Microscale Transport Processes

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Module No. # 01
Lecture No. # 02
Introduction

Good morning.

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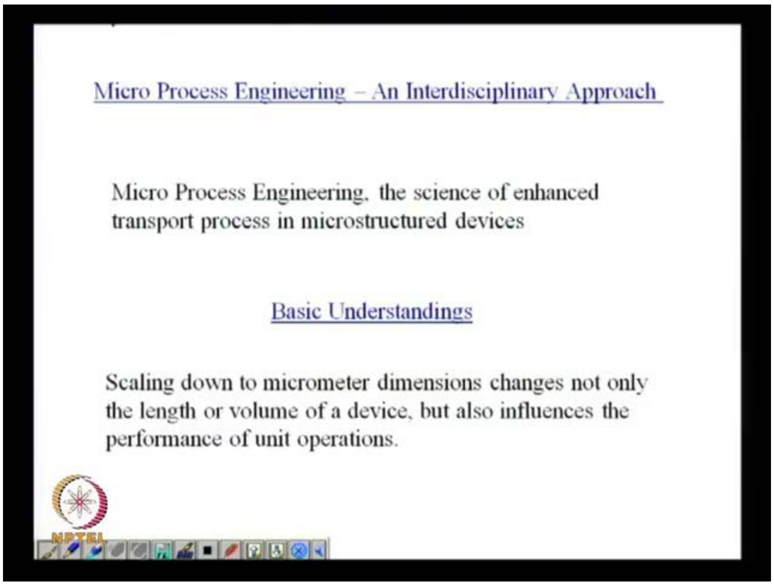

We are going to start our part of the course micro scale transport process with an introduction in micro process engineering which is an inter disciplinary approach.

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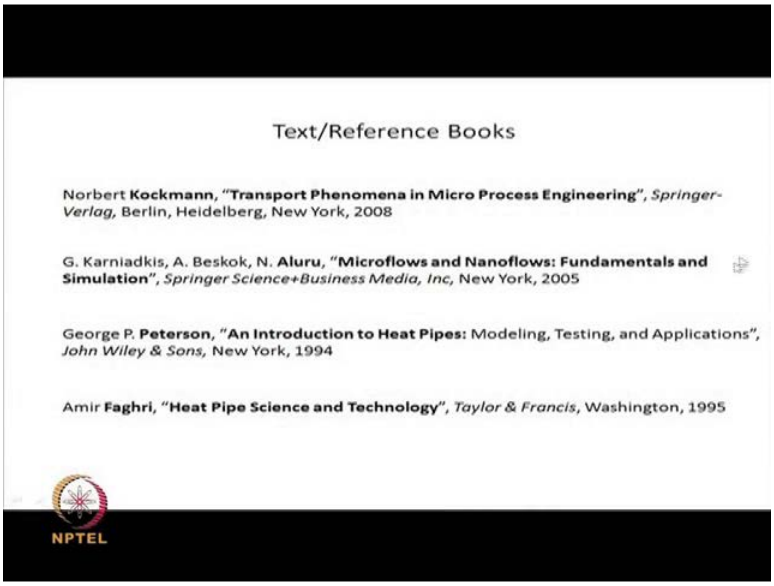

And towards the middle of this lecture,we would see how different branches of science has enriched micro process engineering and which is quickly becoming an effective tool for physicists, chemists and the engineering issues involved are immense.So, we would like to how the micro process engineering which is a science of enhance transport process in small devices.

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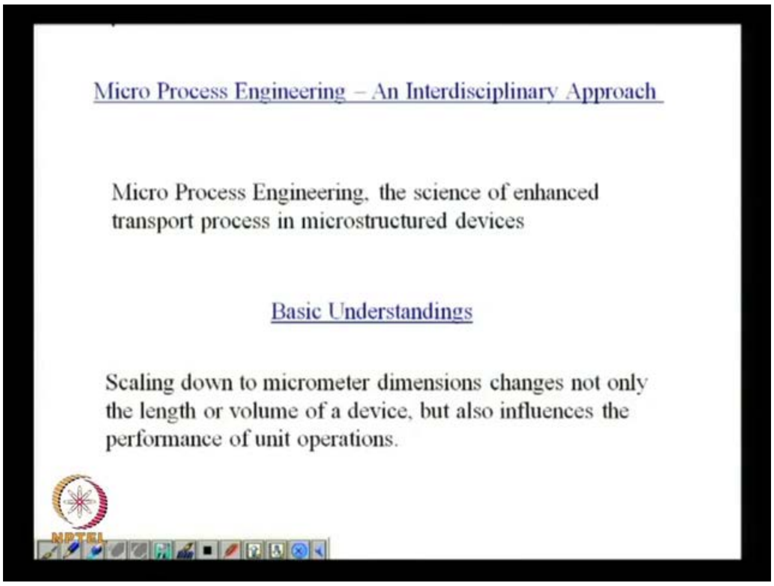

Basically, what we are looking at is that, whenwe scale down to micrometer dimensions; this not only changes the length and volume of a device but, init influences the basic physics invariant physics of the process and thereby affecting the rates of the unit operations which are prevalent in such devices.

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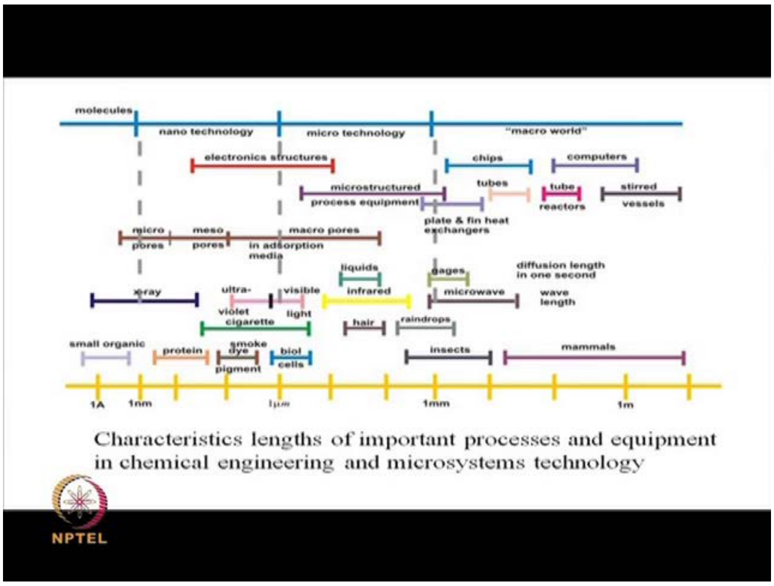

Just to give you an overview of the different processes; the time scales involved and the length scale, mostly in this slide we will concentrate on the characteristic lengths of some of the processes and equipment commonly used in chemical engineering andcompare them with the equipments used in micro systems technology.

If we look at the top one; thelet us say, when we talk about computers over here this is of the length scale of about a metre whereas, the computer chip is of the order of few millimetres to centimetres.The electronic structures in those chips areless than a micron.If we think of a chemical engineeringequipment such as the starred vessel; then the stares vessel consists of reactors and tubes.Whereas, on the other hand if we compare that with micro structured process equipment they are in the range of few microns to about thousand microns or so. When we think about let ussay anadsorbent or let us say catalyst consisting of consisting ofpores mesopores and micropores obviously the time scalelength scale are quite different from that of a computer or even from an electronic chip.If you think of a basic process, a diffusion process, a diffusive process by which a material goes from one point to another through molecular means; the diffusion coefficient of gases are relatively large whereas, the diffusion lengthof liquids are of the order of may be 100s of microns.

So, we go from 1 millimetre of diffusion length which is characteristic of a gas to about thousand or to about 100 microns for that of liquids.When we compare the wave lengths like we can start with microwave where the wave length is few millimetres and we can go all the way up to x-ray where it isit could be even smaller than a nanometre.Some of the common examples which we see inour everyday life; rain drops about 1 millimetre of length scale whereas, thecigarette smoke can be as small.The particles present could be as small as less than a micron which is one of the cause of why it is so harmful.

We can also think of these sizes of the mammals.Compare that with that of a protein so from few metres we come to few nanometres and also we can think aboutthe small in organic molecules which are the building blocks of all of us.So, less than nanometre length to about a metre length.Now, when we think of the different processes the equipments the processes and so on what we see here is that the length scales involved are enormously different between a computer and an electronic structure or between you and the small in our organic molecule which is the building block of our our bodies.

So the physics could be vastly different between what is happening on this side of the figure to the processesis which become important, the forces which become important on on the other side on the nanometre and micron length scales and theyou would see that some of the forces which are important in this region will become almost negligible in this in this in the in the smaller scale in the micro scale and some of the forces which are which are not which are present but, not important would probably govern the entire process.An example of this could be let us say the gravity force is extremely important in the macro scale whereas, the gravity force or the body force loses its importance when we go towards the towards the micro scale.A surface tension which may not be important in terms of a starred vessel that reaction taking place in a macro reactor but, when you think a flow through a micro channel, the surface tension force will start to become a verystart to play a very important role.

So, these are some of the basic inherent differences which can happen whichwhich will govern different forces, different processes and multimode physics which are involved when you go from a macro scale to a micro scale.

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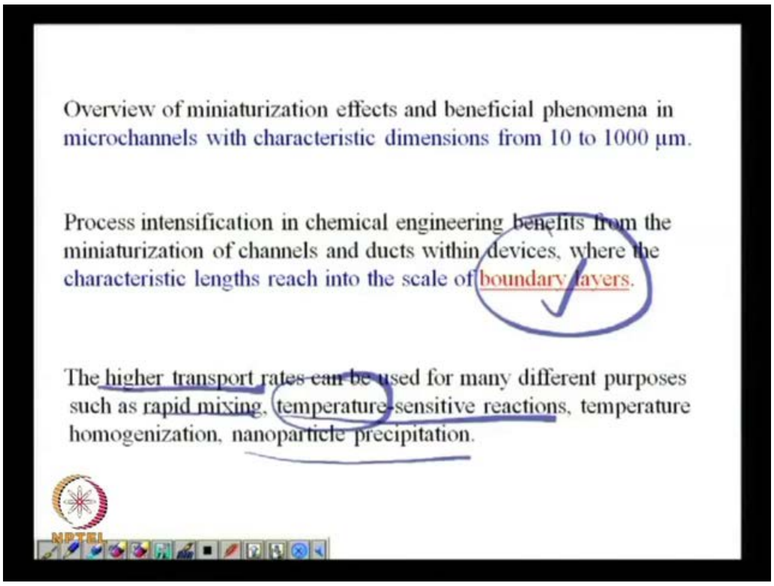

When we we would like to give in this course an overview of the effects and the phenomena for example, in a micro channel which can have characteristic dimensions from 10 to about thousand micron and one of the basic reasons why the processes taking place in a micro channel are so fast or how the miniaturisation of the channel size canplay an important part in the intensification of the process, in the better yield of products on in the process or for example, to maintain the constancy in temperature in an exothermic reaction is due to the fact that most of the processes usually in chemical engineering take place within a very thin layer closed to let ussay a solid liquid interface or a solid gas interface.

Let us say think about thereaction which is taking place on catalytic surface.What would happen is from the bulk.Let us say it is a it is a gassolid reaction solid is the catalyst and we have two reactants coming atwith the gas phase with the inlet gas phase they will diffuse, reach the solid surface on the presence of the catalyst, the reaction will take place a product will form and the product has to diffuse back to the main stream to be carried with the bulk flow.

Now, this reaction and subsequent back diffusion all this will take place in a very thin layer closed to the surface which is known asboundary layer in this case mass transfer boundary layer.We also have hydrodynamic boundary layer and thermal boundary layers.These boundary layers are generally millimetres inthe length scale would be involved would be aboutfew millimetres and most of the transport phenomena takes place in this thinregion closed to the solid surface.

So, if you think about the transport process the rest of the fluid outside the boundary layer they do not take part into the reaction or into let us say the frictional force or intointo thermal thermalinto thermal transport at all.So, if we code somehow reduce the length scale of the devices down to the size of the boundary layer then the overall efficiency of the process has to increase. This is the reason why the micro structured devices or micro devices will have a high value of a, will definitely work in terms of a its its transfer length is going to be very small in the scale of the boundary layer and the higher transport rates which one encountersin these type of devices is a is a direct resultthat the sizes are going to be comparable with that of the boundary layer and you would see the examples ofreactions taking place into micro reactors.For example, if they will be characterised by rapid mixing.If you have a temperature sensitive reaction then you would be able to maintain the temperature to a preset level in a much better way if you have such a small system because your system is of the dimensions of a boundary layer.So, it would be easier for you to control let us say the temperature to control let us say for example, precipitation of nano particles in a system or to have reactions take place in such a way, thatthe undesirable side reactions can be can be eliminated or if noteliminated completely, they can be reduced and the yield of the product will be increased.We will will seemore examples of that in the future.

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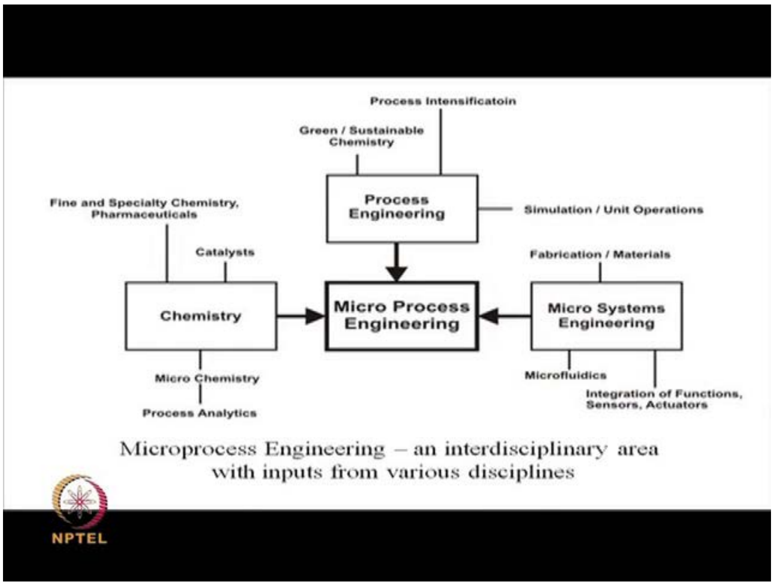

So if we have to think about micro process engineering let us first start with the macro scale engineering processes which is process engineering.Now, process engineering can be divided into mainly three parts; one is the simulation or the unit operations which are the building blocks of any engineering, any macro scale engineering process.There is an renewed thrust on green and sustainable chemistry which is also affecting, which is also going togoing to affect the process engineering outlook of today's engineers. But, the basic aim is tohave some sort of a process intensification.The process intensification would increase the efficiency of the process on one hand also yield increase the yield of the product and so on.

Now we would like to integrate the process engineering with micro systems engineering.If we think of the processintensification part, we would like to see how micro systems engineering can play a part in the in in the intensification of the process.So, if you let us think about the micro systems engineering micro systems engineering consists of three parts; one is fabrication and what kind of materials are going to be used for micro systems engineering?If you think of fabrications the newer and newer methods of making smaller and smaller devicesbecoming available everyday and materials available to us willkeeps on increasing and we can have exotic materials for a very specific purpose.In all these fabrication techniques, newer fabrication techniques newer materials enable us to integratedifferent devices.For example, sensors, actuators having specific functions.

Now, combine these together the fabrication part and the sensor part together; we have come across a new area of engineering which is known as which is known as micro fluidics micro fluidics is nothing but, the transport of fluids through micro devices with associated physics which could be vastly different from the physics that we encounter in macro devices.So, in order to in order to attain process intensification we look towards micro fluidics which is based on the available micro systems engineering technique, fabrication techniques that are available to us.

So the combination of process with the with the aim of process intensification micro fluidics can be applied and the branch which has generated out of these two is commonly known as micro process engineering.Now, one has to also identifythat micro process engineering gets inputs from different branches of science. I have given the example of chemistry over here with let ussay the catalysts.So, newer and newer catalysts are becoming available witheveryday and how do we incorporate the knowledge of chemistry and physics into micro fluidics with an aim to intensify the process; that is becoming a challenge and we are going to meet that challenge and this has given rise to newer technologies and specifically that is going to be the thrust of the subject which I am going to cover in this part of the course.

So, we would see how micro fluidics is going to helpintensification of the process, increase the efficiency of the process, enhance the selectivity of a reaction, can maintain temperature equallyat all points in a micro device, can work towards a better selectivity for a desired product and many other interesting applications.So, my building block for this course would be our knowledge in micro fluidics and based on the knowledge in micro fluidics and its application in different areas; we would see how a new branch of engineering has been created and which would probably provide us with better methods to make a specific chemical in the future.

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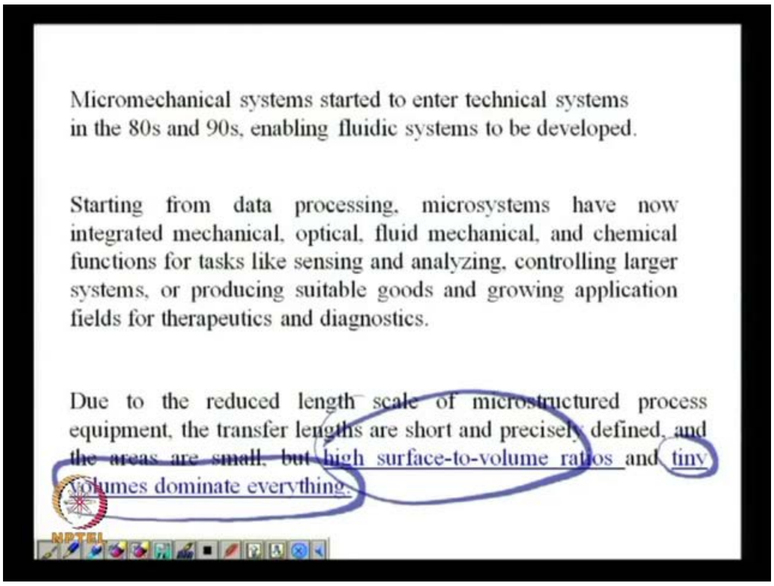

Now, if I give just you a brief history of the genesis of micro mechanical devices; they have started coming into the literaturein the nineties, late eighties and early nineties which enables fluidic systems, different fluidic systems to be developed.So, we now have micro systems which are presentin data processing, in many optical fluid mechanical and chemical having many fluid mechanical, chemical functions and they they perform a variety of task in case from sensing analysing controlling the chemical controlling the chemical functionsystems and producing goods and growing application fields in therapeutics and in diagnostics.

Many of us have heard about the word lab on a chip.So, if you think of if you know what is lab on a chip;it is it has bought revolution in the diagnostics field.Now, we all have given blood for 1 reason or another to have certain tests performedby the doctors.Now, it require certain quantity of blood usually in the order of a few cc and a host of reagents and in this process could be very chemical intensive, time intensive and you will have a large number of different tests to be performed for somefor a specific patient.

If we could have on the other hand, a small quantity of blood which will flow through parallel micro channels and the parallel, each of these parallel micro channels will have certain reagents which are parked in it and as the blood flows through that specific micro channel that reagent is going to react with the blood and gives a specific signal which can be interpreted to let us say, it can be calibrated with the concentration of blood glucose or concentration of blood urea present in the system.So, using a tiny volume of the blood and using a fraction of chemicals involved in the process; one would be able to1 would be able to perform an array of different tests on a single chip.

So, this has generated interests and there are manylab on a chip devices which are presently in use and are coming up and will very soon be available commercially and some of them are already available in which you can do specific tests with a small quantity of blood and a small quantity of reagents compared tobefore.So, this will revolutionise the diagnostics as we know today.

Now when we think aboutwhy it is so important,the so useful thatwe again come back to I think what I have covered before that a micro structured process equipment are.So much superior to other devices to macro devices because of two distinct reasons; one is that the high surface to volume ratiowhich you would obtain in a micro device and secondly this is probably the keywords of this course.Tiny volumes dominate everything in a micro device.So, not only you are working with very small volumes; millilitres less than millilitres, 1 100th of a millilitre and at the same time since the sizes are so small the radius of the droplet is so small that your surface to volume ratio is going to be very large.Some of the forces which were important before will be unimportant for micro scale devices and some some forces can become very useful and can control the flow of a fluid because the surface area is surface area is very large compared to that of a volume.

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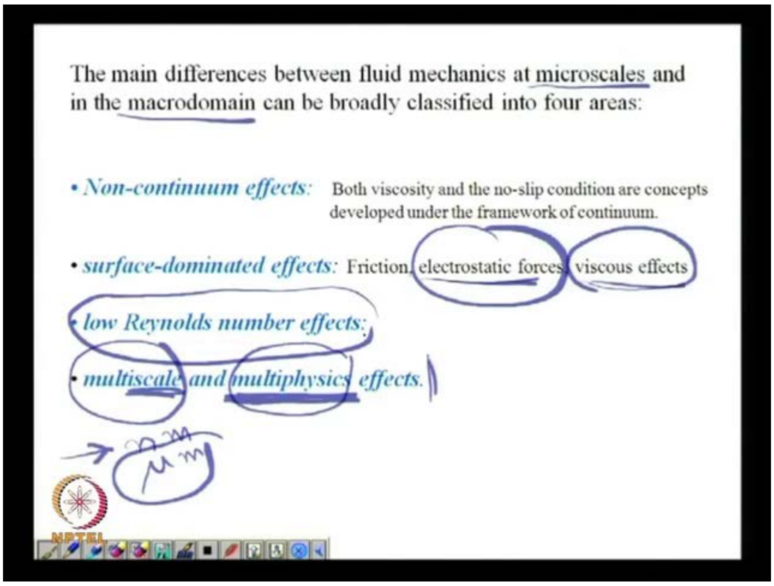

So, if we try toorganise our thought so far as that we are just going to be difference between the fluid mechanics at micro and micro scale and in the macro domain and we are going to concentrate on four specific points to highlight the differences in between the two. The first is going to be the non-continuum of effects.We know thatvery common boundary condition that we are very much familiar within fluid mechanics is a no slip boundary condition.We know thatin most of the engineering the macro engineering process is the no slip condition would be valid.That means the relative velocity between theliquids molecules and solid molecules at the liquid vapour interface would be 0 liquid or gas molecules.

Now, this no slip condition may not be valid if we scale down to millimetre or micron level.So, there will be situations in which there can be slipvelocity non-zero slip velocity present at the interface.This would be even more pronounced when we think of low pressure gases.So,for example, a gas in which is at very low pressure such that theinter molecular spacing or the molecular mean free path becomes comparable to the device size, it is very well possible that the continuum limit may not be valid for such a case and we are going to have actually a slip at the at the fluid solid interface.

So the non-continuum effects one has to be very careful about while analysing the physics of flow inside a micro scale device.The same applies viscosity what would be the viscous fluid viscosity how would it vary based on how close to the surface we are.Based on how many particles how many particles are present in such a system. So, the non-continuum effects the different flow regimes which are going to be characterised by different types of non-continuum effects would be very important in understanding flow in a micro channel.And there would be surface dominated effects.The surface forces which were probably not very important in a macro scale will start to become important in micro scale.The electrostatic forces, the viscouseffects are going to give rise to situations in which we may have flows, which are going to be, due to entirely due to electrostatic forces.The viscous forces near a charged surface could be different and this difference in viscosity due to the charges present on the sides of a solid channel will give rise to interesting effects which we will covertowards the later part of the course. They are known as viscoelastic effects.So you would seewhat they are.

Most of the flows which take place in a micro channel are going to be smaller Reynold's number flows or low Reynold's number flows because it is difficult due to the higher values of pressure drop associated with flow in a micro channel to a very high velocity flow inside such small channels.So, the flow is going to be at low Reynold's number flow and the approximations that one can make for low Reynold's number flows will be equally applicable, mostly applicable for low Reynold's number for micro channel flows.So one has to think about how the low Reynold's number effects are going to create some sort of difference between the fluid mechanics that we know atat macro scale and at micro scale.And finally, this is going to be important as I have described before the scales aregoing to be vastly differentfrom a metre or a centimetre scale that we are, that we are comfortable with.That we know of at the macro scale we are probably going to the to the scale ofnanometre or micro metre level.

Soso the devices could be a few micrometre and in some cases we can devices which would be asthe length scale could be in nanometres as well and then we have multi physics effects.The different forces which are acting or acting inside such a system would give rise to phenomena that can be only explained by a a treatment which is going to be paradigm shift from the treatment that we have encountered so far.So, this multi scale and multi physics effects are also going to make certain differences between the fluid mechanics atmicro scale and at themacro domain.

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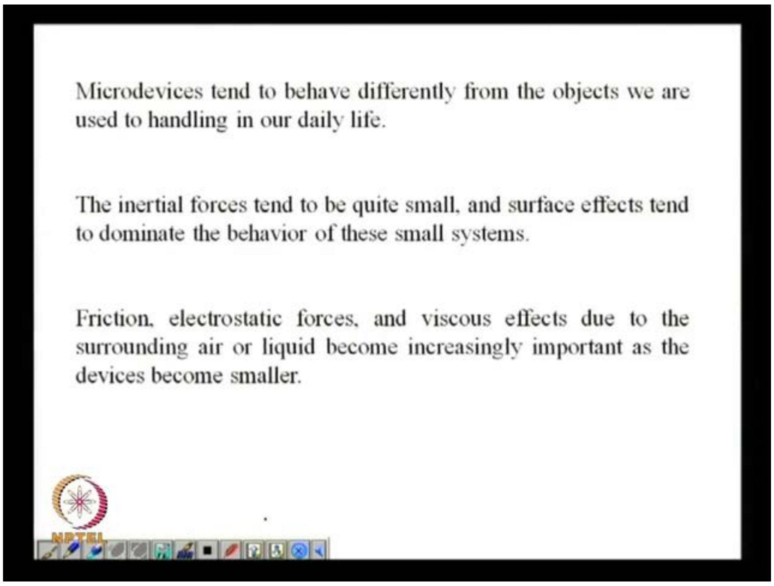

So we we can say that the micro devices they are tend tobehave differently from the objects that we are generally encountered with in daily life and as I mentioned before.The gravity starts to become relatively unimportant surface effect starts to dominate the behaviour of fluid in such small system and the forces, the friction electrostatic viscous surface tension forces due to the surrounding air or liquid they are going to become more and more important as the device size become smaller and smaller.

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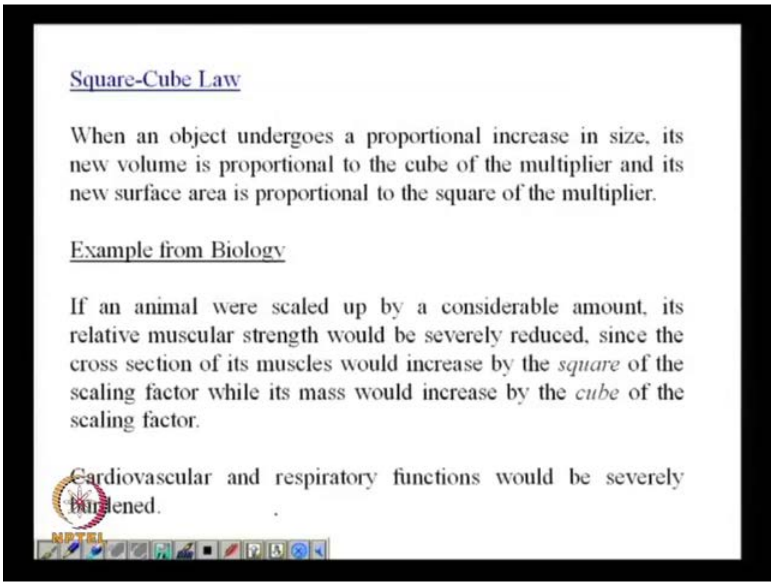

In this I would like to bring to your attention to an very interesting preposition or law which is there, which is existing for a very long time it is known as the square cube law.And over the years it has found use in different branches of science and engineeringand biology.So, what is square cube law?So, it simply says that when an object undergoes a proportional increase in size or a decrease in size; the new volume is proportional to the cube of the multiplier and its new surface area is proportional to the square of the multiplier.All of us know that.That the volumewhich is going to increase with l cube and the surface area is going to scalewill be different as l square.

So if we think about the surface by volume it is going to be l square by l cube would be somewhat related to it will scale as 1 by l.So,let us think about aan interesting example from biology.Now, what you can see is that when an suppose you scale up an animal, an antyou scale it up three times.So, its volume is going to be scale, volume is going to increase,it is mass is going to increaseconsiderably.Since,it is going to beproportional to l cube whereas, its muscles the cross section of the muscles are going to increase only by l square.

So it is weight is going to increased by l cube whereas, its its the strength muscle strength is going to increase somewhat to some extent it will scale with the squarethe scaling factor would be the square of thesquare of that factor.So, its mass would increase by the cube of that scaling factor as a result that ant which has beenwhich you have arbitrarily increased its size by its length scale by three times, its mass is going to be 9 times but, its strength of the muscles, are not going to be increase in the strength of the muscles and not going proportional to l cube.As a result it is going to have cardiovascular and respiratory functions which would be severely affected.

So,that is you canwe can have some commonidea common or commonality with the weight of a person.So, if the weight of a person increases thenhe he or she will iswill most likely going to have cardiovascular and respiratory problems and alsoalso muscle problems and they will they are basically due to the reason of the square cube law.

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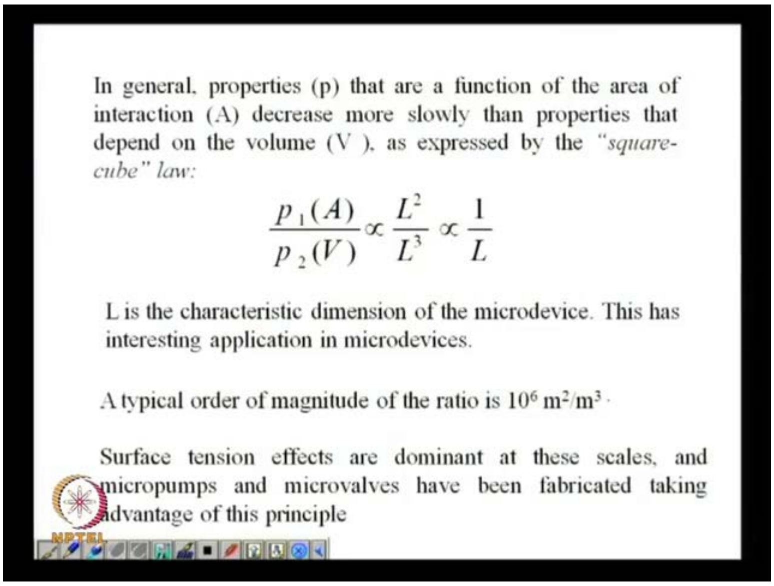

Now, if we if wetry to express it more scientifically what we see is that any property which is a function of the area of interaction; it decreases more slowly than properties that depend on the volume.

Sowe, if we think of mass then it is going to scale as l cube but, let us say we are talking about surface tension which is a function of the area it is going to vary with l square.So, the propertywhich let us say is surface tension and the ratio of that with the mass of the system is going to scale as 1 by l, where l is the characteristic dimension of the micro device and this this has very interesting applications or the the result of this could be very interesting when you think about micro devices.A typical order of magnitude of this ratio ofp 1 which could be surface tension and p 2 which is something which depends on the volume, which could be mass.So, p 1 by 2 is going to scale as 1 by l and for a micro device, if you think of this as a micron size micro device then this ratio is going to have a a ratio of 10 to the powerof 6 metre square per metre cube.Now, if you think of it this way, you would see that when you skip on reducing the size of a device slowly the surface tensionwill start to predominate over something, over a force which denotes on the mass.It could be the inertia.So, surface tension effects are dominant at these scales when the size of the device is in in the order of microns and there are micro pumps and micro valves which have been fabricated taking advantage of the principle where the surface tension is going to cause or going to make the fluid flow from one point another and the inertial effects are rather unimportant.So, we can device off surface tension driven pumps to make liquid flow or to deliver a packet of fluid from one point another.

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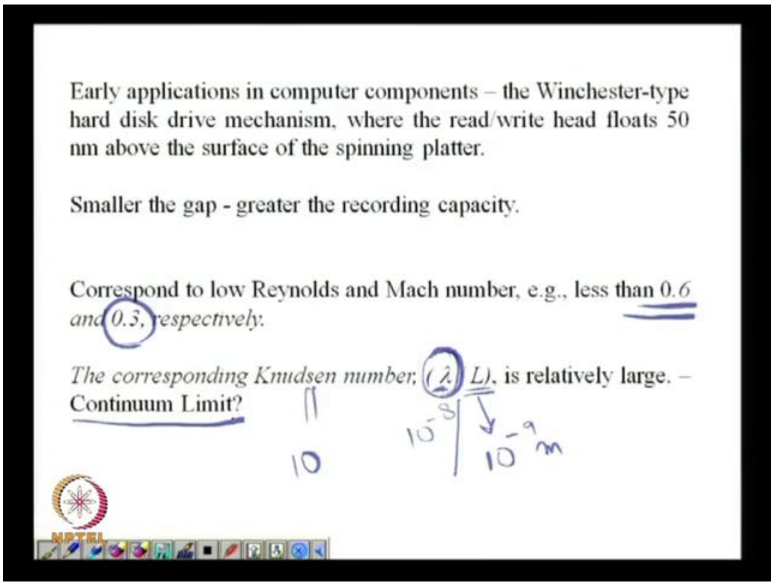

So you would see an example of that in in in subsequent slides.When you think of the applications thisinitial application 1 can think of is in computed components which is the Winchester's type harddiskdisk drive mechanism where the read write head floats roughly about fifteen a micron over the spinning disk.So, the separation between the 2 two solids; one the head and the other is the disk is about 50nanometer and no matter whatever be the speed of the spinning disk; the flow is essentially going to be a very low Reynolds number flow.It is also itsmach number is also going to be small you we have a typical situation in which the mach number is about 0.3 could be 0.3 and the Reynolds number even though that thisdisk spinning at a very high speed could be as small as 0.6.

Now, when you think of the think of such a situation low a Reynolds number, low mach number flow even though the velocity is involved a very large since the length scale involve is only 50 to 100nanometers.Theseare prime candidates for large Knudsen number flows and the Knudsen number is defined as lambda which is a mean free path by l divided by l which is the length scale.So, here we have the length scale as about 10 to the power over the order of 10 to the power 9 meters in at some conditions thisinter molecular, the molecular mean free path could be of the order of 10 to the power minus eight.

So you have a situation in which this Knudsen number could be as large as 10 or even beyond.If that is the keys for values of Knudsen number which ofof the order of 10, you are going to definitely not going to work in the continuum limit.You will be definitely working in a in a in a situation in which many of the assumptions of continuum limit will not be valid anymore.

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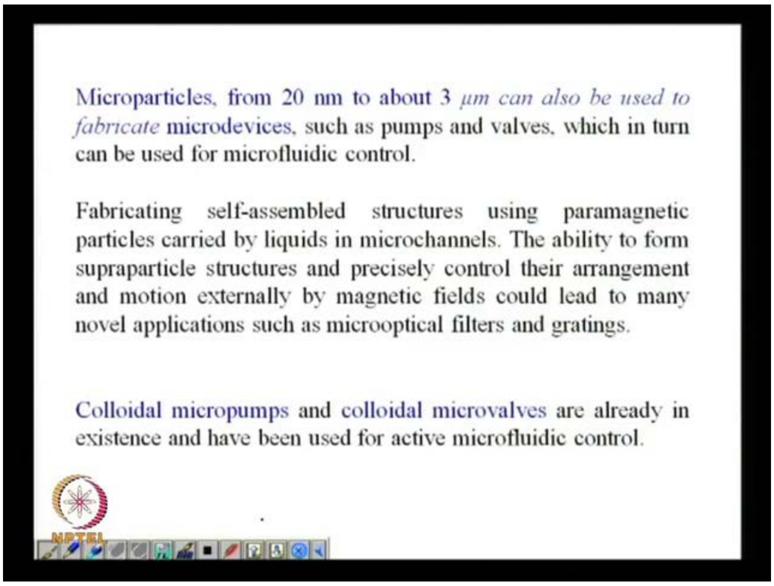

To give youanother example ofhow theseparticles, some nono particles or micro particles can be effectively utilized their motion manipulated from outside so that they can give rise to the working of a pump.It has comeinrelatively recent paper in science, I think I believe it is in 2002 where itit was shown that micro particles of the size 20 nanometres about 3 micron can be used to fabricate micro devices, micro pumpswhich can be used in turn for the control of microfluidic devices.So, we have a microfluidic devices in which the flow rate could be microliter, smaller than microliter in many cases it could be nanoliters.So, how do you device a pump which would create a flow such a small flow.So one of the novel and innovative examples of use of ofofof these micro particles is one can fabricate a self assembled structures using paramagnetic particles by liquids in micro channel and their ability to form such a large particle, large structures and you can control their their motion from outside would give rise to colloidal micro pumps and colloidal micro valves.I will give you an example over here.

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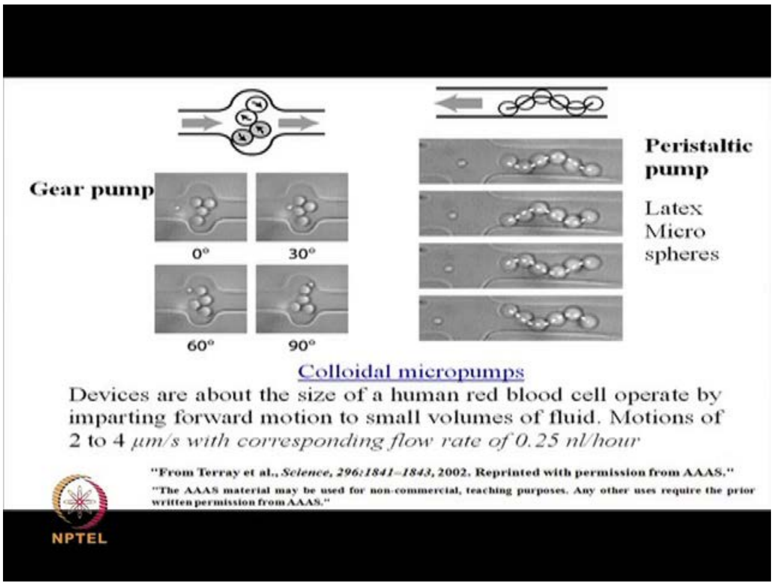

So if you concentrate on the right hand side of the picture; you would see that there thereare there are thereare particles which are going to form a string a string like structure and you you can create the motion of this particle.Let us say this particle in such a way that it is going to,it is going to as if there is sin wave which is going through these particles.As a result of which the liquid is going to be pushed.The liquid is going to be pushed from one side to the other in the direction and small packets of fluid canflow due to the motion.Due to the controlled motion of these particles of these large relatively large particles in this case latex microspheres through a nano tube and you can have a flow as slow as 0.25 nanometer per hour.

So the motions of this particles can be as small as 2 to 4 micron per second but, interestingly this would give rise to a flow which isonly nanoliter per hour order.So, if we have a very, if we have a small, if we have a reaction which is taking place and you have to supply reactantsin a very small device at a very small flow rate you cannot have normal pumps peristaltic pumps or such suchor such pumps.Then 1 has to device and this is an example of how to design a pump based on the motion of latex microspheres.

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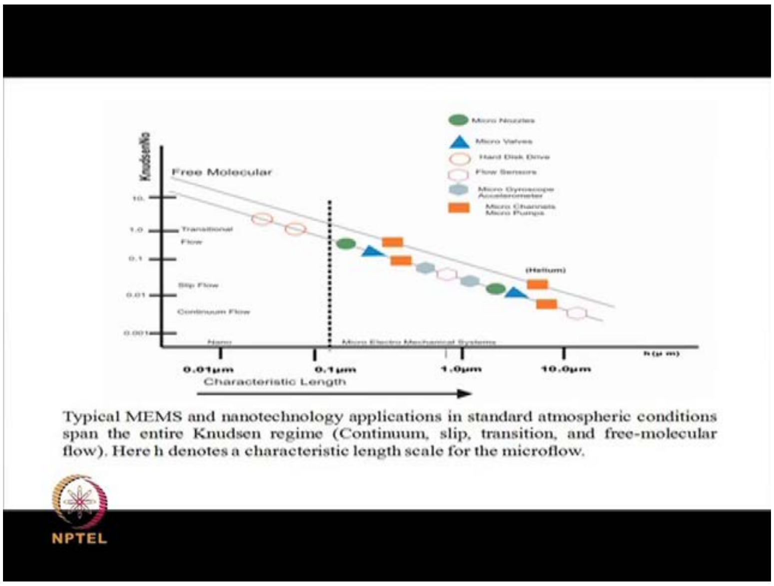

AhThis is a graph which tells us about on the x axis the values of Knudsen number and correspond to each of the values of these Knudsen number where we are in terms of the types of motion that is taking place in a device.So, usually Knudsen number less than 0.001; we are going to have 0.01 we are going to have continuum flow.So, from here down for a value of knudsen number of 0.011 can assume it continuum flow.You are going to have no slip condition valid in such a in such a zone and your no slip, your properties are going to be invariant with position so if you maintain other conditions the same the property will not change in such a system but, the moment you go beyond point 1 up to beyondpoint 0 and up to point 1 then the properties will still remain same but, you have to assume slip flow at the solid fluid interface.So,that is known as the slip flow regime.If you go beyond that for even high values of slip flow for Knudsen number greater than 10 the motion of the motion of the species present can be interpreted as free molecular flow and in between .1 and 10 you have a transition where the flow changes from slip flow. But, still property is same to free molecular flow where the properties are also going to vary with position and time and in somewhere in between you have transition flow.

So when we think of micro channelsthis 1 the micro channels over here are generally at the border line between continuum flow andslip flow.So, the analysis of micro flow, micro channel flow that you would see the boundary conditions in many cases will involve a slip boundary condition.So, one has to be careful to find outthe based on the value of knudsen Knudsen number whether we can assumea continuum mechanism that is in place or we have to go to slip or transition flow as well.

So some of the devices which you see here are placed areare placed along along these two lines where slowly we go from this which iswhich iscontinuum flow up to the point where the flow is not continuum and whenever we have, we are working with let us say about point 1 micron and smaller that isnano technology and on the other side we have mems and in this course we are mostly going to concentrate on this side.What happens to a micro system, the transport phenomena that is taking placein a micro system and these are some of the devices which we arewhich we are going to concentrate on, which we are going to concentrate their physics of flow inside such devices, how to fabricate such devices, the design issues, the engineering issues which are involved in such devices that is what we would like to analyze in depth in this course.

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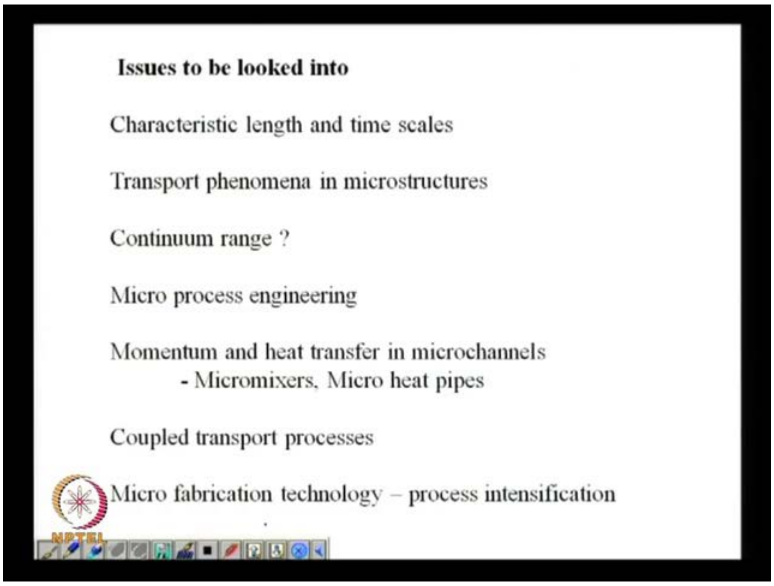

Soto summarizewhatever we have covered so far; the relevant issues which are going to be important in this course are what is the characteristic length and time scale involved in the process that we are going to that we are designing?What is a transport phenomenawhich is taking place in such microstructures?Is the phenomena phenomenon taking place in the continuum range or we have to think of a slip flow or a transition flow?The engineering aspects involved beenthis micro process how to what are how to make how to fabricate such micro devices?We would also like to know what is the momentum and heat transfer how is the,what is the mechanism of momentum and heat transfer in such devices.Are they coupled?Are the heat transfer and fluid flow for example, heat transfer and fluid flow are they coupled together?Do we require any unified solution or is it possible to obtain the velocity profile from the fluid mechanics part of the problem and then use that velocity profile to obtain the temperature profile in such a system?Or are the processes coupled in such a way that independent solutions of fluid mechanics is not possible, you have to solve both together which would make the process even more difficult?So you would see that as well.And finally, we are also going to look at the micro fabrication technologies which are available today which is a still evolving at a veryrapid rate and how the use of this fabrication technology results in intensification of any process.That is going to be the goal.

So, we in through all these studies our main goal is how to intensify the process, how to increase the rate of formation of a specific materialin a much more controlled way, in a process and that is what we are going to look at in this course.

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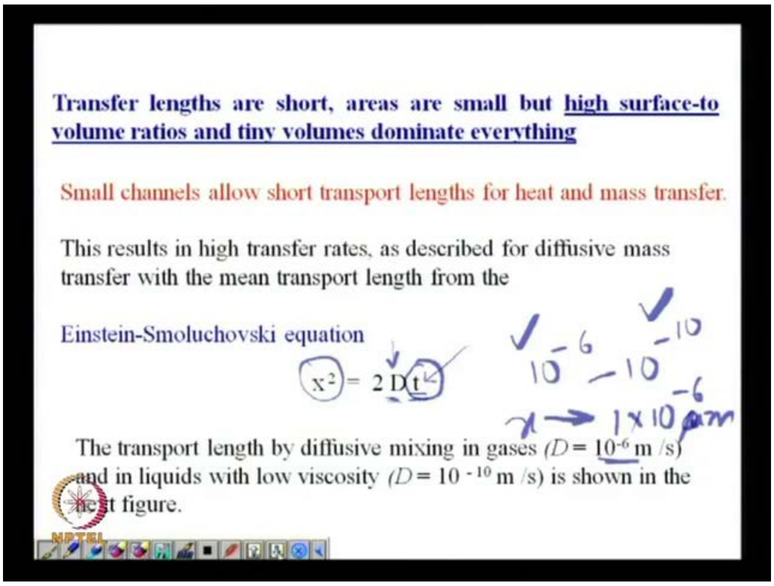

So we come back to again what as I said the most important line of this course that their transfer lengths are short, areas are small but, high surface to volume ratios and tiny volumes are going to dominate everything.

Now we would like to put a slightly mathematicaltreatment to this and see what what exactly do we mean by that.If your channels are small then you are going to have shortertransport lengths which would definitely be beneficial for heat and mass transfer.So, if your shorterif your length scales involved are very small, transfer lengths are very small then they are going to lead to high transfer rates.And the diffusive mass and heat transport and momentum transport could be could be very large and this is a famous equationwhich relates the property of the material that we are handling, the length scale which is given by x and the time scale which is given by t.

So,let us think of the diffusion coefficient of gases or liquids.They are of the order of 10 to the power minus 6 to about 10 to the power minus 10 where as x the length scale involved in micro fluidic devices; they are of the order of 1 into 10 to the power minus 6 microns meters.So, about 1 micron.So, what you see then is the result gives you a very small value of time scale.So, the transport length could be a could becould betransport length by diffusive mixing is for gases is 10 to the power minus 6, liquids its 10 to the power minus 10 and this would this would give rise to a very small value of the time, the frequency the time scale of of the transformation frequency and which is connected with the property of of the system.

So, the diffusion coefficient the transport length theirway,they govern what would be the time scale of the process and we can see that the time scale of the process is going to be very very small.So, the transformation frequency of such a process is going to be small which ismade clear in the next figure.

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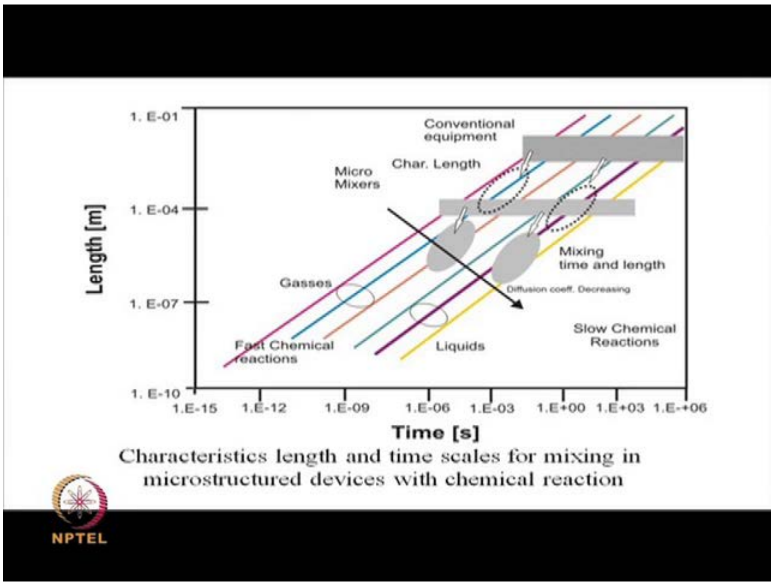

Now, over here we have the length n k l o in on on thex axis we have the time.So, it is basically a characteristic length and time scales for mixing in small devices.

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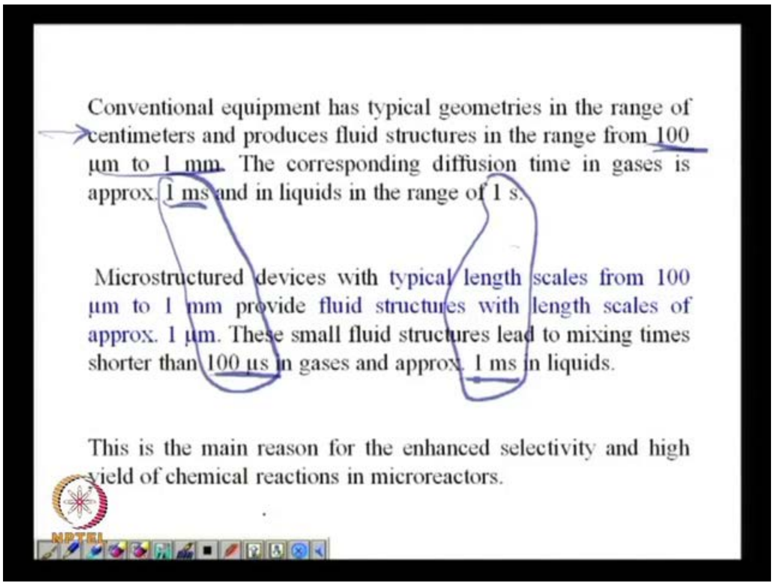

Now when we think ofa macro device a macro device has a length scale which is typically in the range of centimetres. In in this fluid packets with with which you can represent the thethe process in a conventional equipment their sizes are for from 100 micron to about 1 millimetres and a corresponding, if you look at the corresponding diffusion time over here.So, we are we for micro devices we are we are working in this length as far as as far as the length scale is concerned and this would give rise to this as of time scale for gases and for liquids this is roughly of the order of 1 into 10 to the power minus few 1 millisecond.

So we are probably working at 10 to 100 millisecond to aboutI amsorry 10 into 1 into 10 to the power minus 5 seconds for gases where as 1 mille second for the case of liquids when we think about the micro mixers.For conventional equipments the same things are roughly over here.So, this is the time scale of a micro mixer where as this is the time scale of a macro mixer or a conventional equipment.

Now, that is what I have written over here if we think of micro structure devices; their typical length scales from 100 micron to 1 millimetre and the fluid structures are having lengths of approximately one micron.So, your mixing times are shorter than 100 micro second in gases and approximately 1 mille second in liquids.So, you can seewhat is the difference between this for gases and this is for liquids.So, you get roughly about a thousand times change in the in in in the mixing times between a macro scale device and a micro scale device.So, this shows why working the main reason for the enhance selectivity yield is of maintaining constant temperature in a micro reactor compared to a macro reactor.

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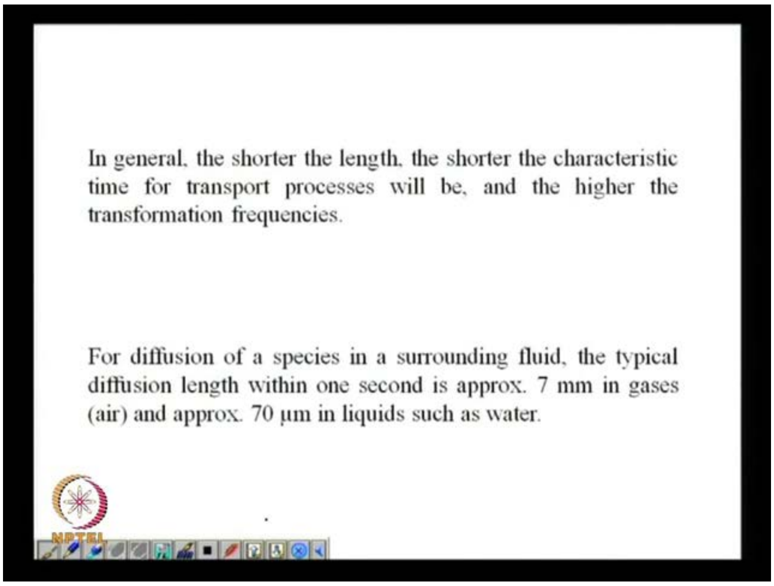

So, summary we can say that the shorter the length, the shorter is a characteristic time for the transport process and the transformation frequency is going to be higher.Andjust to give you an idea that what we are talking about in terms of diffusion length, is roughly about 7 millimetre in gases and approximately seventy micronin liquids.That isthat is the diffusion length length covered by a diffusing molecule in a second.

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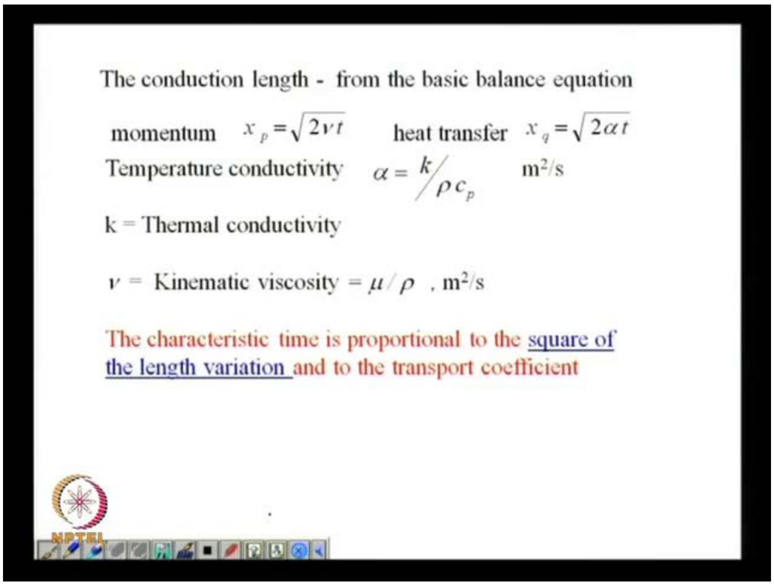

When we try tolook at the conduction lengthfrom the basic balance equation; we know thatfor momentum the conduction length is given by root over 2 nu t where nu is the kinematic viscosity and t is the time scale.For heatheat transfer the length scale involved isroot over 2 alpha t where alpha is thethermal diffusivity.So, the characteristic time is proportional.This is important to the square of the length variation and to the transport coefficient.So, the smaller if weif we if you can keep on making a device size smaller and smaller if the characteristic time is going to be reduced by square of that. So,its one can see that how the time requiredto complete a process decreases drastically once the sizes of such devices are made smaller.

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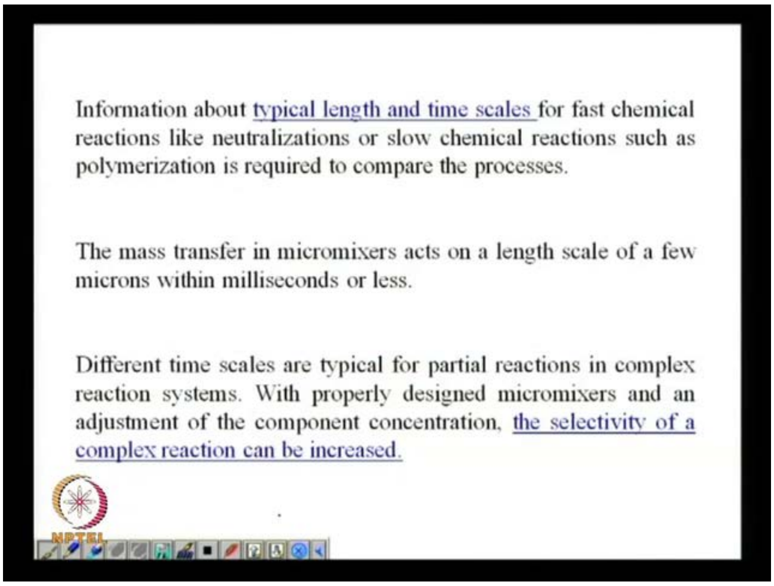

So, information about this typical length scale and time scale for first chemical reactions are necessary in order to compare the processes and the mass transfer in micro mixers they act on a length scale which could be a few microns and they take place the the time required would be a few milliseconds or less.So if we have three or four reactions; 1 principle reaction and the other side reactions are taking place in a in a device 1 can control the process in such a way that the slower reactions the side reactions would be made even slower and using the less smaller values of the frequency of transformation of such reactions. The main reaction can be made faster.Thereby the product form, the yield of the product form would be a much higher and in such a way the overall yield of the desired product can be increased many times in a micro device.So,that is the direction in which we arewe are going in the design of micro reactors.

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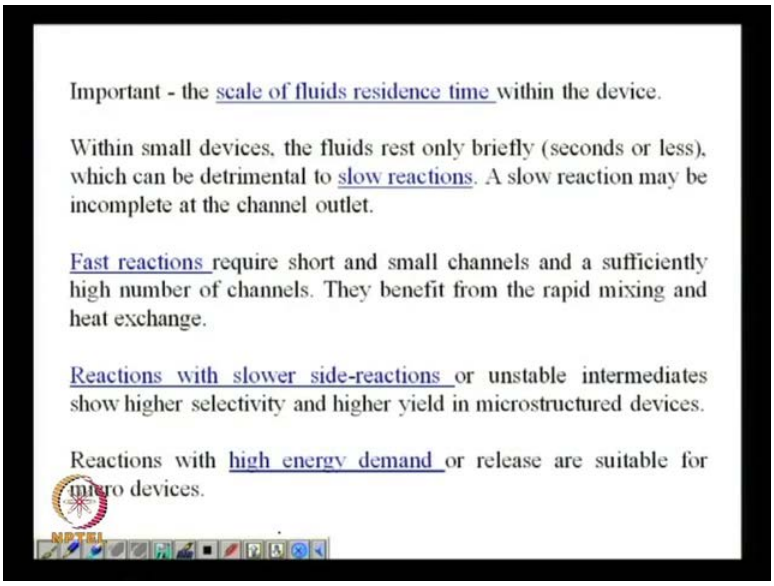

Another important thing one has to keep in mind is what is the scale of the fluid residence time inside such a deviceandwithin what we know is at within small devices the fluids are going to rest only for a very short time inside the reactor. So, if you have a slow reaction a micro device may not be the ideal option available for you because the residence being small the reaction may not be complete at the exit of the micro device.

So, you have to probably, generally speaking it is a faster reactions who are prime candidates forprime candidates for a for a micro device.So, a slower reaction you probably have to use a conventional method.The faster reactions require very shortlength of the micro devices.Similarly, if you have an exothermic reaction; exothermic reaction would be the right candidate for a micro device because you can control the temperature of the reactant and the products very well in a micro device since the length scale involved are close to that of the boundary layer thickness.

So for temperature homogenization, a micro reactor would be ideal.So, fast exothermic reactions are preferred over slow reactions in a micro reactorfor better control and for better conversion of of the reactants to the products.

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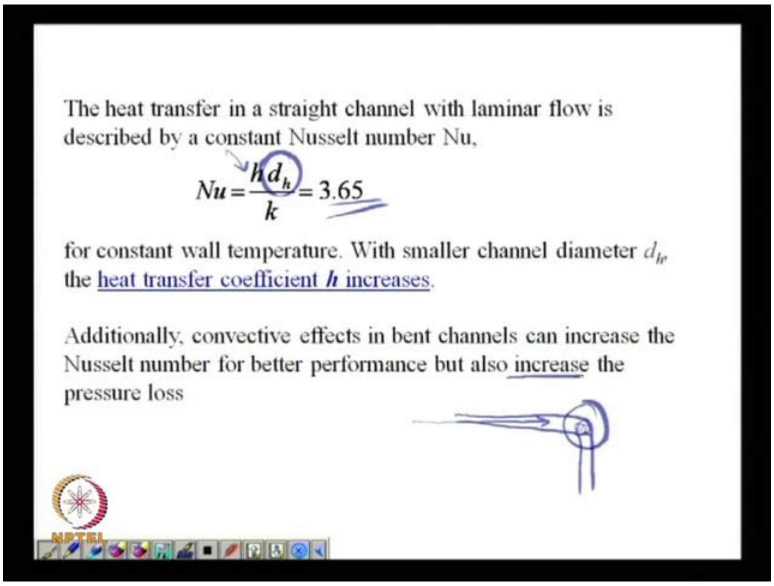

Andwhen we think about the, this is just to look at theenhanced transport that is taking place, enhanced values of the transport coefficient which are which are available in a micro device.All of us know that the Nusselt number, the constant Nusselt number for a constant wall temperature case when a fluid flows through a pipe when a flow becomes thermally fully developed; the Nusselt number becomes constant and is equal to 3.65. And we also know that the Nusselt number is nothing but, h d by k h being the convective heat transfer coefficient, d the length scale in this case the diameter of the tube and k the thermal conductivityof the fluid.So, if we are using smaller diameterchannels for suchsuch reactions then, the value of d is going to be so small, the value of h is going to increase.So, as a result of which you can see that the value of d h as it reduces the value of h will automatically increase since h d b by k is a constant.So, this tells us that small channel diameter, the heat transfer coefficient h increases andthis is one example of why we should have a high value of transfer coefficient in a small channel flow.

Additionally we are going to havenot straight channels but, channels which are probably bending in this form.So, if we have flow in such a micro channel then over here there is going to lot of lateral mixing, vortex formation and these lateral mixingsand vortex formation will additionally increase the value of h beyond that that is predicted by this equation. So, this is also something which one should look at while designing a micro channel for a heat transfer for any experiment.

So wecome back to, so but, everything comes at a price whenever we increase the value of a transport coefficient by making it flow through a small channel we also increasethe pressure loss in a system.So, the pressure loss in a micro fluidic system is going to be many times more than that of a macro scale flow.So, how do we provide this excessive pressure drop in micro channel flows?So you want to see that in a micro channel, the flow is mostly laminar.The pressure drop per unit length is quiet high and this is one of the1 of the limitations of a micro scale effectiveeffluelization of micro scale devices for fluid transport.So, the high values of h or any other transport coefficient can be offset by the requirement of high pressure drop.

So in many cases the, we would go for micro channel flows for some specific applications.

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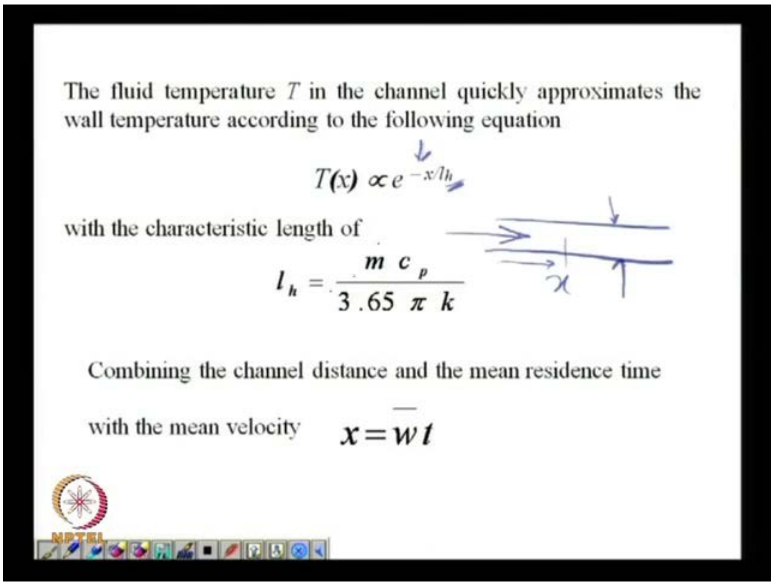

And we will give I will you examples of that later on.Now very quickly I will go through something whichyou are familiar with that is temperature of the temperature of the fluid flowing through a tube is going to vary exponentially and where x is the length scale of the device. I mean l is the length scale of the device and x is the channelis ais a distance at which its flows. So if we have flow of liquid through this then this is your x andl h could be the diameter of the channel.

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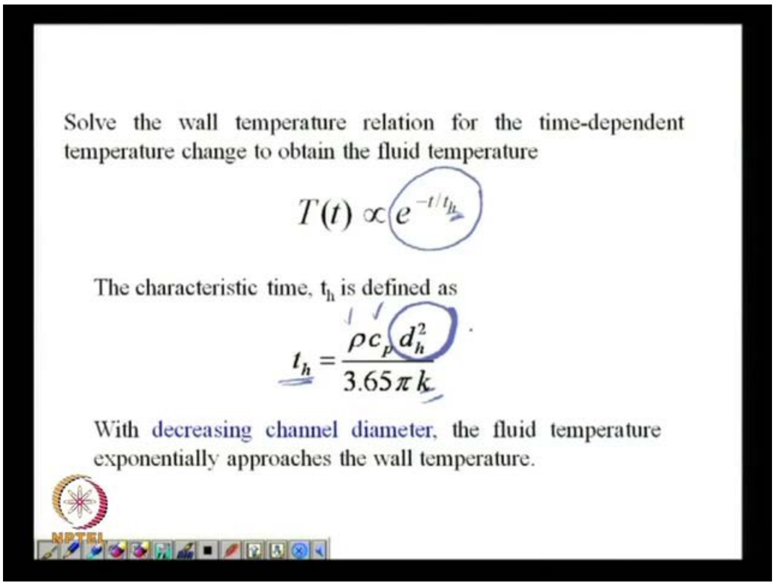

So, the temperature isgoing to exponentially change with the distance traversed and when we connect this characteristic length with the velocity and so on then this t x, the temperature change in temperature can be related to an exponential change with time andwe could see that the characteristic time which ishere in the denominator is it can be connected with rho, the density, c p thec pthe heat capacity thermal conductivity but, most importantly with the square of the size of the device.

So this simply tells us that with decrease in channel diameter the fluid temperature exponentially approaches the wall temperature.So one can have the temperature of the fluid approaching that of the,that of the wall very fast if its flow in a micro channel.So, this is anotherexample how the homogenization of temperature can be obtained in a micro channel compared to a macro channel.

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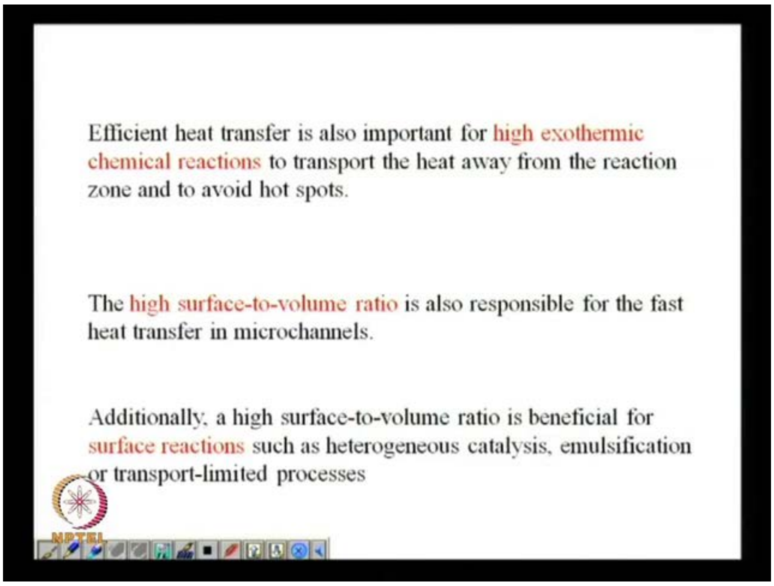

So we need to look at the requirementrequirement of efficient heat transfer where high exothermic reactions andthis slide is essentially a summary of what we have covered so far.We know that high surface to volume ratio is responsible for fast heat transfer in micro channels and additionally we have very high surface to volume ratio which would be very important beneficial for surface reactions such as catalyzecatalysisheterogeneous catalysisemulsification or other transport limited processes.

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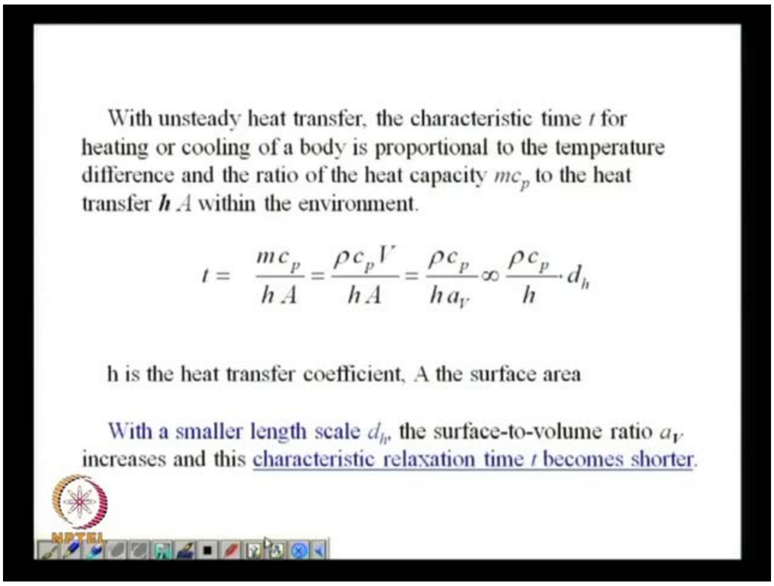

And this again is tells us something about the timenecessary for the time scale involved in unsteady state heat transfer processes. So, a smaller length scale the characteristic reduction relaxation time also becomes shorterand we will have aa faster reaction taking place.The system is going to reach steady state at a much, at a value which issmaller than that of a macro system.

Thank you.