Multiphase Microfluidics
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Lecture – 01
An Introduction

So, let us start with the understanding the term multiphase microfluidics. So, this course the title of this course has 2 terms multiphase and microfluidics, and first we will try to understand what does the term multiphase mean, and what does the term microfluidics mean. And then try to understand each term individually and then look at the different aspects of the course. So, the term multiphase has 2 syllables into it multi and phase. Multi means many, and phase; phase generally refers in a general sense it refers to the thermodynamic state of the matter which is generally gas, liquid and solid.

So, in a general sense multiphase refers to flow of gas liquid, gas solid, liquid solid or gas liquid solid. And if; however, it can so happen that 2 immiscible phases can coexist, or multiple phases can coexist in the same state of matter. As in this course we are concerned with the fluids or the flow of fluids. So, such a case can arise when we have flow of 2 immiscible liquids. For example, water and hexadecane flowing in a channel, and the interaction between them in terms of the flow pattern, flow structure, flow behavior the size of the droplets or the different flow structures for example, parallel flow angular flow and so on and so forth.

So, that is about what the term multiphase means, now coming to microfluidics. So, microfluidics as the term suggests micro and fluidics. So, micro is the flow at micro scale, it can be flow in a channel of micron size or flow in a constriction of micro size, sometimes it can also refer to the flow of micron size droplets, or bubbles or particles. So, it is at the micro scale when I say micro it can be from few microns to few 100 or sometimes few 100 microns or sometimes it can be even few millimeters.

And fluidics is flow or manipulation of fluids. So, basically what we are going to study in this course multiphase microfluidics is, what happens when we have flow off more than one phase in microchannels.

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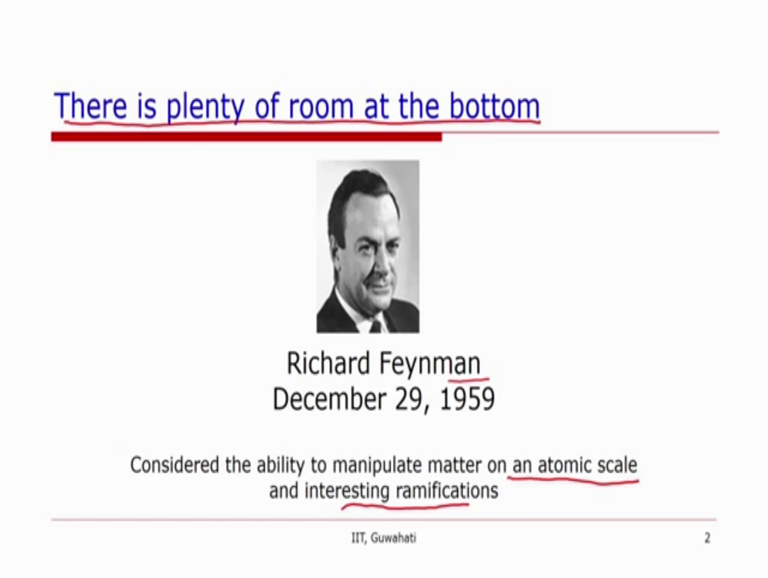

There is plenty of room at the bottom

Richard Feynman
December 29, 1959

Considered the ability to manipulate matter on an atomic scale and interesting ramifications

So, in last 2 decades, there has been lot of emphasis in micro of fluidics and nanofluidics or in general if I talk about micro technology and nanotechnology. If you look at the trend in the technology has generally been towards miniature miniaturization looking at the small and small.

So, if we look at what Feynman envisaged in his now very popular or very celebrated lecture titled as there is plenty of room at the bottom; where he looked at the possibility of manipulating matter on an atomic scale. That might be probably the smallest scale possible that can be manipulated. And he are described interesting ramifications of such phenomena. So, I would suggest you to look at the lecture and understand the ramifications that he described about 60, or about 60 years ago without any real development in the field of micro technology and nanotechnology ok.

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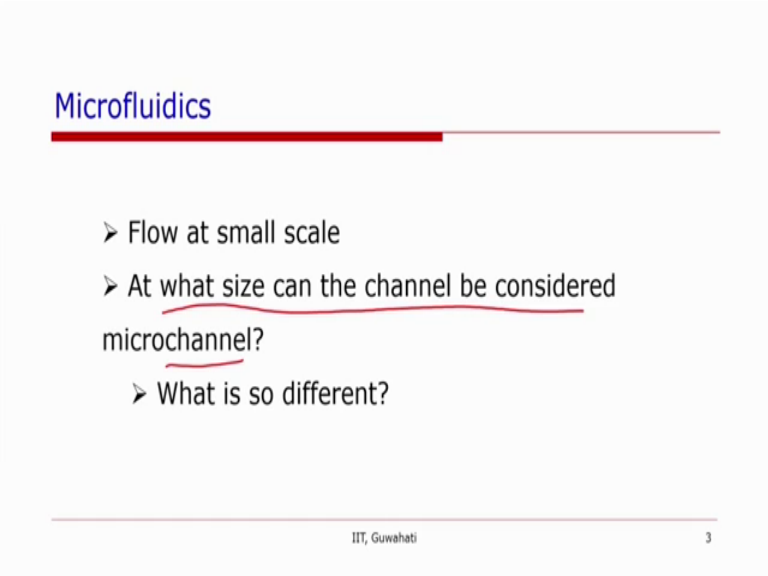

Microfluidics

- Flow at small scale
- At what size can the channel be considered microchannel?
  - What is so different?

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So, in microfluidics what we are looking at is flow at small scales. So now, the question comes that what how small is small. At what size can the channel be considered in microchannel? You will see that in the literature, the flow happening from few microns or say tens of microns up to few millimeters; the term micro has been used frequently. So, the question arises what is my question. So, in my opinion, the first question we should ask what is so different about microfluidics, or flow in microchannels that we need to study it separately.

What are the effects, or what are what is the physics that was not present in small diameter channel or in conventional channels, but has become dominant in the micron size channel, or small diameter channels when then we look at that effect, then probably it will be easier for us to define or cut off if there is one such thing for classifying the channel to be a macro channel or channel to be a microchannel.

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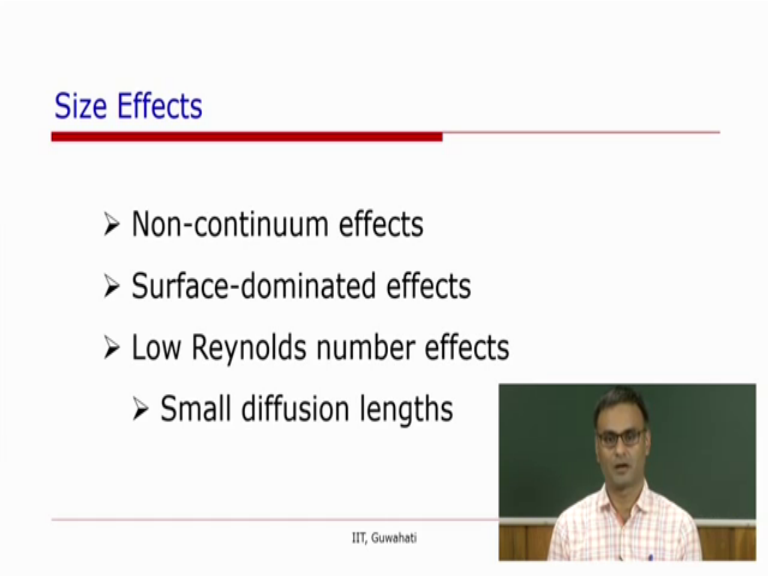

Size Effects

- Non-continuum effects
- Surface-dominated effects
- Low Reynolds number effects
  - Small diffusion lengths

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So, let us look at some of these size effects. So, if we look at the different size effects, can be classified into these 3 different classifications. And when I look at or when I talk about the classifications, I would suggest that are not only microfluidic, but nanofluidic of going to a small scale, one need to consider, one need to take into account, one need to check are these effects changing; are these becoming important are these losing the significance. So, let us look at these effects non-continuum effect, surface-dominated effect, low Reynolds number or a low diffusion length effects one by one.

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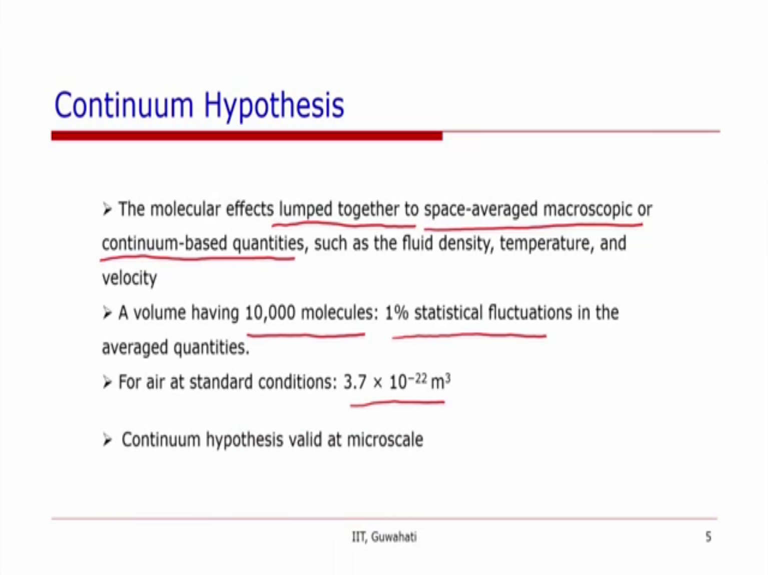

Continuum Hypothesis

- The molecular effects lumped together to space-averaged macroscopic or continuum-based quantities, such as the fluid density, temperature, and velocity
- A volume having 10,000 molecules: 1% statistical fluctuations in the averaged quantities.
- For air at standard conditions: 3.7×10^{-22} m^3
- Continuum hypothesis valid at microscale

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So, let us look at continuum hypothesis. Many of you might not be aware of what the continuum hypothesis is. So, let us look at. We all are know that of fluid or a matter a gas, a liquid, a solid, they are all constituted of small molecules. And these molecules are randomly in motion, depending on what state of matter the distance or the mean free path will depend on that. So, basically, they have in a room or in the space, there are number of such molecules millions or trillions of those.

Now, when we look at the description for the engineering purposes. For example, for the fluid flow, we describe the properties of such systems or properties of such materials these fluids liquids and gases as a continuum; that means, we do not consider that at one particular point of space, there is a molecule or there is not a molecule. We take or the as has been written here, that the molecular effects are lumped together to space average micro macroscopic or continuum-based quantities such as density temperature, and velocity. we can do so because the number density of molecules. It is so large that we can treat the molecules to be continuum, and analyze the fluid or analyze the system.

So, for reference a volume which have 10,000 molecules, there is one percent statistical fluctuation in these average quantities. So, probably that should be good enough. So, how we describe? Because then the question will come, that when you go to smaller and smaller scale probably you might not have enough molecules to assume it to be continuum. So, every time we go to a smaller scale, we need to check the continuum hypothesis ok. So, for air at standard conditions this volume is about 3.7 into 10 to the power minus 22-meter cube in which one can expect to have about 10,000 molecules ok.

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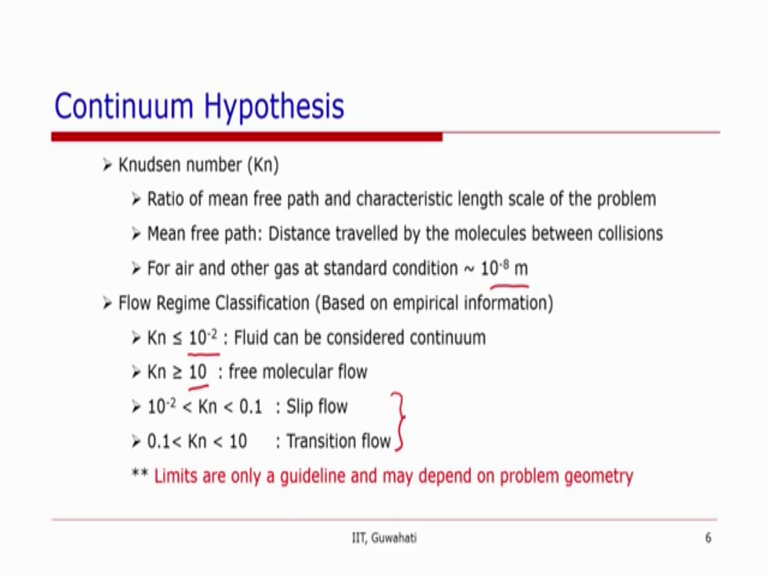

Continuum Hypothesis

- Knudsen number (Kn)
  - Ratio of mean free path and characteristic length scale of the problem
  - Mean free path: Distance travelled by the molecules between collisions
  - For air and other gas at standard condition ~ 10^{-8} m
- Flow Regime Classification (Based on empirical information)
  - $Kn \leq 10^{-2}$: Fluid can be considered continuum
  - $Kn \geq 10$: free molecular flow
  - $10^{-2} < Kn < 0.1$: Slip flow
  - $0.1 < Kn < 10$: Transition flow
  - ** Limits are only a guideline and may depend on problem geometry

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So, if we look at the continuum hypothesis. It is often described or determined by a non-dimensional number, or it can be described by a non-dimensional number which is known as Knudsen number. And this Knudsen number is the ratio of 2 length scale, one is the length scale for the molecular motion which is mean free path of the molecules, and another one is the character length scale of the problem or of the system or of the channel that we are looking at.

So, when it is obvious that, when the mean free path is very small or the sufficiently small then the character skill characteristic length scale of the problem, then we can assume or that or then we can use the continuum hypothesis, then the continuum hypothesis will be valid. So, for a low value of Knudsen number where means; that means, a low value Knudsen number means mean free path is very is very small, then the characteristic length scale of the problem the continuum hypothesis is valid.

So, for those who do not remember what mean free path is, the mean free path is the distance traveled by the molecules between collisions. So, the molecules of a fluid they are moving continuously in the fluid; they have a thermal fluctuations, and because of that they will collide with each other very frequently. So, the distance that the molecules on in an average traveled between the 2 collisions, that is called mean free path. And for air and other gases; this value is as you would expect that, this will be the largest out of the 3 phases. It will be largest for the gaseous phase. So, that is about the order of 10 to the power 8 meters for air and other gases.

So, it can be considered, the literature suggests that when the Knudsen number is less than 10 to the power minus 2, then fluid can be considered continuum. And when it is greater than 1 then we have to consider it as free molecular flow and in between there are 2 different classifications slip flow, and transition flow with. So, based on this, we can see that in a channel, the characteristic length scale will be few microns.

Say let us say 10 micron. So, in such a case the Knudsen number will be above 10 to the power minus 2. So, the continuum hypothesis will often be valid in microfluidics. Having said that one of another effect of continuum hypothesis is slip boundary condition at the solid surfaces. And it has often been a contentious issue that is there a no slip condition, at the microchannels or is there slip condition at the in microchannels.

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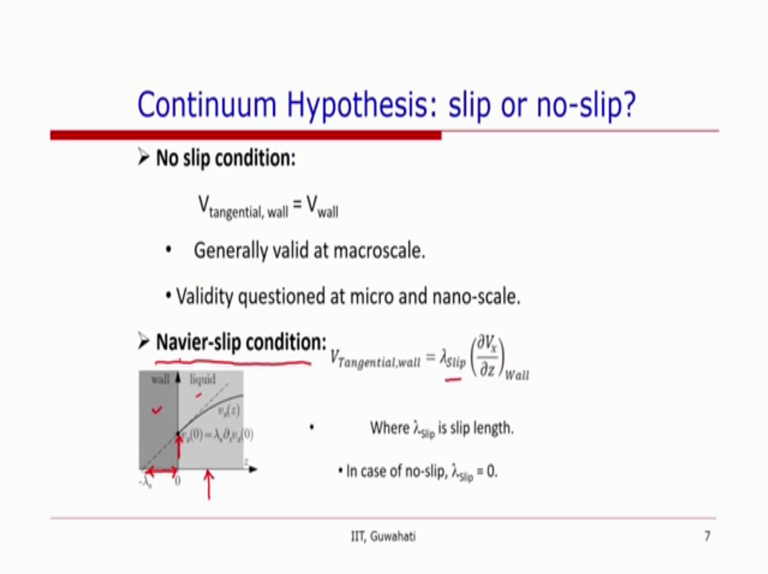

Continuum Hypothesis: slip or no-slip?

- **No slip condition:**

  $V_{\text{tangential, wall}} = V_{\text{wall}}$

  - Generally valid at macroscale.
  - Validity questioned at micro and nano-scale.

- **Navier-slip condition:** $V_{Tangential,wall} = \lambda_{Slip}\left(\frac{\partial V_x}{\partial z}\right)_{Wall}$

  - Where λ_{Slip} is slip length.
  - In case of no-slip, $\lambda_{Slip} = 0$.

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So, let us look at what does this no slip and slip business each above. As we all know if you have done a course an undergraduate course in fluid mechanics and we have studied about the viscous fluid flow, then you will know that at a surface, the no slip conditions refers that on a surface, the velocity of the fluid will be equal to the velocity of the surface. So, that means, there is no slip between the solid surface, and the liquid layer adjacent to it. This is um the only this from the empirical from the experimental observations. So, other some experiments in microchannels have suggested, that there is some amount of slip at the walls. However, another group of researchers, another school of thought is that the slip behavior that has been observed in microchannels is because of the roughness effects or the air trap in the channel, and not because that there is that the no slip condition is not valid.

So, I would suggest you to be aware about the fact that in microchannel there can be a no slip condition and due to analyzing data, you should look at these effects we will talk about this a bit in detail in later lectures. I would also like to point out here that, when there is slip condition, it can often be modeled using navier slip condition; which suggests that if this is your wall, and the liquid flowing adjacent to a it if say from bottom to top, then in case of slip, the there is some non-negligible velocity at the wall. And if you consider a linear variation of velocity inside the wall, then the length at which the velocity will be 0 is known as an area slip condition.

So, the parameter for such a model for the slip will be the slip length, which is lambda slip, and this has to be either found out from experiment or some other means ok. So, the next size effects we are going to discuss is about surface dominance.

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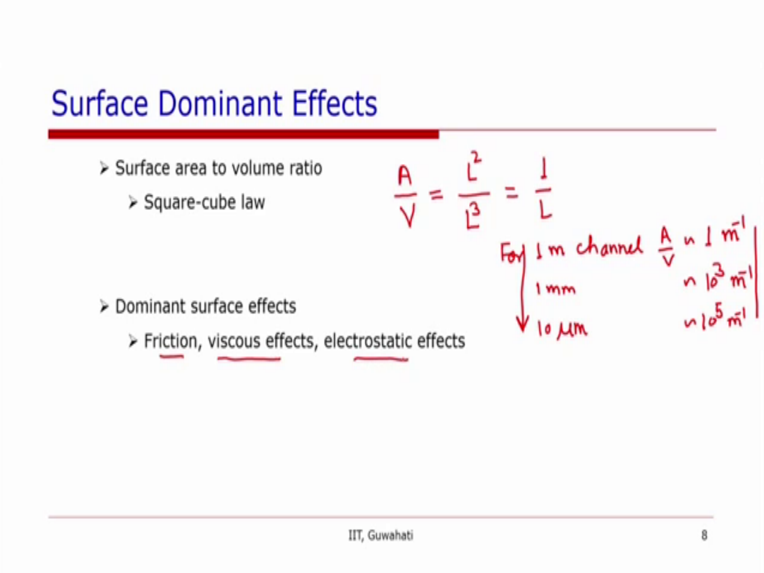

Surface Dominant Effects

- Surface area to volume ratio
  - Square-cube law
- Dominant surface effects
  - Friction, viscous effects, electrostatic effects

$$\frac{A}{V} = \frac{L^2}{L^3} = \frac{1}{L}$$

For 1 m channel $\frac{A}{V} \sim 1\ m^{-1}$

1 mm $\sim 10^3\ m^{-1}$

10 μm $\sim 10^5\ m^{-1}$

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So, In microchannels surface area to volume ratio. So, let us write this surface area as A and volume as V surface area is proportional to length squared. And volume which proportional to L cube. So, we will have this as 1 over L. The ratio of surface area to volume varies with respect inversely proportional to the length. So, for one-meter channel, this value will be about 1. For 1 mm it will be about 10 to the power 3. And for 10 micron is value is going to be 10 to the power 5. And that is what makes surface effects so important in microchannels. If we look at number of physical effects, some of them are proportional to the volume, and some of them are proportional to the surface area.

So, in general this ratio in a conventional channel or in a macro system a by V is small surface effects may not be so dominant in large channels. But as we can see as the size decreases, this ratio becomes important, or this ratio becomes larger and larger. So, surface force which become important in large diameter channels. Now we need to look at a bit in detail, what these surface effects can be. So, as I have listed here these can be friction in liquids, this can be viscous effects can be electrostatic effects.

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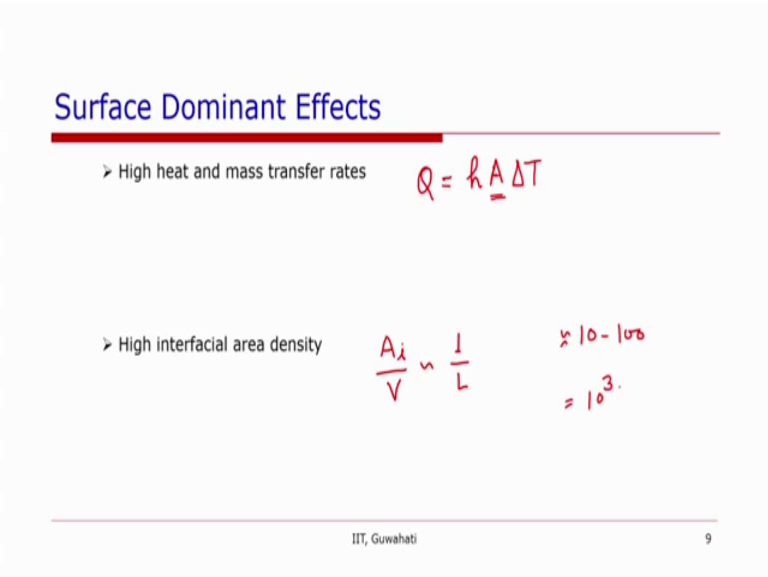

Surface Dominant Effects

- High heat and mass transfer rates $Q = h\underline{A}\Delta T$

- High interfacial area density $\frac{A_i}{V} \sim \frac{1}{L}$

$\sim 10-100$

$= 10^3.$

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So, and at the same for the same region, you might here that in microchannels, the heat and mass transfer rates are very high. So, if you write the heat transfer rate for convective heat transfer, you will write Q is equal to h A delta T; where A is the area of the surface. So, this area of the surface or the Q is proportional to the area of the surface. Similarly, in the mass transfer the rate of mass transfer is proportional to the area of the surface.

So, higher the area per unit volume; which is interface or a which is area density. Higher this area higher the rates of heat and mass transfer going to be. So, that is the region that in microchannels, there are number of heat transfer applications of microchannels. For example, in electronics cooling. In 2 phase flows or in multiphase flows, say for example, gas liquid flow the interfacial area that one can achieve in microchannel is 2 or 3 order of magnitude larger, than one can achieve in smaller channels in general.

So, the interfacial area density is the interfacial area, we represent this by ai per unit volume is again proportional to 1 over L. And whereas, the interfacial area will be order of 10 or 100 in conventional channels it can go up to 10 to the power 3 or more in microchannels. So, it will be beneficial, or it will be advantageous to conduct fast gas liquid reactions. For example, which are limited by the rate of mass transfer. So, if one have high interfacial area density; that means, if one have high interfacial area available for the mass transfer, then the rate of mass transfer will be high, and the yield of the fast reactions can be bettered in microchannels.

Similarly, in the electronics cooling, or where one need to remove high heat fluxes any such applications, one can remove very high heat flux is by the use of microchannels ok. Now coming at the third effect which is you can see another surface effect, that in microchannels the viscous forces are dominant.

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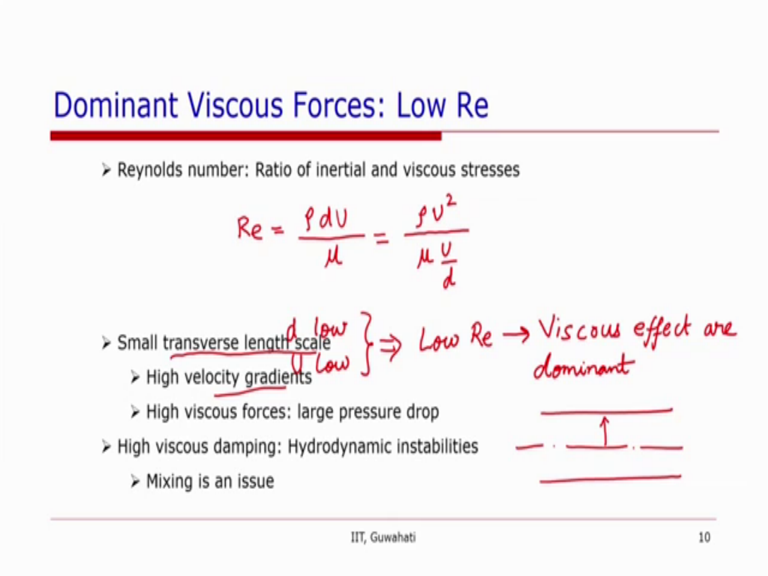

Dominant Viscous Forces: Low Re

- Reynolds number: Ratio of inertial and viscous stresses

$$Re = \frac{\rho d U}{\mu} = \frac{\rho U^2}{\mu \frac{U}{d}}$$

- Small transverse length scale
  - High velocity gradients
  - High viscous forces: large pressure drop
- High viscous damping: Hydrodynamic instabilities
  - Mixing is an issue

$\left.\begin{array}{l} d \text{ low} \\ U \text{ low} \end{array}\right\} \Rightarrow$ Low Re → Viscous effect are dominant

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So, viscous force they can be represented by a Reynolds number; which is the ratio of inertial forces and viscous forces or in terms of this the stresses.

So, Reynolds number is generally defined as rho d U over nu where U is the velocity of the fluid. And we will also try to see here, how we can represent this in terms of the 2 stresses. So, mu U over d, which is the length scale of the problem. And inertial stress is generally represented as rho U square. So, the ratio of rho U square and mu U by d is the Reynolds number. And at low length scale, the d is low say microchannels the d is low, the velocity will also often be low. So, we will have low Reynolds number. That in turn mean that viscous effects are dominant. So, viscous effects are dominant. And the other thing is that the transverse length scales are small.

So, when the viscous effects are dominant; that means, the flow is laminar. Now in general in conventional channel flow is often turbulent. So, the turbulent fluid means, that there will be a number of ades, and the mixing of the fluid occurs because of the turbulent flow, in a number of applications especially in chemical engineering one need to have the mixing of the fluid. So, where as one can achieve the mixing by the turbulent nature of the flow it becomes a problem in microchannels.

So, if you look at the literature in microfluidics in last 2 decades, there have been a number of efforts or to devise different strategies to achieve mixing in microchannels, because this is not the flowage not turbulent there, and one need to devise new ways of mixing this can be by the means of electrokinetic effects utilizing the electrokinetic effects or utilizing a meandering channel, or or many other passive or active scales or active means of mixing.

So, this can be a disadvantage. But at the same time when one have the flow as laminar, then one can predict it very accurately. One can control it in a better manner. One can know what is going to happen and knowing that one can try to manipulate and control the flow, and do number of things precisely the way one wants to do. So, that is the advantage of having low Reynolds number, but at the same time it is also has a disadvantage that no inherent mixing is present in the flow. The small length scales or the transverse length scales are small, so that means, the velocity gradient in a channel.

So, if you look at diffusion that is happening, the length scale over which the diffusion is required is smaller and smaller. So, any diffusion process it might be momentum transfer which is discussed way where the diffusivity is or momentum diffusivity is kinematic viscosity, and it can be heat diffusion, or it can be a mass diffusion in all cases. The diffusion lengths are small. So, the gradients velocity gradient or the temperature gradients or the concentration gradient will be large, and the rate of that is transfer will be larger in the fluid flow because the viscous force is dominating. So, the pressure drop per unit length or will be larger ok. And we have already discussed that mixing is an issue, because the flow does not become unstable and turbulent. So, viscous damping dominate the flow in most of the cases ok.

So, one of the effects surface tension one of the surface effects that we have looked at in microchannels is that what can the viscous effects too now, another physical phenomena which becomes very important microchannels is surface tension.

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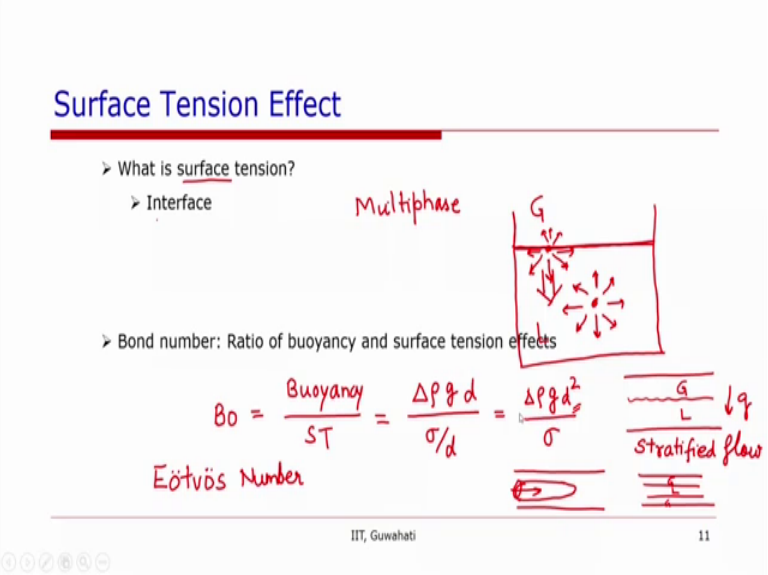

Surface Tension Effect

- What is surface tension?
  - Interface
- Bond number: Ratio of buoyancy and surface tension effects

Multiphase

$$Bo = \frac{\text{Buoyancy}}{ST} = \frac{\Delta \rho g d}{\sigma / d} = \frac{\Delta \rho g d^2}{\sigma}$$

Eötvös Number

So, what is surface tension? Surface tension of course, occurs at an interface. So, an interface is a boundary between 2 fluids. So, for surface tension to occur of surface tension requires that there is an interface. So, it is an multiphase phenomenon. If there is an interface, then it will have multiphase associated with it.

Now, what is surface tension? So, if we have a bulk fluid, let us talk about having a liquid, and a gas above it. If there is a fluid molecule in the center, it will be attracted by different molecules from all the sides. So, it will have an equilibrium. Whereas, a molecule which is at the surface, it will be interacting with the molecules in the bottom half with the liquid molecules. Whereas, the interactions with the gaseous molecules will be relatively weaker.

So, there will be a net tendency, or there will be a net pull on the molecules towards the inside. And that tension and that will be that is what in a microscopic sense or in a macroscopic sense is required to as surface tension, and because of this effects the fluid tends to minimize it is surface area, so that the surface energy can be minimized.

And again this is a surface phenomenon, and it happens only at the interface between the 2 fluids. So, as we have discussed previously, that when the surface area to volume ratio becomes higher surface tension becomes important. So, there are number of applications in microfluidics; where the surface tension effect or is taken into account or it is being explored or it is utilized to manipulate the droplets on liquid bubbles and so on.

So, there is non-dimensional number, which is called bond number, which compares the buoyancy force and surface tension force. And this is represented by sigma over d and buoyancy force is delta rho g into d. So, rho so, that will be delta rho g d square over sigma. So, this often this number is also known as eotvos number. And this is often used in gas liquid flow to demarcate a boundary between the minichannel or between the microchannel and the large channels.

So, this can be used to find out for a particular gas liquid system, at what size one will have the surface tension effect dominating the gravity force. So, for example, in large channels one often observe stratified flow; where the liquid is at the bottom the gravity is acting in this direction. And the gas is at the top and one call is stratified flow; however, in large diameter channels. So, one objects the stratified flow; however, in small diameter channels, because of surface tension the interface does not remain like this it one has annular flow and bubbles forming either one will have bubbles forming there or one can have annular flow where liquid in between and the gas.

So, the bond number is as you can see it proportional to d square. So, when the length size becomes smaller. The effect of gravity becomes a smaller, which is a body force and the surface turns and start dominating the flow. And we will see number of difference on.

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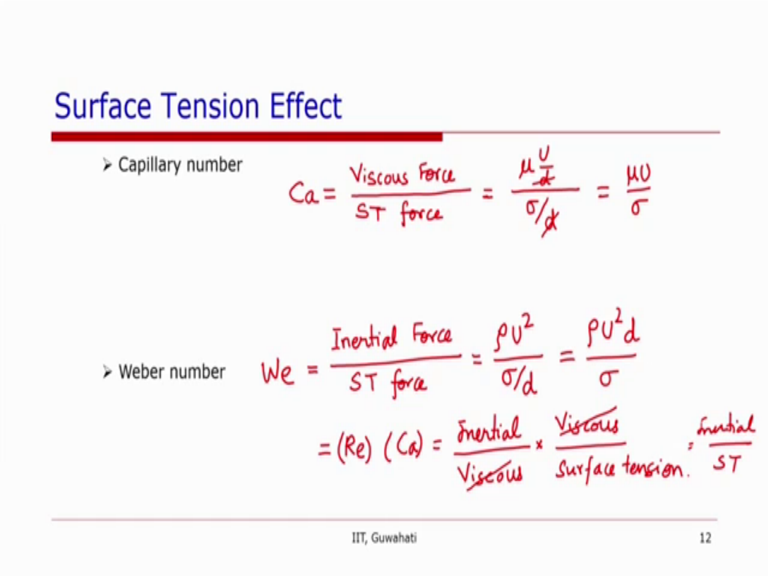

Surface Tension Effect

- Capillary number $$Ca = \frac{\text{Viscous Force}}{\text{ST force}} = \frac{\mu \frac{U}{\cancel{d}}}{\sigma/\cancel{d}} = \frac{\mu U}{\sigma}$$
- Weber number $$We = \frac{\text{Inertial Force}}{\text{ST force}} = \frac{\rho U^2}{\sigma/d} = \frac{\rho U^2 d}{\sigma}$$ $$= (Re)\,(Ca) = \frac{\text{Inertial}}{\cancel{\text{Viscous}}} \times \frac{\cancel{\text{Viscous}}}{\text{Surface tension}} \text{.} \; \frac{\text{Inertial}}{\text{ST}}$$

So, another non-dimensional number which compares surface tension, with another source which is important microchannels, which you can remember we have discussed just now is a viscous force and surface tension. We often define the ratio of these non-dimensional numbers in terms of forces. But in my opinion it is better to define this in terms of stresses, because that is what the generally write while deriving these. So, for example, viscous a stress is given by mu U by d. And surface stress or surface tension generated a stress is sigma over d.

So, this will be mu U over sigma ok. Another non-dimensional number which is called weber number, and it is a ratio of inertial force and surface tension force or the stress it because of the 2. So, the inertial stress is given by rho U square, and the surface stress surface tension it is sigma over d. So, this is rho U square d over sigma ok. So, that is weber number and one can see that weber number can be defined as a product of Reynolds number, and capillary number Reynolds number is inertial effects divided by viscous effects in capillary number is the ratio of viscous effects are surface tension effects.

So, this becomes the ratio of inertial and surface tension effect. So, by the way when we talk about liquid liquid, there also we have our similar effects present. But this will not be so dominant as in gas liquid, and this is often known as interfacial tension in the case of liquid liquid. In case of miscible liquids, the interfacial stress is 0. For example, between a salt water solution and fresh water solution and the interfacial stress is 0. Another effect that has been explored or utilized very well for several microfluidic applications another surface effect is called electrokinetic effects.

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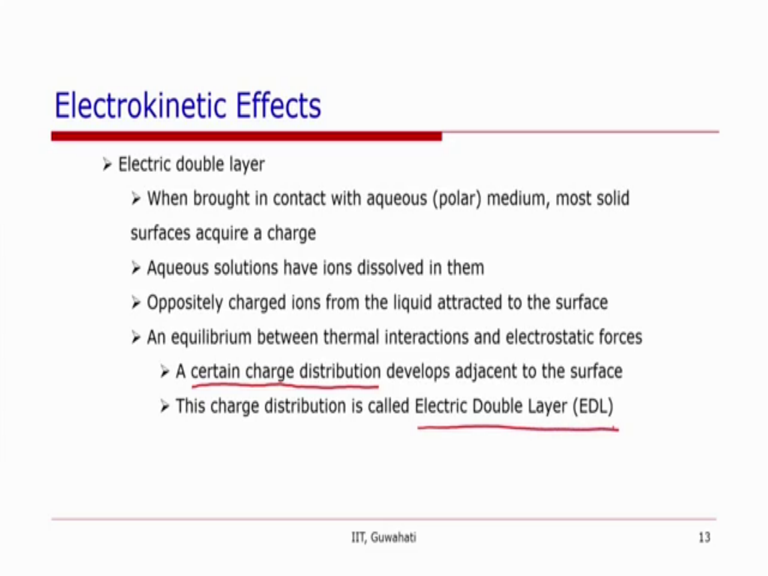

Electrokinetic Effects

- Electric double layer
  - When brought in contact with aqueous (polar) medium, most solid surfaces acquire a charge
  - Aqueous solutions have ions dissolved in them
  - Oppositely charged ions from the liquid attracted to the surface
  - An equilibrium between thermal interactions and electrostatic forces
    - A certain charge distribution develops adjacent to the surface
    - This charge distribution is called Electric Double Layer (EDL)

So, how does this combine? When we have a charged surface, or not not charge surface, when we have a solid surface, and it is brought into contact with a aqueous medium, which is polar which has ions present in the liquid, then there is a charge; that is established on the surface this charge, can be positive or negative depending on the conditions depending on the aqueous solution. What is there in the aqueous solution? Depending on what the surfaces. So, the surface acquires a charge, and now the aqueous solution has ions which are present in it in the aqueous solution and the surface has the charge.

So, as a result the the ions will have thermal motion as well as or the ions near the surface will have a electrostatic force because of the attraction or repulsion from the surface, or the from the charge present and the surface. So, a equilibrium will be established, and a certain charge distribution or a certain distribution of the ions will happen. Just adjacent to the surface and this charge distribution is known as electrical double layer. So, this electrical double layer does not have significant effect in large channels because it of any such effect can be neglected; however, this can be utilized for number of applications in electric in microchannels.

So, the 2 effects which are often used in microchannels are electro osmosis and electrophoresis.

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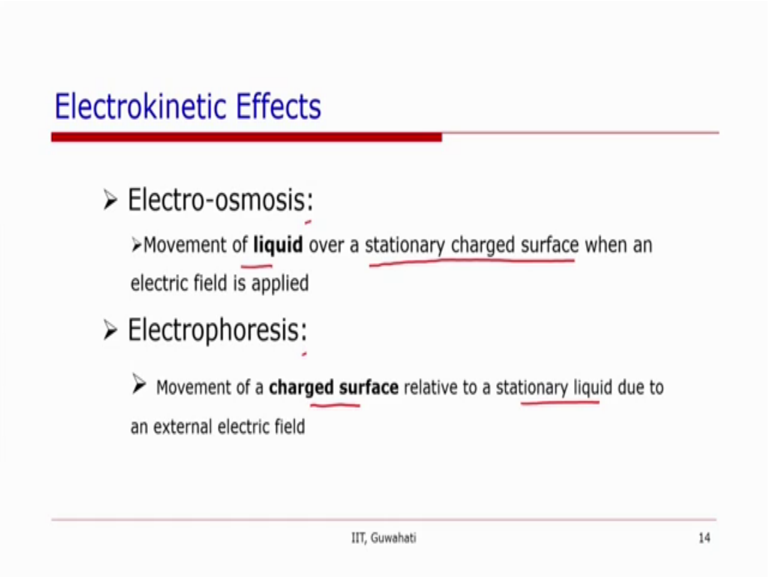

Electrokinetic Effects

- Electro-osmosis:
  - Movement of **liquid** over a stationary charged surface when an electric field is applied
- Electrophoresis:
  - Movement of a **charged surface** relative to a stationary liquid due to an external electric field

So, electro osmosis is that the stationary charged surface, which is not necessarily it is because of the electric double layer. In general, if the surface is charged and when a electric field is applied, the movement of liquid so, when an electric field is applied on a stationary charged surface and the liquid move, then it is known as electro osmosis. On the other hand, electrophoresis is that a charged surface itself moves related to a stationary fluid, because of an externally applied field.

So, you can see the difference between the 2 effects electro osmosis is that when an electric field is applied the liquid moves over a charge surface it is called electro osmosis. But when the solid or the charged surface itself moved related to the stationary fluid it is called electrophoresis.

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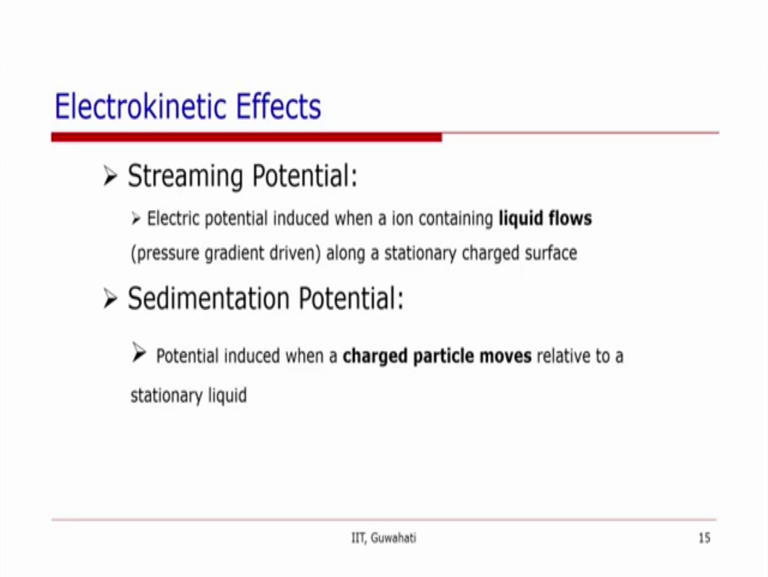

Electrokinetic Effects

- Streaming Potential:
  - Electric potential induced when a ion containing **liquid flows** (pressure gradient driven) along a stationary charged surface
- Sedimentation Potential:
  - Potential induced when a **charged particle moves** relative to a stationary liquid

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Now, 2 other effects which happens because of these electrokinetics 2 different potentials are induced, one is called streaming potential and another one is called sedimentation potential. So, electric potential reaches induced when a iron containing liquid, when a liquid which has iron and it moves over a surface which is charged, then the electric field or the electric potential that is generated, because of this is called streaming potential. So, because of the stream of the fluid which contains ions, and it moves over a charge surface the potential generated or potential induced, because of this motion is called the streaming potential.

On the other hands sedimental potential is the potential that is induced when a charged particle moves related to a stationary liquid. So, for example, a charged particle when it sediments or when it drops from top to bottom say because of buoyancy, then it will induce a potential when it is moving in a stationary liquid, then this potential is known as sedimentation potential.

So, in summary in this lecture what we have looked at what are the size effects which are important in microchannels. Initially we looked at 3 phenomena or the discussed 3 phenomena which might be important. One is the continuum hypothesis, we looked at what continuum is, and is it valid in microchannels, and it appears that most of the cases that we consider in microfluidics the continuum hypothesis is going to be valid.

But it is a good practice or one need to look at the validity, especially then was slip or slip boundary condition. Then comes the surface effects we looked at that because of the high surface area to volume ratio small scale, the surface effects becomes dominant; which causes high rates of heat and mass transfer, the diffusion paths are small, again which causes the high transport rates.

We looked at 3 specific surface phenomena viscous effects; which gives rise to low Reynolds number and the flowage laminar. Then the surface tension effects; which have number of interesting applications and the third one is electrokinetic effect. So, we will explore more and more the surface tension effects in this course. We will look at gas liquid flow more and we will look at both diabetic as well as adiabatic flow in microchannels. We will look at droplet microfluidics, bubble generation techniques etcetera, in the microchannels.

Thank you.