Microscale Transport Processes

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Module No. # 01

Lecture No. # 01

Introduction

I welcome you all to this course on micro scale transport process.

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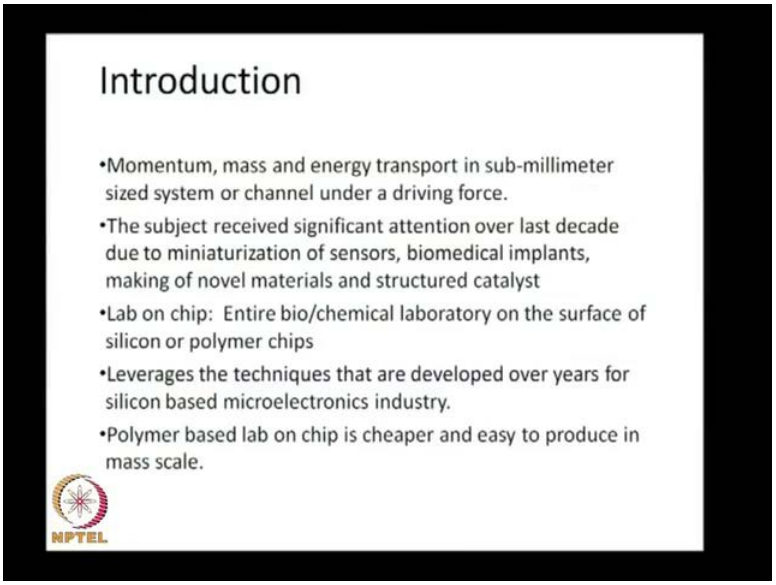

Let me give you a brief introduction of what this micro scale transport process.Why this course is important to you?Firstly this momentum mass and energy transport is sub millimetre size system or channel under a driving force that comes under the preview of this course.This, subject received significant attention over last decade due to miniaturization of sensors, bio medical implants, making of novel materials and structure catalysts.There are several other applications as well these are some of them I could think of right now.

There is one important application that primarily put this subject in a primarily added lot of importance to this subject which is known as lab on chip.That means entire bio chemical laboratory on the surface of silicon or polymer chips.What that means is that think of a say, somebody doing a blood analysis the way it is done is the blood is taken in a bottle and then, it is kept in a pharmacy shop then some reagents are added to it and the analysis is done on that sample.So, if some the patient goes there gives the blood and wait for a day and after a day the results come that this is this is the this is the result.

Now, if there could be a chip may be in a simpler way I can think of a say a credit card type object in which the reagents are already loaded and a blood sample is just added a drop of blood sample is added inside the chip.and theAnd then, this this reagent gets mixed with the blood sample inside the chip itself inside inside the credit card itself inside the credit card like object itself and then the then it gets mixed and finally, it is left inside inside that chip at some place where this sample can be optically interrogated, means something similar to swiping of the card inside a scanner

So if this instrument is sitting on doctor's table and a patient goes there she can go he can he can give the sample and immediately he can get the scan done and immediately he knows what the disease is. I mean some this is this is a kind of paradigm shift that is possible in in day to day analysis.This is just a just an example blood sample it could be just an effluent coming out of a chemical process plant chemical process out of a chemical plant some effluent stream is coming out and then that stream needs to be analysed.So, you take that in a bottle and then send it to the laboratory it takes it takes some time by that time there could be some changes taking place within the sample itself you never know.And then it goes there and it it goes goes all the way to the to the lab and then it would be analysed so there therethere instead of that if you can have a scanner and a chip and you go to the field where the effluent sample is coming out and if you can if you can get the scan done there.That nothing like it so that is kind of the idea behind putting this lab on chip what what is mentioned here in this slide entire bio or entire chemical laboratory on the surface of silicon or polymer chips.

Few people got enthusiastic about this idea is that it can leverage the techniques that are developed over years for silicon based microelectronics industry.If you can you if you can arrange transport of electrons so precisely inside a chip; so why not doing it for a laboratory analysis?So, that is we can leverage the leverage the technology that is

already there people have been developing for microelectronics industry to accomplish accomplish the design or production technique for lab on chip.

So and and there could be polymer based chips as well instead of silicon based you can have this chip made of polymer which is cheaper and easy to produce because it if it is a biodegradable polymer.It can be use it can be made on use and throw away basis.So, these are some of the things which is driving these driving thesethese micro scale micro scale processes or micro scale elements.The major major concern here is that major interest here is of course, miniaturization of sensors as I pointed out bio medical implants and making of novel materials and structured catalysts and there are more more interesting areas that are coming up.However, this lab on chip is one such example that I put here.

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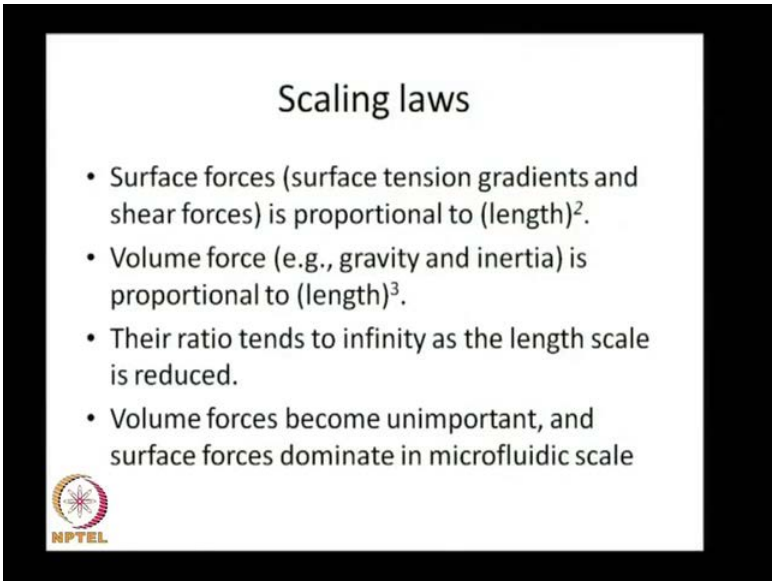

So, when we get to this micro scale transport process I mean you are already familiar with transport phenomena.You have already studied transport phenomena.The way it is different this micro scale transport process, the way it is different is that there are certain scaling laws which I need to visit first.The scaling law I can put it like this.

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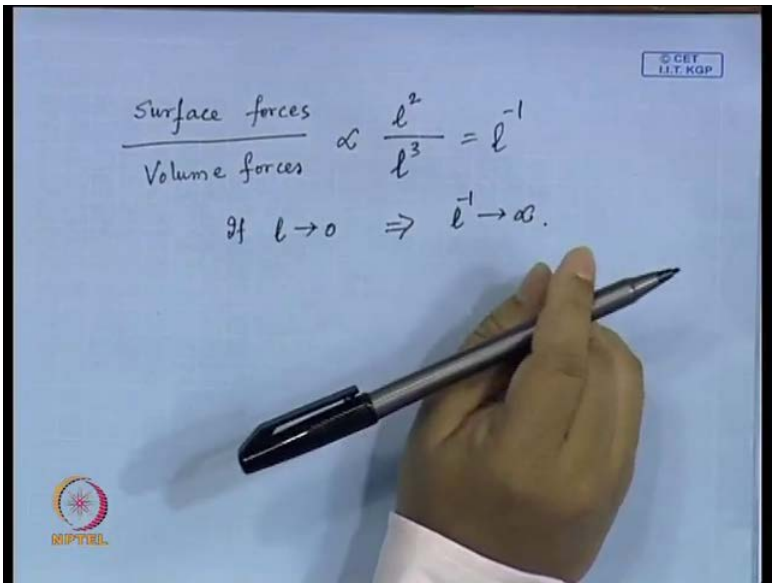

If you write surface forcesdivided by volume forces, by surface forces I mean surface tension gradients or sheer forces sheer stresses and volume forces are gravity inertia.So, if you write this you will find that this is proportional to the numerator is proportional to l square where l is the length scale, numerator is proportional to l square and the denominator is proportional to l cube so this is equal to basically l inverse 1.So, if l tends to 0; this implies that l inverse tends to infinity.

So what this means is that volume forces are volume forces become unimportant as you reduce the length scale.However surface forces become dominant.So, this is something which you have to keep in mind that we are more keen about accounting this surface forces rather than a volume forces in this process.

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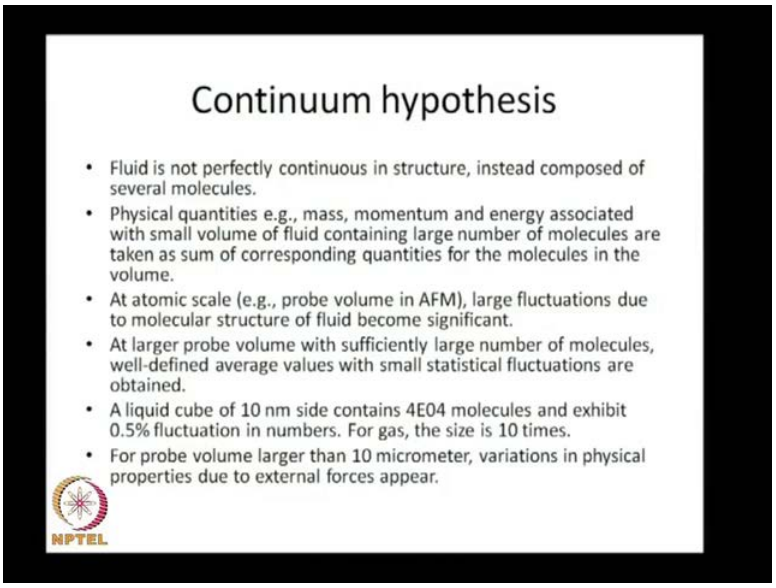

Another issue here in this in in in in micro scale transport process is that fluid is not a perfectly continuous structure instead it is composed of several molecules.You remember in fluid mechanics class we have studied Lagrangian formulation and Eulerian formulation.So, when you go to a reduced when you when you reduce your channel size I mean we are talking about l l tending to 0 when you go to that level whether the continuum hypothesis stands there or not that that that needs to be visited.The, what continuum hypothesis in this regard I mean let me put together; here it is physical quantity such as mass, momentum and energy associated with small volume of fluid containing large number of molecules are taken as sum of corresponding quantities for a molecules in a volume.What that means is, you take a volume around which you would like to know what is the mass what is the momentum and what is the energy associated with that volume ok.

So what you do is you sum up the all the molecules and sum up the corresponding quantities for all the molecules and you call that the mass.That means you you sum up the all the mass of the molecules and you call that a mass. I mean that is that is the idea of this continuum hypothesis.

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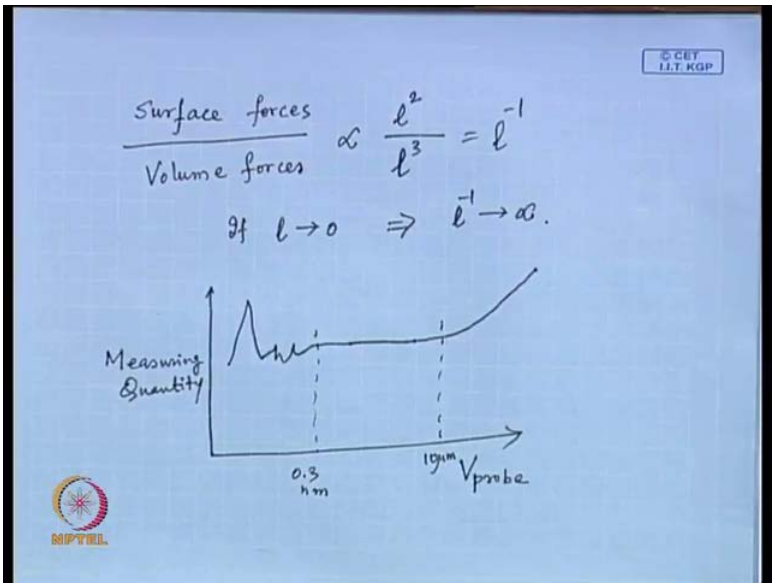

Now if you plot if you plot something called a measuring quantity.Suppose on y axis if you are if you plot something called measuring quantity and on the x axis if you plot volume of the probe, you are using a probe to find out what is the density or what is the pressure at a point.Now, the volume of the probe if measuring quantity is plotted as function of the volume of the probe you find a trend something like this. If you say if you if you are looking at an atomic force microscopy if if you look at atomic force microscopy and a volume of that probe you will find that there would be large fluctuations due to molecular structure of fluid.You take up you take a volume, you take a cube say now you can have the size of the cube, you can choose the size of the cube.If the size of the cube is the one side of the cube cube has cube is l cube basically volume is length to the power 3.If that length l is less than .3 nanometre you find that there would be some large fluctuations because then what you would be doing is the you would be measuring something where the molecules which are going in and coming out.They will be interfering to the observation so the measured quantity, the quantity that you measure that would be affected because of the molecule coming into that cube and the molecule leaving that cube.

However, if you increase the length scale if you if youincrease the length scale you will find that these variation subsides.This this the measured quantity becomes constant.The the measured quantity is not changing with the volume of the probe.It is it is you can I mean I can point out that when the side is if a for a liquid cube of side 10 nanometre that

means a cube of 1 side 10 nanometre that contains approximately 4 into 10 to the power 4 molecules and it has about 0.5 percent fluctuation in numbers.So, if your probe volume is a cube of side ten 10 nanometre you can expect 4 into 10 to the power 4 number of molecules sitting there inside and the number of molecules would be joining them and number of molecules would be leaving them that number is basically the fluctuation is basically restricted to 0.5 percent.For gas to have this same number of molecules and same level of fluctuation, you have to have 10 times the length.So, that is that is a typical example I can give.

Now, you will consider 10 nanometre side I mean if 0.5 percentpercent fluctuation is acceptable. I mean you do not probably care much about it.So, you can assume that whatever may quantity I measured that is just fine but, if it is as I said below .3 nanometre you will have a very large fluctuation.So, you cannot I mean you will not be that that cannot be that cannot be taken,that that kind of measurements I mean that measurement can be it would be interesting to study the other interactions but, if you want to take that as the average take take that as the representative quantity for that area that would be little difficult.

However, when we go to the higher side of it that means when it is more than 10 micrometre; you understand what a micrometre is. I take it you understand what 1 micrometre is.So, if it is a 10 micrometre that means you you express that in millimetre how much it would be?

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0.01 millimetre.So, if it is above 10 micrometre then I see that the measured quantity it has a turn it it is it is increasing.It is not increasing in a, it is not changing in a random manner but, it is increasing consistently.Can you, do you have any idea what could be the reason for this increase?The the reason here is that variations in physical properties due to external forces appear.Suppose, there is a fluid flow taking place, so pressure at 1 point has to be higher than the other point because fluid will flow from higher pressure to lower pressure.

So, these macroscopic changes I mean these these variation in physical properties due to external forces that will become significant.So it has to go either up or down. I mean I mean the the parameter will change or it can remain constant. I mean if the system if it is a static system if the system decides that yeah it should be constant.That that should that will remain constant but, if there is a variation that variation is due to external forces that can that you can take it is not because of molecular interactions.So, this so thesethese you can understand how the how the length scale how they play out here, how the length scale play out here and how these how the measuring; you have to be careful with the measuring quantity when it comes tocomes to working with these these scales.And ideally if you if you are looking for a measurement of physical properties per volume; it should be in that the this is this is referred as this is referred as microscopic region. This is referred as mesoscopic and this is referred as macroscopic.

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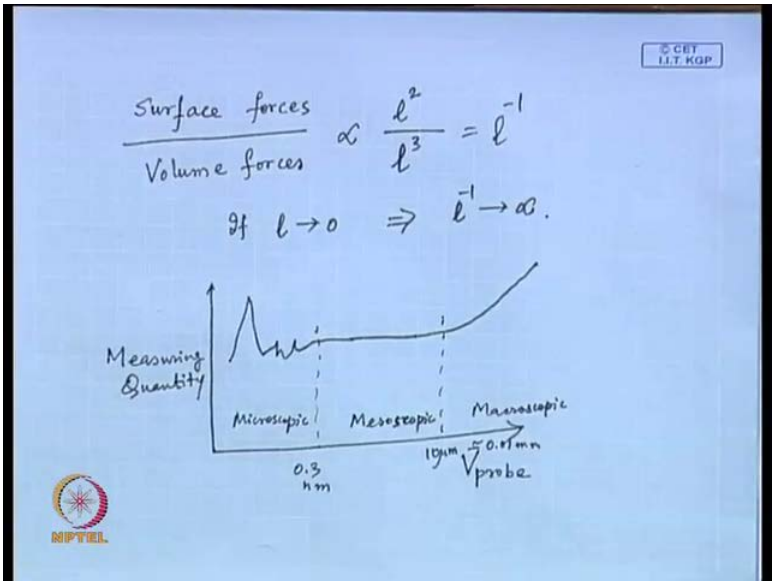

So, if you want to know some parameter per unit volume; you should be working in this region because you want to capture whether it is increasing or decreasing with external forces.So, you do not want to play want to work with this, your probe volume should not be there here but, this part would be just fine.If it is below this then you will have molecular fluctuations.You would be probably this this this is a very important part, this microscopic part if you can really gather this information.However, if you are treating it as aneulerian fluid then, you should be working with mesoscopic region.

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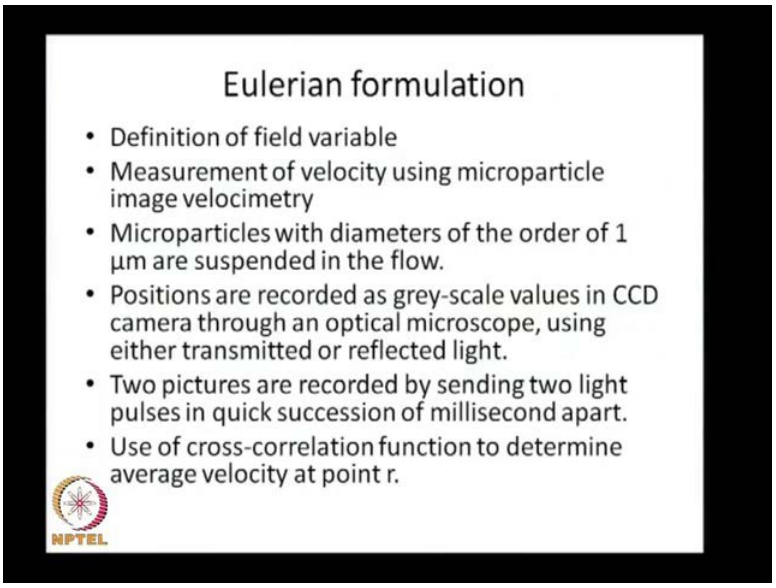

Now, when it comes to the Eulerian formulation there is a definition of field variable.There is a definition of a field variableA field variable is defined as the average value of corresponding mole molecular quantity.

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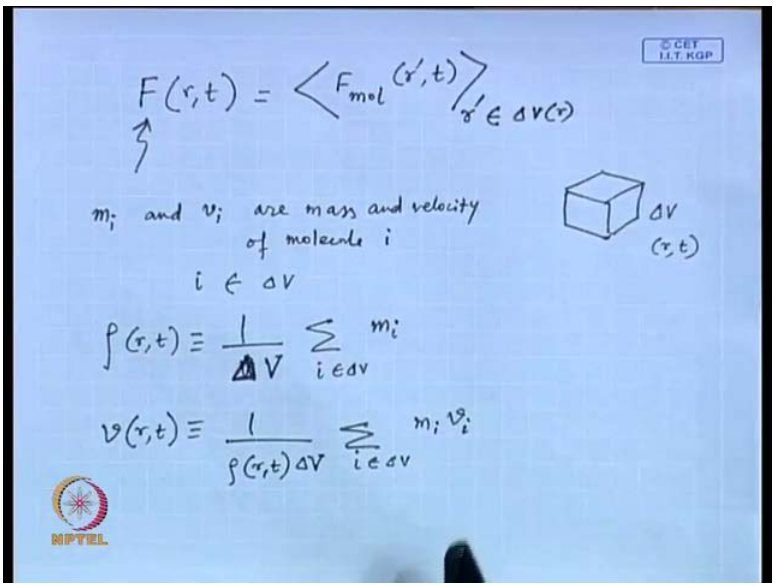

Let us say, let us write this expression as if r t is equal to average of some molecular quantity where this r prime belongs to this set.So, here if r t is defined as average value of, so this is basically average value of corresponding molecular quantity, if this f

molecular quantity are prime t for all molecules contained in some liquid particle,it in some liquid volume of delta v positioned at r at time t.

So, what you basically, what you are doing is you are picking up a volume which is at position r at time t and that volume is basically delta v.Within this volume, the molecules that are there, within this liquid volume the molecules that are there, you take them as if that corresponding molecular property is if molecule are prime t and that r prime belongs to that position belongs to this element this volume element.

So, if m I and v I m I and v I if they are mass and velocity of mass and velocity of molecule I of molecule I and if I belongs to delta v; then you can write you can define density as1 divided by 1 divided by delta v sum of I belongs to delta v m I and other expression that you have is say velocity as a function of r and t that is given as 1 divided by rho r t delta v sum of I belongs to delta v m I v I.So, what is done here is that you have defined these field variables you have defined these field variablesone is density, another is velocity and that is defined for all the molecules that are existing inside these volume element delta v.The velocity that we calculate here the density part is fine, you just sum all the masses and then you divide it by the volume but, the velocity that we calculate here this is a special kind of velocity what is that?

(( )).

This is this is this is not just average velocity it is it is there is a waiting factor involved in this.You you already you can and and I suggest you check the units to make sure that we have the, we put the expression.Put the unit of density put the unit of volume and find out that we have written the expression. So, this would be the this would be the field, this would be the field variable.Now, when it comes to measuring the velocity I mean why why we are treating it differently is that when wewewhen it comes to measuring the velocity; this measurement cannot be done by a Peter tube or other type of operators because we are operating at a scale which is too small.

So, if you want to measure a velocity inside a channel where the length is so small, this has to be done by some other method.The common method which is there in available is available in the sense it comes at a very high price tag is that measurement of velocity using micro particle image velocimetry.That is that is that is the name of that technique.The way this technique works is that micro particles with diameters of the

order of 1 micron are suspended in the flow.Micro particles of diameter 1 micron they are suspended to the flow.

Now, there would be a ccd camera that records the, through an optical microscope the transmitted or reflected light.So, there would be recording two pictures will be recorded by sending two light pulses in quick succession of millisecond, in quick succession which would be a millisecond apart and then there would be use of a cross correlation function to determine average velocity at point r.How is it done? In a CCD camera in a c c d camera the positions are recorded as grey scale values.

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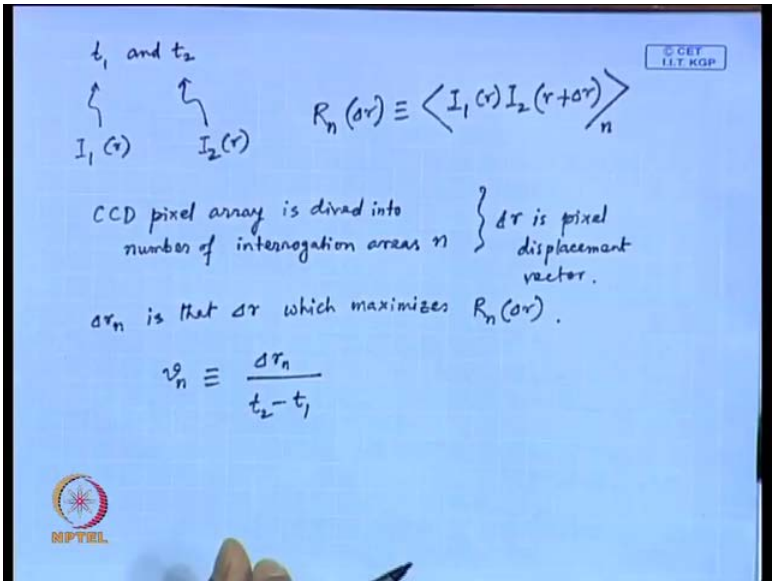

Now if it is defined say say that time the 2 light pulses they are in quick succession so, they are at time t 1 and t 2.So, at time t 1 there is a pulse light pulse and at time t 2 there is another pulse.The light intensities in each CCD camera, the corresponding light intensities in each CCD camera.

So lightlight intensity is given as I 1 r and in this case the light intensity is given as I 2 r. I 1 r and I 2 r r is a particular position and the camera records the light intensity.So, I 1 r is the light intensity at a particular position at time t 1 and I 2 r is a light intensity at time t 2 for that same position.What you do next is you write a cross correlation function which is defined as r n delta r which is equal to average of I 1 r I 2 r plus delta r, average over n.What is n?N is you youyou can say, you can divide the CCD pixel array c c d pixel array.You understand what is CCD pixel array is?There would be several pixels,so

you have an array of pixels that array is divided into number of interrogation areas number of interrogation areas n and within that interrogation areas you have an area of pixels, within that you have identified 1 interrogation area and that particular interrogation within that interrogation area, you are finding out this I 1 at a location r and I 2 at a different location I plus delta r.And this is averaged over all pixel coordinates in the given interrogation area n.And so delta r here is defined as delta r is defined as pixel displacement vector.Then, you choose delta r n such that delta r n is that delta r which maximizes r n delta r.

So, you are picking up an interrogation area and then you are calculating this cross correlation function and then you are finding out that delta r which maximizes this r n delta r and then you define velocity v for that particular interrogation area as delta r n divided by t 2 minus t 1.So, over this time instance t 2 over over this time interval t 2 minus t 1; you are finding out what would be the delta r? I mean how much this where is the over what delta are?The maximum change of intensity has taken place and that you are that you are relating to the velocity

So, this would be the way you will be measuring velocity at a point when it comeschannel of this length scale.So, you can so similarly, so, you can you will see that there is there is a shift of the way the the way we think about convectional measurements.So, all of them will shift as you go to these length scale.This is I i just give you 1 example how the velocity is.Velocity can be calculated inside a micro channel and this entire this this pictures are taken through an optical microscope mind it.saySo we can understand how how this whole thing works.What I will do next here is I will try to identify some of the application areas that these micro scale processes, where the micro scale processes will be useful.The number one, I mean let me identify this lob on a chip application because if I read some review article on micro scale processes.

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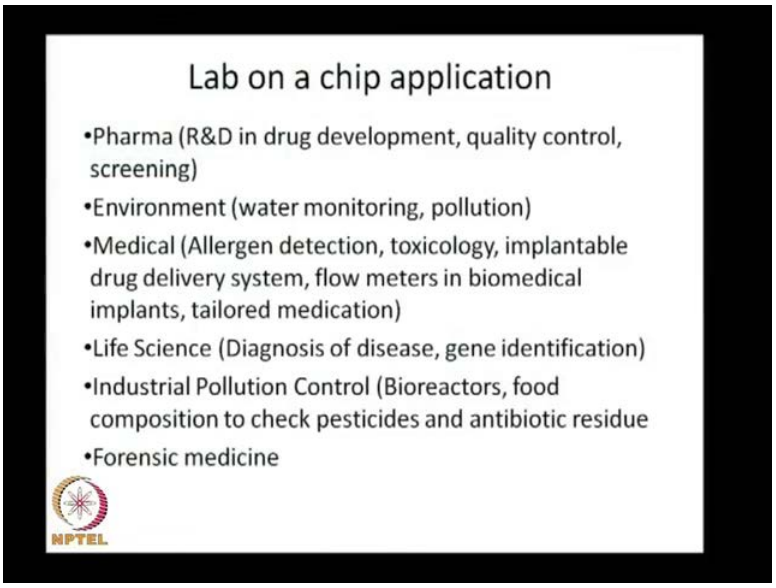

If ifI if I this if I read this if I read any any review article on micro scale processes I find this lab on a chip is something which people find very promising. I mean this these has lot of promise and there would be lot of thoughts put to it.So, there are applications which are identified here in this list.There are pharmaceutical applications r and d in drug development, quality control and screening.In layman's term where what this is all about is; a particular drug when it suppose somebody identifies a molecule that these molecule can cure so and so disease but, from that point to having this in market under some trade name that takes long time, lot of effort from scientists because that drug has to be stable inside human body because in human body itself is a chemical factory.There are lot of chemicals floating around inside.

So this drug has to,drug should not react in a in an unwanted manner with those chemicals.So, you have to first ensure what the reactions would be towards various chemicals towards different conditions.So, this drug molecules has to come into contact with various other chemicals and you have to see what would be the product.

So drug screening a drug screening is a major application where drug has to that that particular molecule has to come in contact with several other chemicals and you have to study the interaction.So these processes I mean you can do it in a bottle of course, however if you do it in a bottle there are issues like you need more chemicals. I mean here the requirement of chemical is much small.Much smaller and you can automate this

whole process in a chip but, there it has to be done manually or through some robotic arm.So,you here the the process can be if if this this a for pharmaceutical uses for r and d and drug development, quality control and screening this kind of lab on chip could be very useful.

The second area of interest here is environmental where water monitoring and pollution control is involved. There you would like to know the concentration of pollutants as it comes out, as it is generated.So, there I i have already discussed this lab on chip would be useful.Then there could be some medical uses, allergen detection toxicology.Then implantable drug delivery system these are very important application.The drug delivery will be done but, it will be done in a tailored manner.It is not that all drug is added to the human body at a time.It has to be released when you want it to be and at the rate you decide.

Then flow meters in biomedical implants; how much of drug released, from where or or the the biomedical implants are used or a there is huge amount of research going on in biomedical implants for various reasons.Then tailored medication; the the drug would be released only when it is required or when and how we want to that that you decide.it'll it it is not the the natured has not decide rather you control it.

Then the life science that has lot of lab on chip has important application in that area as well.Diagnosis of disease, gene identification then industrial pollution control, bioreactors, food compositions to check pesticides and antibiotic residue, tasting of food there the lab on chip has important application because again you need to you need to analyze then and there at the point where the food is being used or food is being generated.There itself you want to use it there there itself you want to analyze it.You you cannot afford to send this to a lab and wait for two days because by that time the food will perish.

The forensic medicine that is also another or rather forensic forensic applications that probably the,one would be forensic applications where the sample is too small and you want to know what that what that is all about.A blood stain is there and you want to know whose blood I that so there you cannot afford to have, large volume of sample and large and you cannot treat it with a large volume of free agent here the sample size itself is very small.

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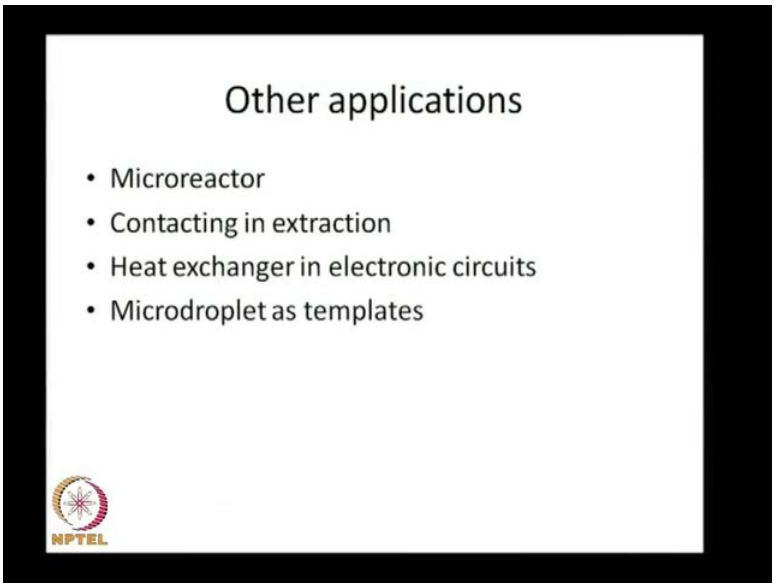

There are other important application 1 application is micro reactor micro reactor there instead of having a packed bed catalyst where catalyst are arranged in a random manner you can have a structure similar to honeycomb with the channel internal walls of the channel could at be the catalyst there you have a very structured catalyst instead of a random one.You can have extraction chamber made I am talking about solvent extraction using this.Then heat exchanger in electronic circuit that is another area, micro droplet as templates you need to generate micro droplets in various applications and there these micro fluidic devices are important.

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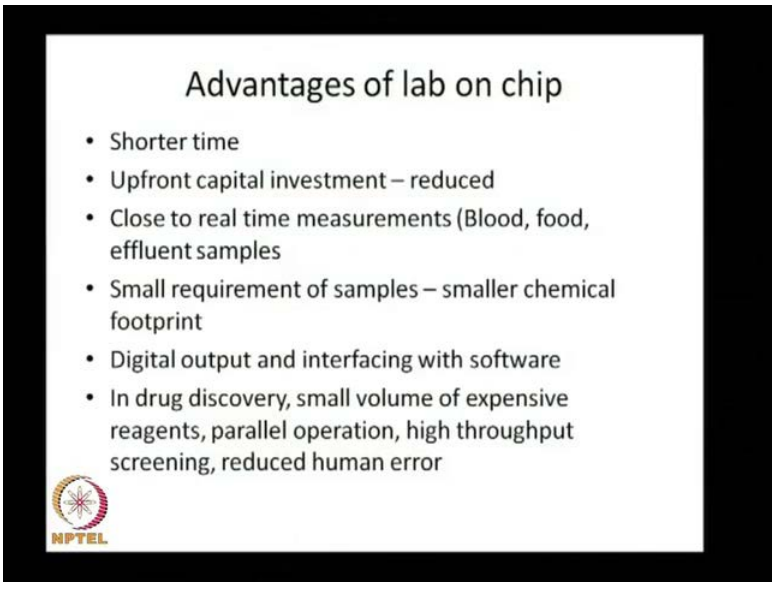

The advantages of lab on chip:The advantages are number one, shorter time if that has to done manually if the analysis has to be done manually.You have a reagent somebody has to add it.Suppose 10 reagents had to be tested to find out what is the target? I mean the sample you have to mix with 10 reagents to find out with which reagent this sample is reacting and from that you try to find out the characteristics of that sample but, mixing it manually if it will take long time but, if you have 10 such channels engraved inside the chip that would be much easier.Second point is upfront capital investment reduced.If you do an analysis using a spectrophotometer which is say which is which can scan over a wide range of wavelength you have to invest that.You have to invest some money to purchase a spectrophotometer but, instead of that if you can make some instrument which can scan only at one particular wavelength.So, that way you do not have to you your your expenditure would be less.Of course, that instrument will not be useful at other wavelengths.However, if this instrument you want to dedicate that instrument completely to the analysis of that particular sample then it is fine.Then you are not going to use any other samples or you know this is the optimum, this is the wavelength setting.So, instrument is meant for analysis of that particular sample.

So that way you can reduce upfront capital investment.Suppose, somebody wants to analyze water in a swimming pool; so he need not have to make a complete lab makes to the swimming pool very comprehensive, very detailed lab to analyze the water.He can have just a small scanner in which he can analyze the water sample.So, that that is that is probably the idea people had in theremind when they are putting up these proposals that yes lab on a chip could be useful etc.

Now, the next point is close to real time measurements; blood, food and effluent samples.You can you can measure as I said, you can measure the sample then and there wherever the sample is generated instead of putting it in a bottle and waiting for another twelve hours to get to the lab and next to a the instrument.So, that advantage is there.Small requirement of samples and smaller chemical footprint, you use 10 chemicals to find out with which reagent, which one the sample reacts in the way you thought and then what will you do with those chemicals.You have to throw them on; the, I mean throw them out in the environment.So, here the chemical footprint would be much less in this if such such type of application is picked up.Then a digital output and interfacing with software that is possible because you check the colour.It is changing from rate this

colourless to purple and you have ways to measure that colour.But, instead of depending on human eyes, you can have you can do the measurement in a digital manner.So, that is that that isone of the objective of bringing this lab on chip in drug discovery small volume expensive reagents parallel operations high throughput screening and reduced human error.

So in drug discovery this these added features that this lab on chip brings.So, these are some of the advantages people put together. I mean if I if I pick up a book on micro fluidic devices I find that they say lab on chip is something which would be driving the micro scale transport process research and this is something people are looking forward to.Of course, it is it is it is not yet available in inin some places for example, in drug discovery people are already using few things there and some companies are already there who are who are in fact the in their websites they show how them what kind organelles lab on chip they build, the pictures etc but, this is something which they which people expect out of a lab on chip and that is why they are a kind of getting interested into it.

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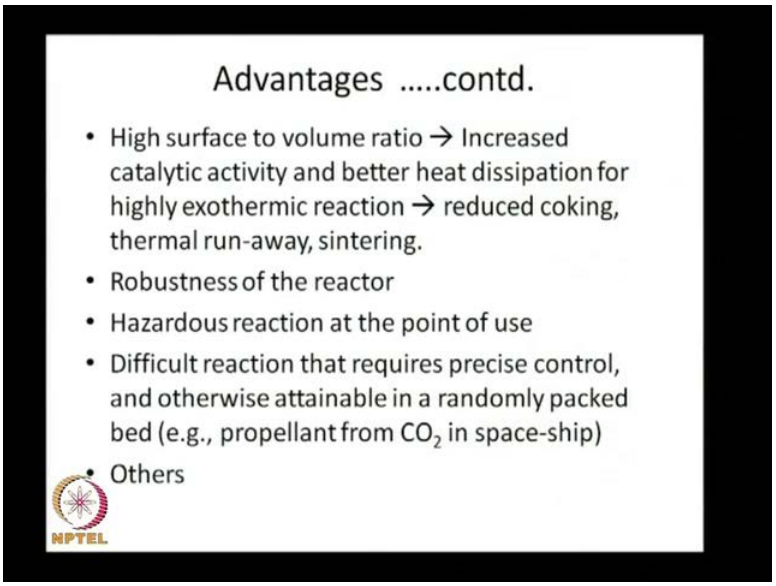

All this generally comes under the censor and controlled release under the under the subject of censors and controlled release.Advantages continued; when we go for a microstructure catalyst as I said instead of having a random randomly packed bed you can have a monolith.Something like a honeycomb with internal walls coated with a

catalyst that we call a structured catalyst.There you can have high surface to volume ratio which is which means increased catalytic activity and better heat dissipation for highly exothermic reaction.If you load the in one place, again you think of a pro volume if you load your catalyst randomly in some places suppose as the as the as thetwo streams enter into a packed bed randomly packed bed catalyst a randomly packed bed of catalyst as the two streams enter it is encountering the catalyst on the way in some volume they find that the catalyst loading is much higher and in some volume they are finding catalyst loading is much lower.

So, accordingly the conversation also would be guided by the amount of catalyst it encounters.So, there could be if if it if too much catalyst is there could be extraneous reactions setting in, there could be thermal runaway.That means lot of heat gets generated and if extra heat is generated and if it cannot be dissipated if it cannot flow quickly.Then there would be sintering taking place the catalyst gets destroyed and also if there is unwanted products generated that will also result in poisoning of catalyst.

So you reduced thermal run-away ant reduced coating thermal run sintering and for these purpose if you if you can have a structured catalyst that means if you can have the channels that are if you have channels whose dimensions are all all uniform everywhere; so in that case this problem does not arise and if you can create more surface area per unit volume in those channels, nothing like it.So you can you youyoumore more catalytic activity induced in this.So, these are these are the advantages for which people are interested in getting into these microstructure reactors.Of course, I mean why they are not getting into these I mean if so, much of advantages are there is of course, the cost because we are talking about borrowing techniques from microelectronics industry and microelectronics that will not come very cheap.And people are used people are used to have in catalyst pellets and randomly packed beds because those are cheaper.

The other issue here is the robustness of the reactor.theIf you have a monolith structured monolith the reactor you can expect the reactor to be more robust.You can have hazardous reactions at the point of use.Suppose some hazardous chemical is required for some use you need not have to make that hazardous chemical and transport it all the way.You can generate that hazardous chemical at the point of use where you are going to use it actually.Difficult reaction that requires precise control and otherwise difficult reaction that requires precise control and otherwisenot attainable please change this.It

should be otherwise not attainable in a randomly packed bed.It should be not attainable.So, difficult reactions that require difficult reaction, that requires precise control and these reactions are otherwise not attainable in a randomly packed bed such as making of propellant from carbon dioxide in a space shape.So, this is some this is some kind of reaction where you need very precise control.So, that kind of control is a possible in a microstructure catalyst rather than in a randomly packed bed ok.

There are other advantages as well and of course, on the, so nothing comes free.On the disadvantage side of course, it is there, the cost.

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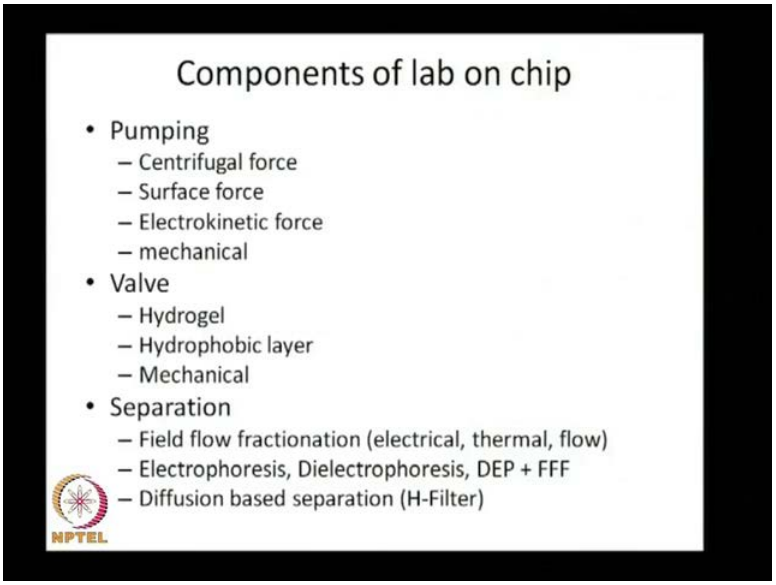

Here I briefly identify the components of lab on chip.The components that are there I mean that these these components need to be there otherwise you cannot construct, otherwise you cannot accomplish the objectives that I mentioned just now.The components are there has to be some pumping element because reagent and the sample that has to be pumped inside the channel inside the channels which are engraved on the chip.Then there has to be some valve arrangement some fluid will flow when under certain condition and it will not flow if that condition is not made.So these these imposed flow I mean I mean you should be able to control the flow in wherever location you wantinside the chip.theThere has to be some separation modules in in conventional mass transfer.We conventional chemical engineering operations we this is a major operation

separation separation.It can be separation of particulates from a liquid stream,it could be other type of separations as well.So, that has to be accomplished inside the chip.

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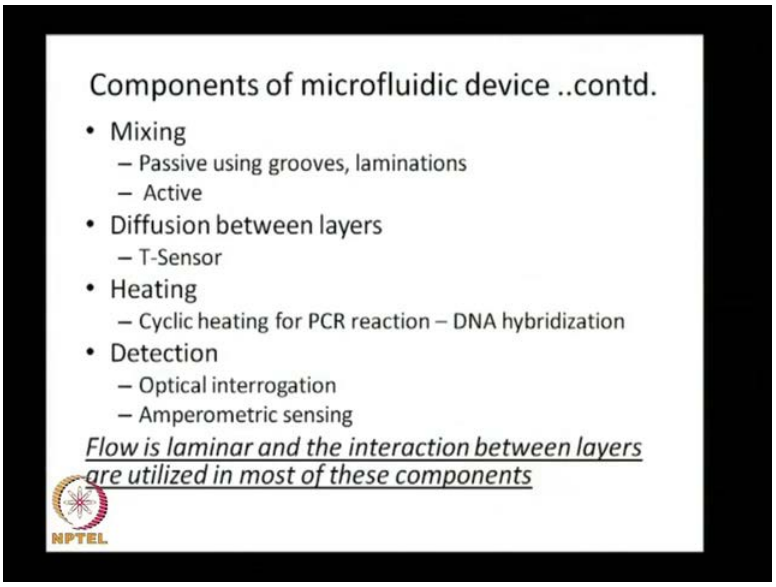

I will go into the details of these.Let me first point what all other components are there.There has to be some mixing elements inside the chip,there has to be some kind of mixing element.This mixing is done in a conventional chemical process and if you are having sample and a reagent, then sample and reagent they are have to mix.There therethere could be heating heating is also another important issue.At some point the stream maybe heated.So, that that is also one issue,one major aspect here which you probably have not studied that much in a conventional operations is detection because this whole purpose of this analysis is itit is. Basically censor or a biomedical implant.So, detection is a major component you have to detect the because finally, the objective is to detect the sample you have collected some sample and you want to find out what pathogen is there.So, whether that that water can be used or not so the pathogen has to be detected so there has to be some detection unit which is which probably you not that much familiar with.

So, these are some of the elements that we have and in the next class what I will do is I will discuss one by onehow these elements can be arranged in the, how these elements can be arranged inside the chip.One thing you must remember here that the flow is laminar and interaction between layers are utilized in most of these components.You will

have laminar flow.There will not be any turbulent flow inside the channel and laminar flow means one layer is sliding against the other and diffusion between the layers that you will try to utilize in many of these operations.With that I stop here for today.In the next class I will go over these elements in little bit more detail and we we will find out how we can implement these elements inside a chip.

Thank you.