid flow, but under certain cases it can be shown that the rough surface may reduce friction not explicitly, but implicitly what it can do that, if you have a rough hydrophobic surface in a small confinement then this surface can give rise to small bubbles; nanometre scale bubbles and the liquid which is flowing on the rough surface is not directly feeling the effect of the rough wall. What it is doing? It is gliding on the cushion layer of the bubbles.

So, we can say that it is a rough that makes it is smooth because the roughness of the surface is one of the key factors that has triggered the formation of these nanoscale bubbles and the water the liquid water that is moving on the bubbles this is just flowing in an apparently frictionless manner because it is not interfacing with the rough surfaces directly.

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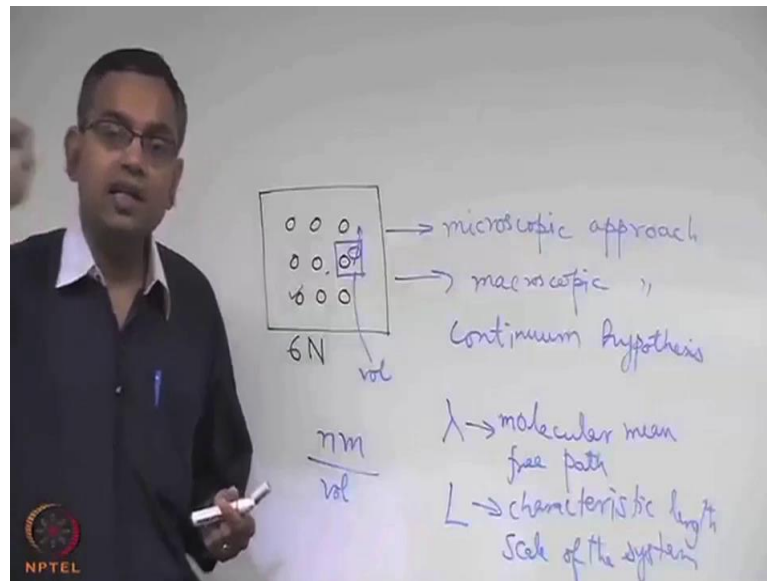


So, studying fluid mechanics we can give a perspective although this is primarily a theoretical course, but we will have several video demonstrations to make like make it like a virtual experimental environment, but we will be mostly discussing on theory and experiments and theory need to go together to learn for us to learn fluid mechanics and from the various examples that I have illustrated my emphasis is that like fluid mechanics can really be used to understand not just fundamental scientific issues, but to help towards the betterment.

So, with this little bit of introductory remarks we will move on to an issue which we want to discuss before discussing what is the fluid, right. In fluid mechanics the initial discussion will typically always start with what is the fluid. It is a very involved question, but it is also important to understand that many times we have an intuitive idea of what is the fluid, but like before that we will try to see that even if we know what is the fluid question is what is the perspective in which we are going to analyse it analyse the motion of it.

To come into more concrete terms, we will consider a gas. When we consider a gas we are definite that like it is a fluid because there are certain substances there are certain substances which fall in the interface of a fluid and a solid. So, we are not going into liquids at this moment and we are just concentrating on gases because all of us agree that it is the fluid by the sense that like it conveys to us from a common sense.

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Now, let us say that there is a container. In this container there are some gas molecules. Question is that how do we analyse the system? One possibility is that we write the equations of motion for each of these molecules. When we say that we are interested to write equations of motions for each of these molecules think about a situation.

Each molecule may have three translational degrees of freedom and three rotational degrees of freedom; that means, six independent equation for each molecule into the number of molecule and the number of molecules think of just one mole and one mole really a small quantity will have Avogadro number of molecules. So, think of a realistic system. So, how many of unknowns you have and you will have this number of matching equations of motion and you have to solve for that to get a physical picture of the molecular motion.

So, it is a fundamental way of analysing the motion and is known as molecular dynamics, but one has to understand that it has practical limitations that it cannot really address a very large system. It can address only a small system with number of molecules not significantly large depending on the computational resources it may be thousands or more, but it cannot be prohibitively large.

So, what is the alternative? There are a couple of alternatives. One alternative is that instead of addressing individual molecules you can make a statistical average of many molecules. So, what you can do is, instead of directly simulating the molecules you statistically represent a group of molecules by statistical properties and that is what is commonly done in kinetic theory

of gases. So, in kinetic theory of gases what you do you address the behaviour of a gas statistically and it is because you do it is statistically you really do not have to simulate individual molecules in a real sense you have to just simulate the statistical behaviour of molecules in a stochastic sense. So, that makes the analysis computationally little bit more convenient and that is known as microscopic approach.

Now, we have to understand that microscopic approach being convenient it may carry some of its important implications. For example, if you want to make a measurement; let us say you want to make a measurement of pressure of a gas. So, microscopic approach really does not give you a clue of how to go about that. Instead of that you may have a more convenient approach you just have a device which measures the time average normal force over a given area and divide the force by the area to get what is known as pressure.

In the microscopic approach you will find pressure because of as a consequence of change in molecular momentum as it encounters the collision. But, in a macroscopic approach you just do not care about all those, but you just find time average force over a given area. So, that is called as macroscopic approach.

If the macroscopic approach is working then that is best for us because then you can create the fluid as a continuous medium disregarding the discontinuities. So, you can think of that the fluid is like a continuous medium and that is known as continuum and the hypothesis that tells that the fluid can be considered as a continuous medium disregarding the discontinuities inside following the macroscopic approach is known as continuum hypothesis.

So, question is, does the continuum hypothesis always work or it may not work? The thing is that if the continuum hypothesis works it is the most convenient to use because we can use well known rules of differential calculus to calculate the gradients of properties. So, we can express the behaviour through well known differential equations of a fundamental physics classical physics to represent the property variations within the fluid. But the issue is that can we do it for all cases.

Now, to get a more detailed insight on that let us say that we are interested to calculate the density of a gas. To calculate the density of a gas what we need to do, we basically identify a elemental volume we find out the number of molecules in that elemental volume. Let us say that small m is the mass of each molecule. So, this is the total mass divided by volume. So far so good, but how small the volume should be. To get a real point to point variation this volume

should be as small as possible, but not tending to 0. It can tend to a critical volume up to which the continuum hypothesis will be valid, not below that.

Why not below that because then the interrogating volume may really have a very few number of molecules if it has a very few number of molecules then what will happen then this molecules remember they are in random motion. So, what is going to happen is that let us say there are two molecules and suddenly one molecule is out of this which is a very common thing that can happen. Then, it can give rise to an error like which is like an 100 percent type of error that it can give rise to. So, or 50 percent type of error depending on how you are measuring the error.

So, when you have this high percentage of error then, that means, that is because of the uncertainties in the molecular occupancy of the chosen interrogating volume. So, when can that happen? That can happen if the volume is very small or the volume may not be that small, but the system has a few numbers of molecules that is called as a rarefied system.

So, we can understand that because of uncertainties with regard to the number of molecules when it has a large number of molecules it is fine, but if the volume has too larger number of molecules then and if the volume is itself is large to handle that then we do not get point to point variation of properties. So, what we really want is a small volume, but that should contain sufficient number of molecules and that means, it is not a rarefied system.

The next question comes what is sufficient number of molecules? How many numbers of molecules you have that it should be sufficient or when you say that the system is large or the system is small, when do you say that? To understand that we will come into more quantitative terms because smallness or largeness is qualitative. If we say that the system is small you may say that it is small to you, but it is large to me. So, it is always important to make a quantitative assessment of the smallness or largeness.

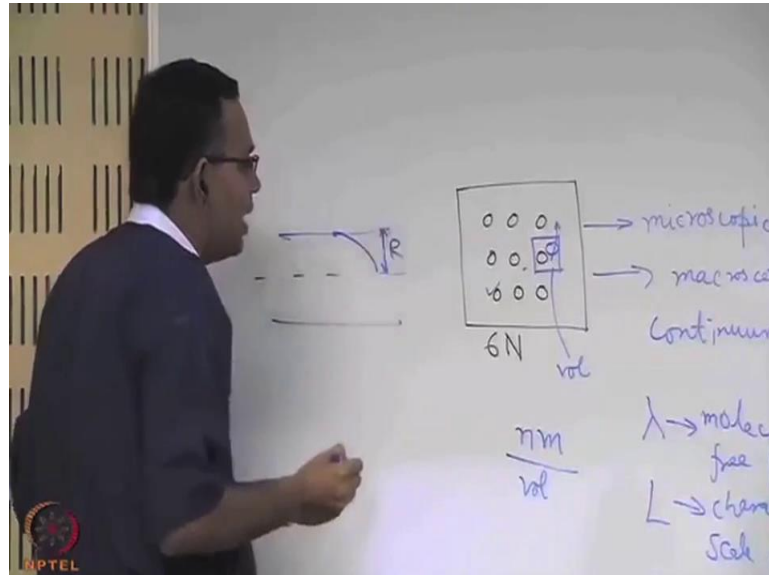
To understand that what we can do is we use one of the important quantities which is λ . What is λ ? λ is the mean molecular mean free path. Molecular mean free path is what? Molecular mean free path is the average distance that a molecule will traverse before encountering a collision. So, that is the molecular mean free path.

Now, a system is relatively rarefied if the molecular mean free path is large; that means, there are few molecules, so that a molecule before encountering another collision has to traverse a large distance, but large and small as compared to what? So, we compare λ with something

called as L which is called as the characteristic length scale of the system.

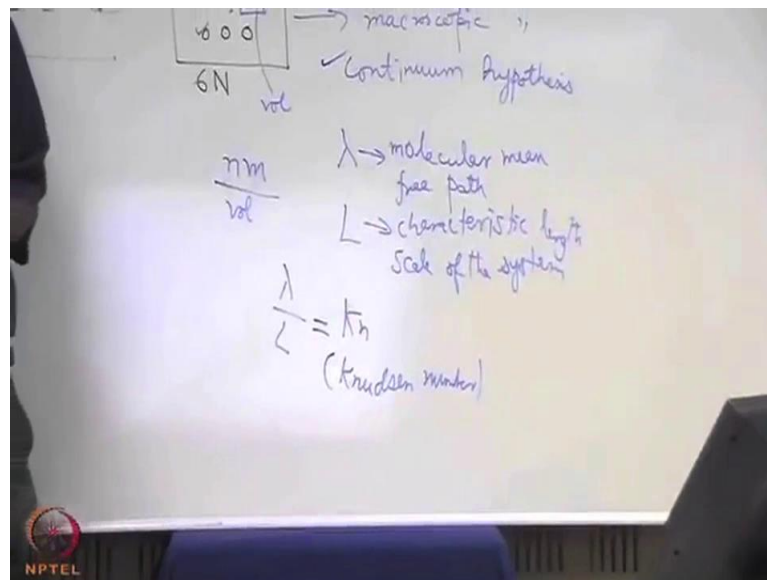
So, what is the characteristic length scale a characteristic length scale is the distance over which characteristic changes can take place.

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For example, like if you have a flow of gas through a pipe. So, you can see that characteristic changes take place from the valve at the velocity is 0 to the centreline where the velocity is maximum. So, the characteristic length can be the radius of the pipe, but in engineering typically it is considered as the diameter of the pipe with an understanding that it does not change the order, like diameter is just two times the radius.

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So, if we compare λ with L if λ is large compared to L then we say that it is a rarefied system, but if λ is small as compared to L we say that it is not a rarefied system. So, it is not just the λ that is important, it is not just the L that is important, but λ by L is a very important parameter that talks about the rarefaction of the rarefaction of the rarefaction of the system.

So, this

$$\frac{\lambda}{L} = K_n$$

is known as a non-dimensional number. This is the ratio of two lengths, so, it is non-dimensional this is called as Knudsen number.

So, a small Knudsen number means the system is not that rarefied and continuum hypothesis can be used. But, if the Knudsen number is large; that means, that the system has a relative rarefaction; that means, that continuum hypothesis cannot be used and one has to go for either statistical approach through microscopic approach or maybe molecular dynamics to analyse the problem.

So, to summarise what we can say is that there are several approaches one is the molecular dynamics approach to analyse the fluid flow and which is most intuitive, but computationally most challenging and there are there is a compromise, one can go for statistically average behaviour of many molecules which is the statistical mechanics approach and the most convenient is the macroscopic approach based on continuum viewpoint where we consider the

fluid as a continuous medium disregarding the discontinuities and the continuum hypothesis can be used only under certain conditions typically governed by this Knudsen number.

So, if the continuum hypothesis can be used then it is very convenient because we can use the well-known rules of differential calculus for solving the problems and because this is a very introductory course, we will be mostly dealing with fluid dynamics where continuum hypothesis can be safely used. So, we will be encountering situations and solving problems which we will address through the use of continuum hypothesis. And, from the next lecture onwards we will continue with the discussion with which we are living today and thank you very much.