Microscale Transport Processes

Prof. S.DasGupta

Department of Chemical Engineering

Indian Institute of Technology, Kharagpur

Lecture No. #05

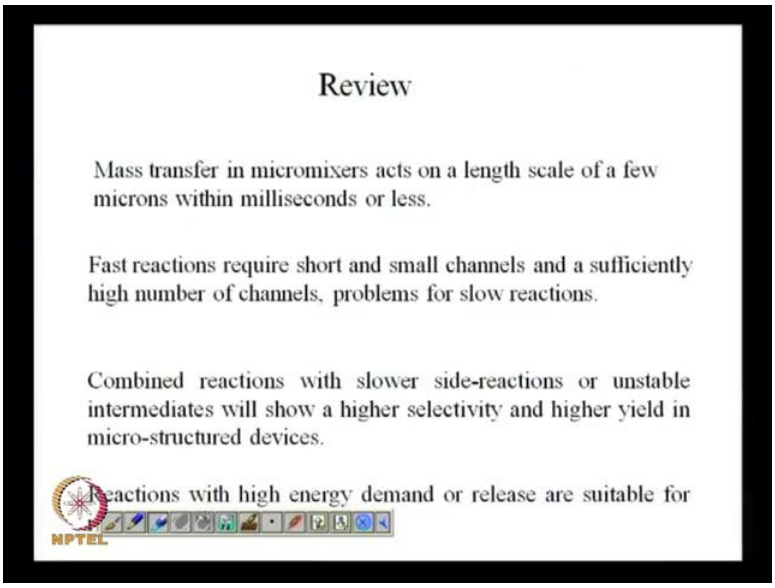
MicroscaleManufacturing Practices

Very goodmorning to you all, andwhat we are going to do in this class is I am going to talk about what I have covered in the last class very briefly.Andthen, we will introducean interesting topic, how much is microscale manufacturing practices.Now, manufacturing of at microscale could be totally different from what we arefamiliar with the microscale,themacroscalemanufacturing processes.Not only the practices are different, the philosophies the conceptsare different as well.So, we would see the two prevalent philosophies in micro machining, micro manufacturing;which one is important,which one is becoming important,inwhether or notwe can totally shift to one of those.

In the later part, we wouldclarify certain terminologies;for example, numbering up of a system, scaling up of a system,and soon; all related to microscale.Andfinally, we willhave a twoexamples of using specific machining techniques,so as to obtain devices.Andthe two devices -one is going to be for heat transfer, heat transfer large scale. So, even though the heat to be transformed is quite small,the areas from which is to be transferred is quite large, as a result of which the heat flux is very, very large.

So, how to handle situations where a high heat flux has to be removed from an object.And the second one isdepending onthe surface properties, depending on the manufacturing process thata specific substrate has gone through.The fluid flow, formation of bubbles, phase transfer, waiting all are going to be different. So, if you think of an experiment in which we have hydrophobic surface, and a hydrophilic surface.A surface which is smooth compare to another surface, how would the phase transition on such a surface take place,and a how is it going to affect the pressure drop and soon.So, you will havea mixture of certain theories, conceptssoto say,and applications in today's class.

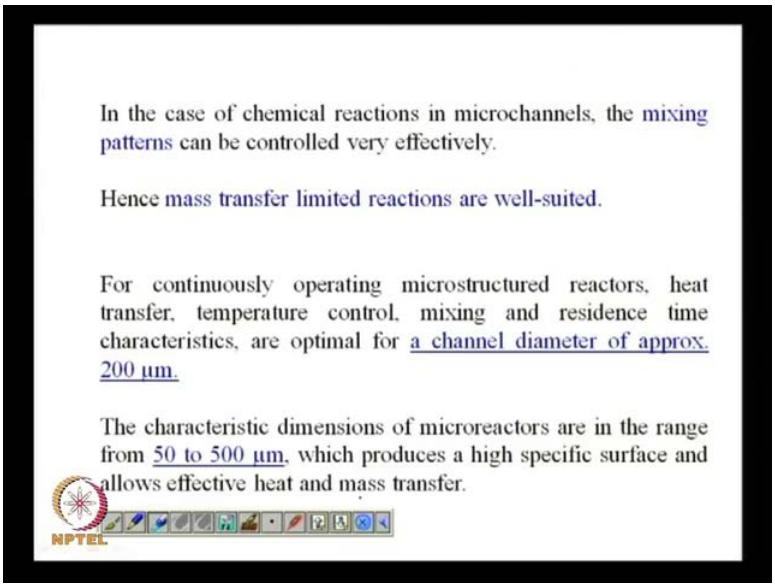
(Refer Slide Time: 02:51)



Butbefore I begin this class,I would like to quickly review some of the things which we have covered in the last class, pertaining to mass transfer.We know thatthere are two thingstotally different in aatmicroscale.One is the length scale,which could be microns or even smaller than that.And the second is the time scale, which in a microreactor could be milliseconds.So, we have said or understood in the last class that we will probably use or weprobablyfor microreactors, if it is a fast reaction.A slow reactions would requirelarger length of the micro device, which may not be possible to fabricate.We may have that technology, wemay know that the mass transfer resistance is even for slower resistance slower reactionscould be handled by a micro reactor, but the limitation of length, you cannot make a channel micro channel, which is of meter length;at the most you can go for few centimeters.

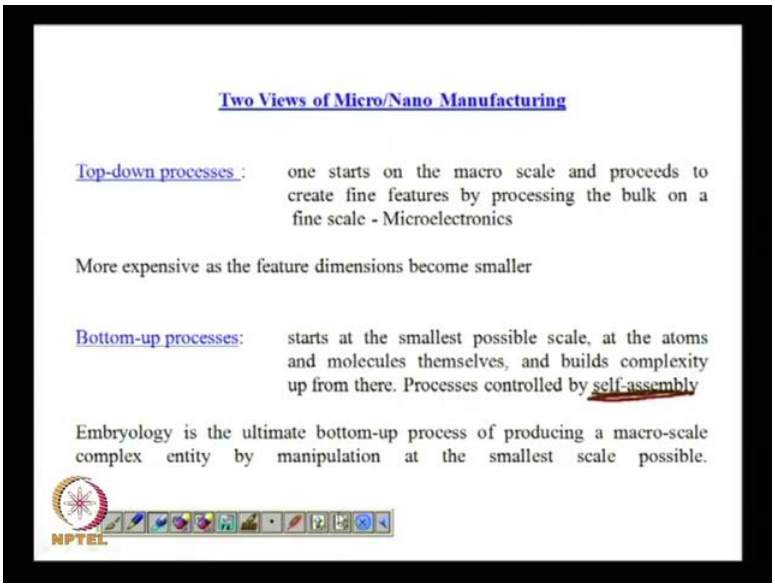
So, how do you do that?You cannot have a slow reaction in a microreactor.Butthere can besituations in which combined reactions, when you have the principle reaction take which is relatively fast; and the other reactions undesired side reactions slower than an effective use of a microreactorcangive us better yield of the system.Andfinally, since it is very small, since all the transport processes are taking place within the boundary layers within the thickness, which is comparable to the boundary layers.Any reaction which is highly exothermic or any reaction which has dangerous side reactions, so that the heat has to be dissipated they are prime candidates for microscaleorreactors and soon.

(Refer Slide Time: 04:40)



So, we know that a mass transfer limited reactions are well suited for microreactors.And it has been shown that a generally the size is of the microreactors approximately 200 micron;it can vary from 50 to 500 micron.For the optimum sizeof a micro reactor will be of the order of 200 microns.So, we have to keep that in mind;200 microns and a few centimeter in length. So, how do you combine, such channels together ensure uniform flow through them.Andto have a system, which would give you at least measureable quantities of the product;that is the challenge. So that is the manufacturing challenge that is a fabrication challenge. So, we would seewhat are the practices?Which are followed in such cases?

(Refer Slide Time: 05:32)



Sotwo views of microor in nano manufacturing;one is top down process and other one is bottom up process.One just the reverse of the otherit seems.How many of you have visited aEllora caves?Some of you, all of you have heard about it.This is a specific cave, which is world famous in Ellora,the cave numbersixteen.anyone a having idea of a what is the structural, uniqueness of cave number sixteen or any cave in Ellora.Is started the top,it start of the top of the hill.In the artisans,these starts cutting from the top and slowly reach to the bottom.So, when everything is finished all the material is removed, then you have a temple or some specific shape; that is the philosophiesthat is one of the philosophies. So, you can think of how much material has to be removed,how much planning has gone into it; that you are going to have a specific shape or structure or may be something from a like a pictorial representation of some mythicalevent and soon.

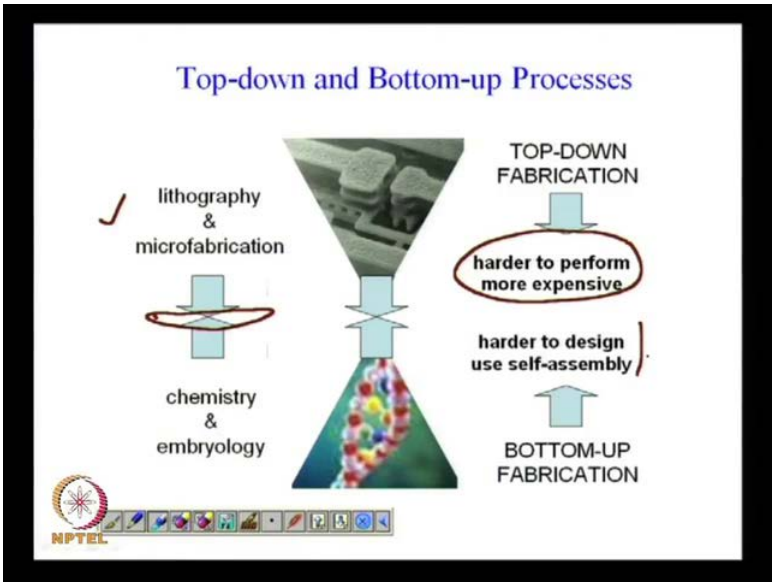
So, what is the difference between the construction of Ellora caves and your body?A human being is there any differencebetween the concept or between the practice of making Ellora caves and a human organ.Human body at searchis start a human body starts with what?

Cell.

Just one cell;and from one cell, the cells assemble,you create something else.Slowly, an organ will evolve;human being our body will be formed. So, if you think about these two approaches, they are the prime examples of top down process and bottomup process. So top down process is when one you start at the macro scale with the very very large rock,as in Ellora cave.And you proceed to create fine features by somehow processing the bulk of material, removing the material which is not needed; and finally come up with a structure, well which all of us can see and enjoy.On the other hand,weif you think of bottom up process, it starts at the smallest possible scale,the atoms in a reaction, cell forliving organisms and soon.And it builds it adds complexity to the entire surface entire object up from the cell and above.

So process a controlled by self assembly,I will come back to thisnumber of times.Some of you are familiar or should be familiar with a self assembly,I hopeany ideaany one with some idea of what is self assembly?Does not matter;I also know very little about self assembly, soit would not matter.Would seewhat is self assembly?and how it is going to be the building block of a bottom up process.Now, it is very expensive top down process is;bottom up processes we do not whether how expensivity is going to be, but we know it is going to be extremely complex.So, let us see what are the problems associated withtop down process, the advantages of top down process, and soon.

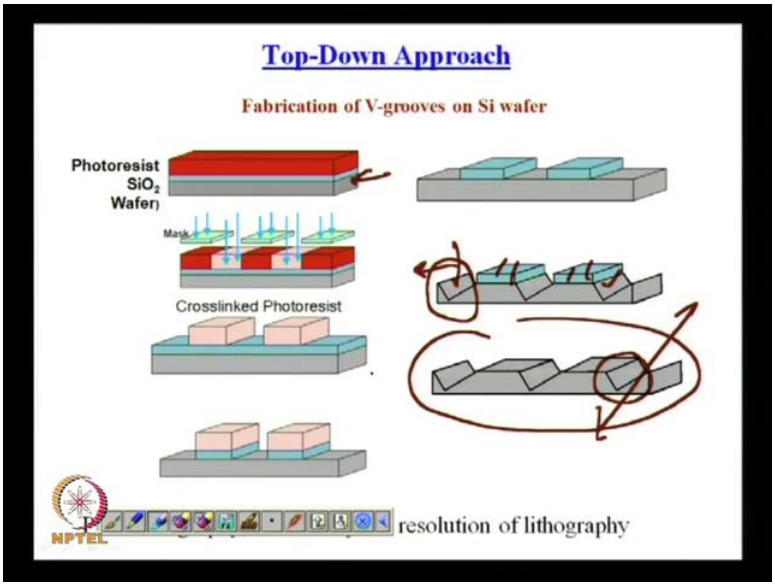
(Refer Slide Time: 09:10)



This figure tells you about the examples of a top down or a bottom up process.IfI see the left hand side of the figure,we know what is lithography. So, I will talk about lithography in this course a many times. So, lithography and microfabrication with our knowledge from chemistry and embryology, these two are going to be meet somewhere.Where and when we do not know, but right now, we are working with lithography and we also are starting to know a little bit more about the chemistry involved in self assembly and in the bottom up fabrication.

So, the top down fabrication becomes harder and harderand it is becoming more and more expensive,specially when the device sizesare becoming quite small. Sothe smaller the size, ultimately we are going to be limited by the wavelength of the light that we are going to use,because your lithography of photolithography depends on the wavelength of the light.And that is going to be some deflection and ultimately the wavelength it cannot go below that; it is difficult even to approach that.The size limit that has been achieved is 65 nanometer. So, let us say 100 nanometer; soyou cannot go below 100 nanometer with the devices with the equipment that we have today.Whereas, on the other hand if you think of the bottom of fabrication process, if you can do it, then you startat the angstrom level and grow up from there. So bottom up fabrication is definitely a harder to design, in something like self assembly willneeded will werequire self assembly.

(Refer Slide Time: 10:56)



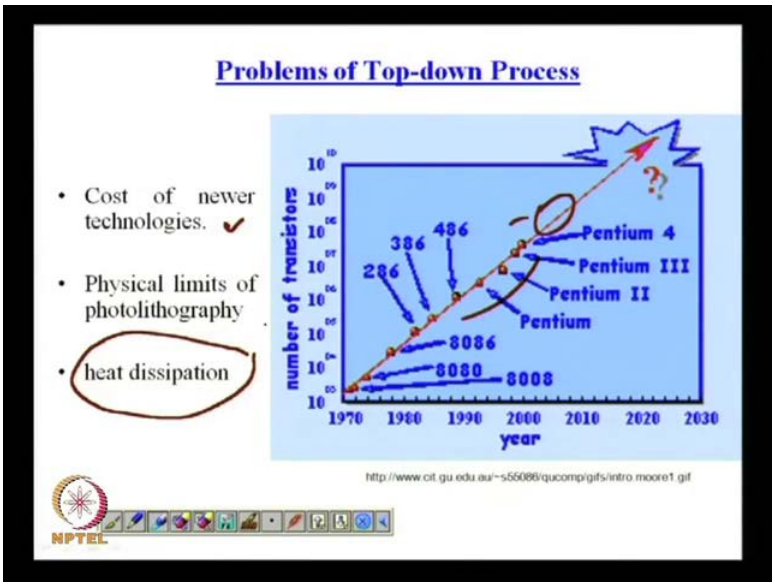
I will give you an example of top down approach,which has been done performed it is a very basic operation, but since we have done it,I would like to advertise it.Let’s say. So, it is fabrication of a V-groove on silicon wafer.Many of you are aware of what is silicon wafer. So, you start with this is the silicon,grey one is the silicon wafer, you grow an oxide over it.Silicon, silicon dioxide; coat the silicon dioxide layer with some photoresist.So when we expose the photoresist to ultraviolet light, there would be some chemical reactions; there would be cross linking and depending on whether it is negative photoresist or apositive photoresist, it may get hardenor may remain as it is.

So, you make a mask.Mask is something which is a negative of this structure that you would like to imprint on the surface. So the mask will allow UV rays from some portion of it, mask will allow theUV rays to pass and interact with the photoresist. So, there will be some portions of the photoresist which would be cross linked, which would be hard in this specific case, the rest will remain as it is, which would be easier to dissolve away using the right choice of solvent.So, now we have aislands of photoresist;you now remove the oxide layer as well. So, here you have the silicon, exposed silicon and some portion of the silicon, which is not exposed, which is protected by silicon oxide. So, you have achieved the first part of your objective; that is you have you have imprinted the, we have protected the areas, where you do not want to h any silicon, remove any silicon, expose the areas where you would like to dosomething.

So, the next step would be use a silicon h, which should be a concentrated KoH solution at elevated temperaturea roughly about 85degrees orso.And depending on the crystal planes,it is going to h. So, depending on which type of crystal hindered or 110, whatever crystal of silicon that you are using,they are going to h and the two crystal planes will propagate and meet at certain point and the h becomes self stopping.So the h does, the etching rate at different crystal planes are differentvastly different. So, it is going to h only in the vertical direction, but it cannot go in the side direction. So, what you end up is nice V-grooves on silicon wafer.Once you will achieves that you remove this oxide layer as well;and here you havea silicon wafer with micron size V-grooves of certain length on it.

So, the roughly the dimension here is about a 30 to 50 micron.The one that that was done here and the lengthof this is about two centimeter.Now this has been used for some purposes, which may be some other time I will talk about.Butthis gives you an idea of a top down approach.You start with the entire to complete material, remove part of the material and end up with a structure, end up with the micron size structure.Now what are the things that you have to use in this process?You definitely require lot of chemicals, you require specialized instruments, which are prohibitory expensive; and it is a we do not have the latest one and it isa any kind of fabrication has to be done at a controlled environment, where there are no dust particles.So, you will hear facilities like class hundred atmosphere, in which you have a the class hundred,I think the definition is there would be a less than hundred particles of 10 micron size or more in one cubic meter of air. So, there will be filtering of air,special specialty chemicals and processes to clean the silicon and soon.

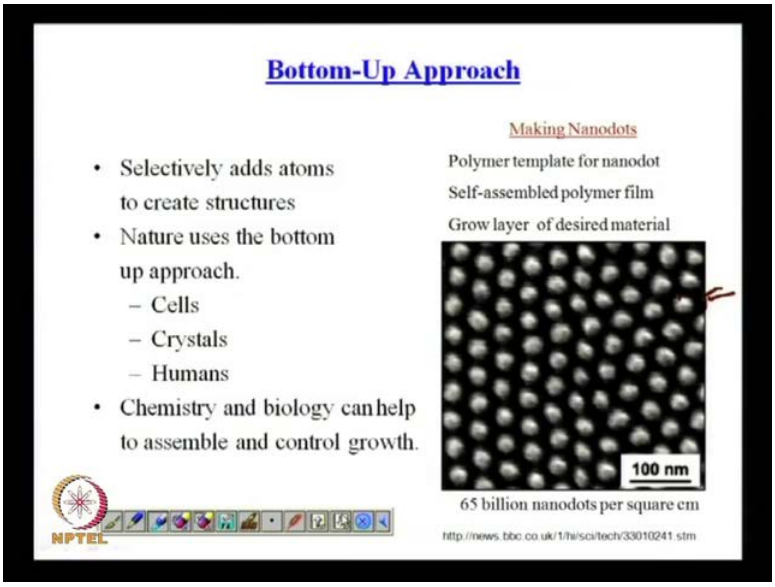
(Refer Slide Time: 15:07)



So, we see that it is becoming more and more a process which more and more of process which requires lot of money and investment and specialized training.And if you look atthis specific graph, which I have got from somewhere,from 1970 till 2010 close to 2010, the number of transistors on a chip it is increasing phenomenonally.Soright now, we have we are somewhere around here right now.

In the problems associated in packing somany transistors on a silicon chip; obviously, the cost of newer technologies and physical limits of photolithographythat had discussed; this is the one which I havenot talked about.Any transistor is going to generate some amount of energy; such a small size transistor will generate very small quantities of energy.Butthe areas are going toso small that the heat flux to be removed, in order to maintain the temperature of the chipwithinallowable limit of about 80 degree centigrade will be enormous.And so far the cooling technology that is being used is just convective cooling,fan, number of fans, andso on.Therehas been propositions of liquid jets to cool the chip or other techniques, but all the newer techniques involve change of phase heat transfer.Because whenchange of phase takes place, you are going to extract the maximum amount of energy; it is going to be much more than convectionmuch more than normal convection conduction or any other process that you can think of.So, how to have a proper cooling technology to dissipate the large amount of that is becoming one of the major challenge is of top down approach.

(Refer Slide Time: 17:00)

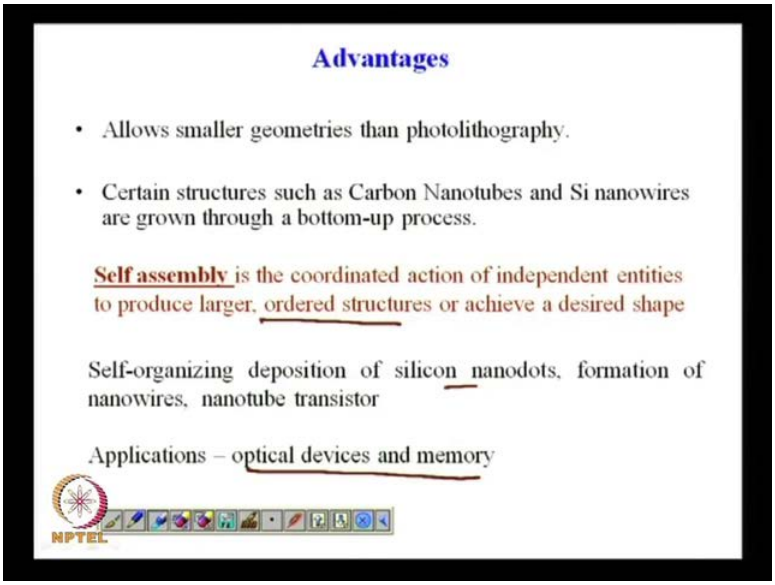


Now, let us think of bottom up approach.Is selectively addyourdevice your strategy in such a way that you can add atom by atom on a surface, on portions of a surface and thereby build a structure from nothing out of nothing.So, first advantage is you are not going to lose material;you are not going to lose any material.The amount of chemicals involved will be less, since you are not going to depend on photolithography that much sothe costly equipments optical equipments are may not be necessary.

And it is something which happens in nature all the time, soif you think of cells, growth of any crystal or ourselves, we all have grown using a bottom up approach.This is an example of making of nanodots on silicon; and we will see what isthe advantage ofnanodots havingto have on a silicon. There are certain polymers which have apeculiar tendency that a they are going tocombine with each other at the molecular level; and they will follow a specific structure and they will remain at that structurefor quite long of for a quite length of time and there inert once you make them they are inert.

So, you can start the process by selectively exposing certain areas for thesefor the growth of these self assembly a self assembled polymers. So, here is an example that you have 65billion nanodots per square centimeter. So, since we are talking about molecular level,soyou can have surfaces by proper treatment of the surfaces, you can make certain points where the nanodots where the self assembly can take place and some points where it cannot; this isnot futuristic technology it is already here.

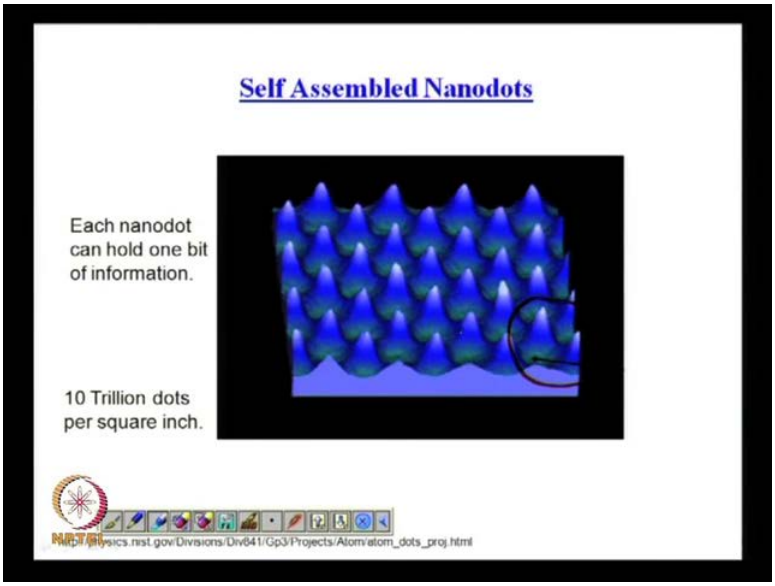
(Refer Slide Time: 19:00)



So, what are the advantages of self assembly andbottom up approach?Definitely you can make a smallermuch smaller geometry than that is available in photolithography.Andwe hear about carbon nanotubes, silicon nanowires, which are going to be the material of tomorrow’s products, tomorrows manufacturing and all are made by a bottom up process.

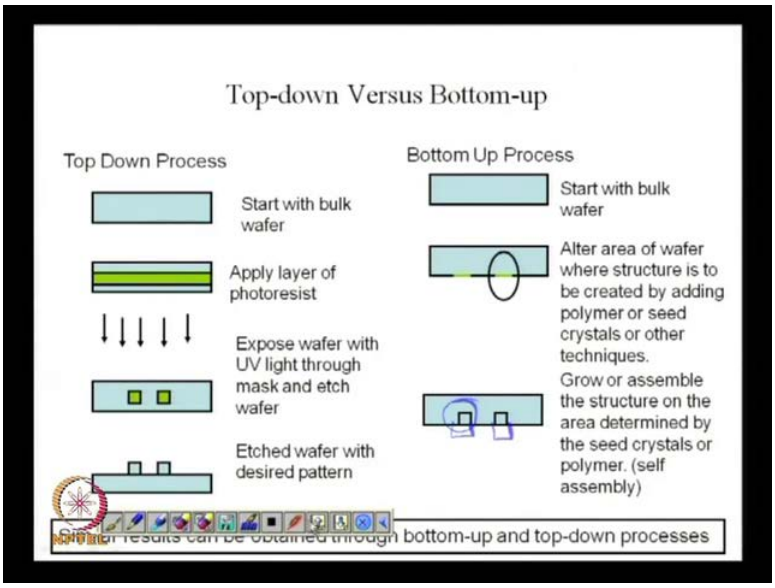
So, if I would like to define what is self assembly? So, it is a coordinate action of independent entities, the independent entities could be molecule, could be a cell, to produce larger; and this is very important ordered structure and may be it would lead to a desired shape like you or me.So, this is the self assembly process.And there are various examples of cells self assembly, in terms of silcon processing likeformation of silicon nanodots,nanowires, and nanotube transistors.If you are able to talk about more exotic applications, but I am not going to talk about right now;the applications the basic applications that I am going togive you an example,it should be optical devices and memory.

(Refer Slide Time: 20:18)



How? Soagain andpicture of a nanodot surface,10 trillion dots per square inch and just think ofeach nano dot holding one bit of information.Sothe one square inch of surface, if you can make the nanodots and these arefrom theI do not know which how they took the picture of this, how much information can be stored using a self assemblyself assemblednanodots on.

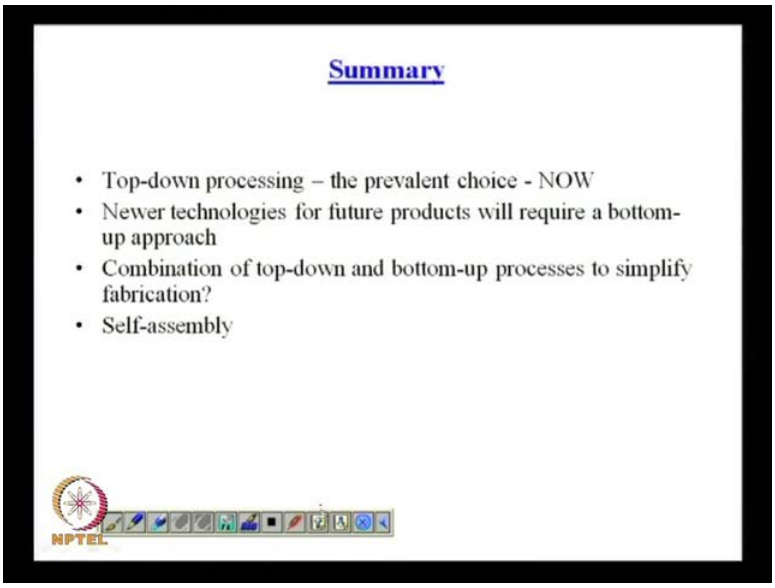
(Refer Slide Time: 20:51)



So, we are going to finally, summarize a between the top down and bottom up process.In the sense thatif you havetop down process, you start with a bulk wafer a silicon wafer; and then by some process, you are going toapply a layer of photoresist on top of it;inthe photoresist will be exposed to UV rays and this through a mask and etched the wafer, in order to obtain certain areas which would be protected in, certain areas which are not going to be protected.Sothe etched wafer then will be subjected to other processes, the example which I have given you is a reverse of this; where we have etched something, in this specific case, we have made two pillars on the silicon wafer.

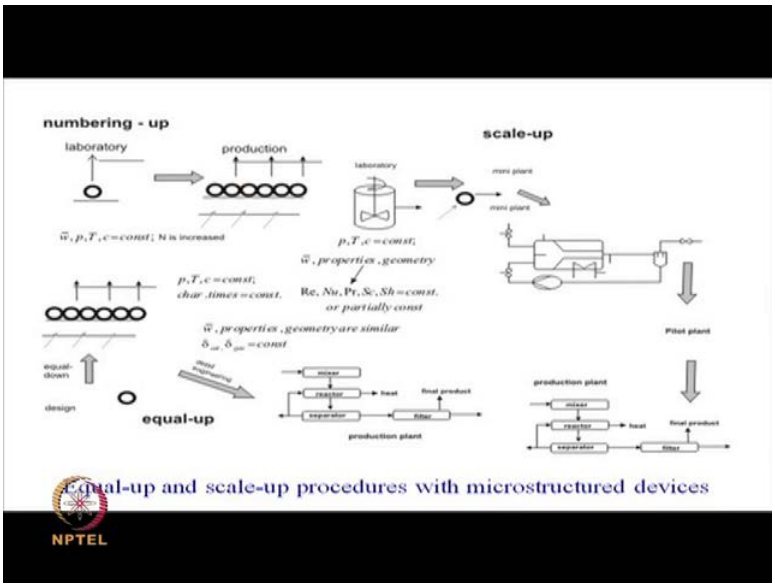
Now,let us say we are going to do the same thing using a bottom up process.For such a process, you again start with a bulk wafer, but you do not remove any portion of it. You alter the area of the wafer, which is the which istopic ofvery active current research,where the structure is to be created; you can add polymer, you can seed with certain crystals or some other techniques and then you grow or assemble the structure, these two are going to with reverse,I mean it should be pointed outward and soit will again look like this. So, you do the same thing using a top down and bottom up process.In similar results, for some of the cases, similar results can be obtained between abetween a top up,top down orbottom up process.

(Refer Slide Time: 22:42)



And the summary, in the summary I can say what we can say is thatpresently top down is still the method ofchoice for now atleast.And newer technologies are coming which will which is severely testing the limits of the top downprocess, specially in terms of cost, in terms of how small you can become and in terms of operational is;for example, heat transfer and soon.Peopleare trying at this moment to use a combination of the two top down and bottom up process to simplify the fabrication; and the methodology, by which such topsuch bottom up approaches can be successful, the key words is self assembly. So, you let moleculesform a group, form a structure, grow a structure, in how small you can become on a molecularon molecular level that is going to decide about the future ofbottom up process.

(Refer Slide Time: 23:47)



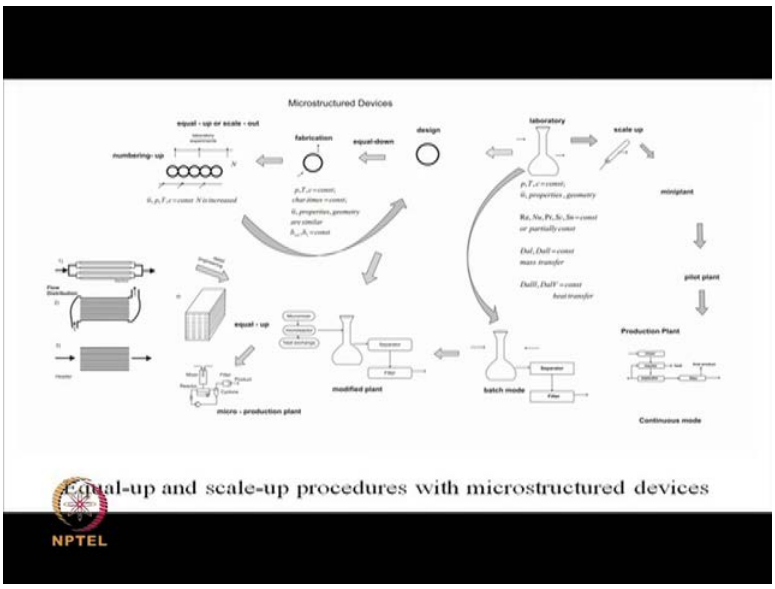
Now, we are coming to something which is which with which we are familiar with one is the scale-up.Let us concentrate on the right side of the picture. So, what we have is something, some reaction, some process which is taking placein the laboratory.You would like to scale it up to a pilot scale first and then to a production plant.The process involves maintaining certain conditions the same between the laboratory and the mini plant.So, we know that there are similarity geometry similarity, you have to maintain as well as dynamic similarity. So in order to maintain similarities between these two processes taking place at vastly different scales, you maintain the pressure temperature concentration constant in both the cases.Not only that such that the processes would be governed by similar laws or correlations, you maintain the similarity parameters;for example, Reynolds number,Nusselt number,Prandtl number, etcetera, the same in all processes.

So, you are concept concepts that you have envisaged to at the level laboratory scale would first be transformed into the mini plant level and using the standard scalar procedure, it would beit would come to the production level.The situation is slightly different when we go at the micro scale manufacturing or scale-up involved at macros scale manufacturing.The first thing you start with, at the laboratory you make one channel, just one channel somehow you make and you try to perform the same reaction or same operation in that microchannel.

So you work withgeometries, first to see where you're going to get the maximum benefit. So, this designed part is going to be important.How did you design it?Whetherit is going to depend on geometry, whether it is going to depend on the nature of the surface that you have, whether there would be number of interconnects in between in between such a channel andso on.Once you are satisfied with the reaction taking place tiny volume of reactantsand products being formed in such a micro channel, you go for a process which is known as the numbering of; you just add thousands and thousands of these microchannels, in order to obtain some sort of an equipment, which could be microreactor, which could be a micro heat exchanger andso on.

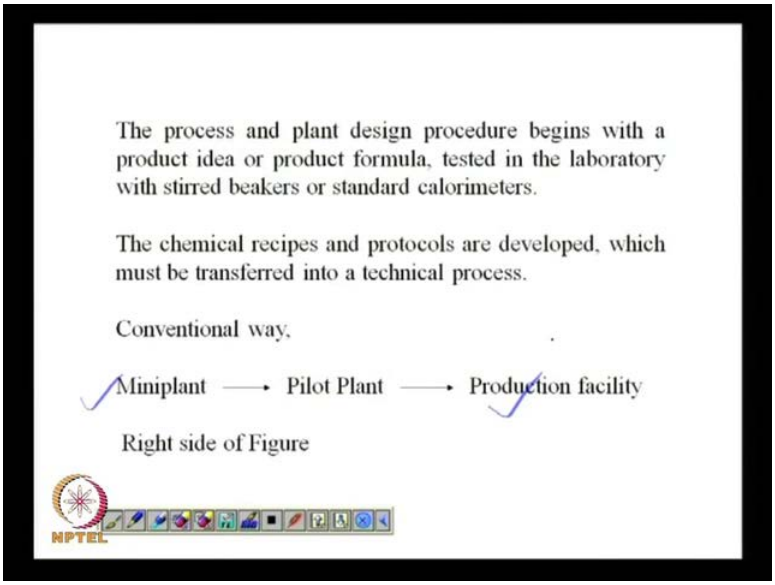
So, there would be problems associated with numbering up.While numbering up, you have to how you are going to ensure that this same amount of liquid or same amount of reactants will pass through each of them.How are you going to ensure that there would not be any leakage or any short circuit in between two channels andso on?How do you cover up the channels?How do you design the manifold, by which equal distribution is possible.Sothese are some of the issues that one has to think while numbering up.So you can make an optimized structure that the laboratories scale of one channel, but how do youconvert that one channel into thousands of channel;the numbering up is going to be a big challenge in such a process.

(Refer Slide Time: 27:07)



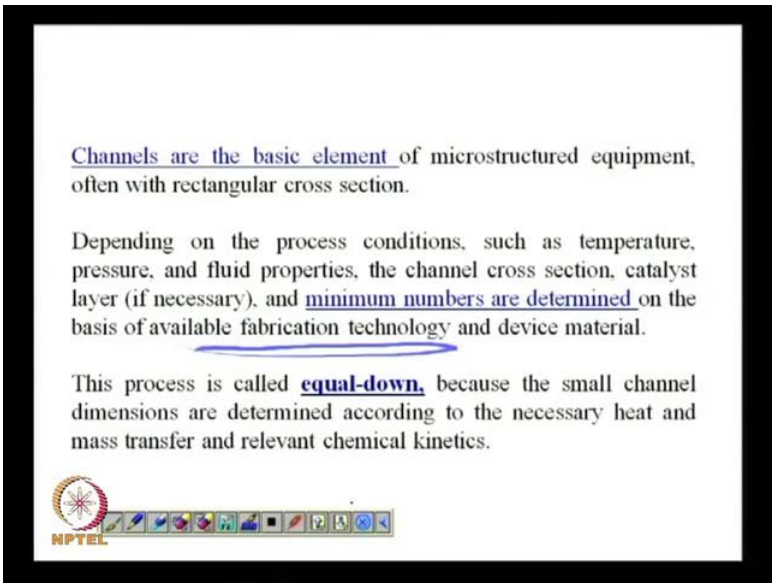
This is the same one with the problems highlighted. So, what you have on one side is we have in the laboratory and we have two ways to go.We can either go towards the microstructured device part or we can go towards a standard large macroscale equipment design.So, when from the laboratory, first is as I mentioned you first design something, some dimensions andso on. So this design now has to be stepped down by the available fabrication technology to a microchannel. So from that fabricated microchannel, you perform the numbering up and you go to a series of microchannels,I mean number of microchannels, probably connectedin parallel.And these are some of the distributors flow distributions that one can think of, which are in use; some sort of manifolds fluidic manifolds which are in use; soas to distribute liquid evenly through all themicrochannel.

(Refer Slide Time: 28:18)



So, let us go to slightly in more detail.Now in a conventional way, you start with mini plant and end up with a big production facility, which is a right hand side of the picture which I have just shown you.

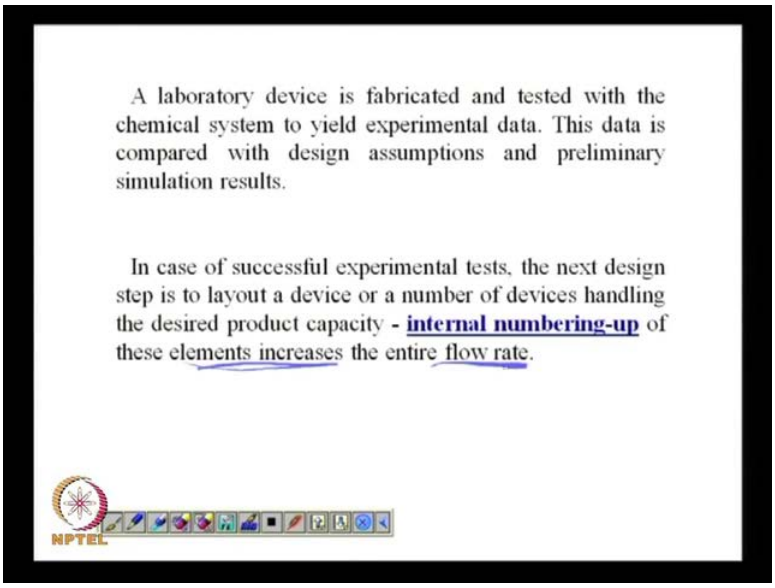
(Refer Slide Time: 28:32)



From there, if we like to think of thebasic elements of a microstructure device,those are going to be the channels.So, you decide about the minimum number of channels that you would require for performing certain operation.You have to be careful the process conditions and what whether or not, you have fabrication technology available that can take care of requirements;sothis process is known as equal-down. So a small channelsimilar dimension, the smallest possible channel dimensions are determined depending on what is available to you,whether or not heated mass transfer and the chemical kinetics; which one is which dimension you would like to reduce.Are you going to reduce a length or are you going to make the two walls very close to each other;because these are going to give you fundamentally different conversions for so to say.

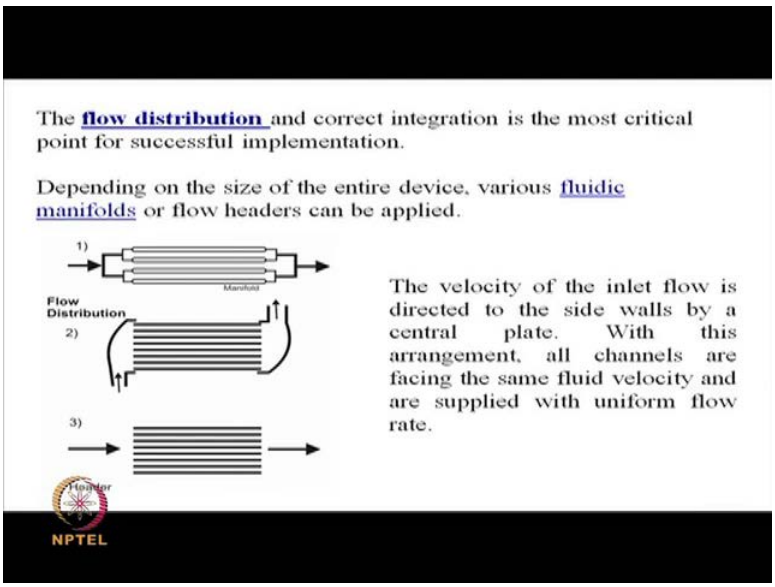
Soif you have a catalyzed catalyst, the catalyst surface then you would probably like to bring the catalyst surface as close to each other as possible; such that the reactions are taking place within the boundary layer itself,the diffusion of the product to the main stream would have the least amount of path to go.If you have a very fast reaction, then you have you probably need a two centimeter channel;maybe half a centimeter would be enough for the reaction to complete.So, your fabrication technology, you kineticsand you heat and mass transfer would govern; the size of the channel to be decided in the equal down process.

(Refer Slide Time: 30:14)



Next is,we concentrate on internal numbering up. So, when you are successful with the experiments taking place in one such micro channel, you try to increase the number by increasing the number of elements, which enhances which increases the flow rate.

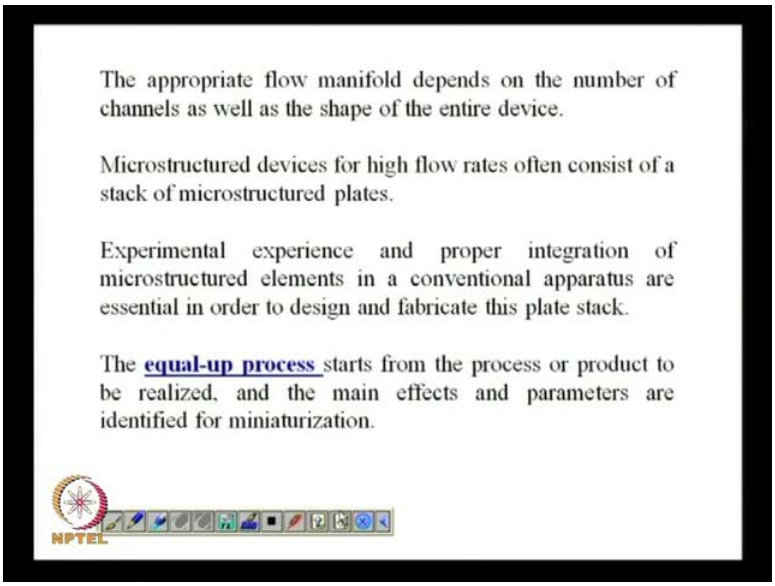
(Refer Slide Time: 30:31)



And these are the some of the enlarged versions of the manifolds the flow distributions, which are being used. So, the velocity of the inlet flow is usually directed towards the side walls, not to the entry of the micro channels.

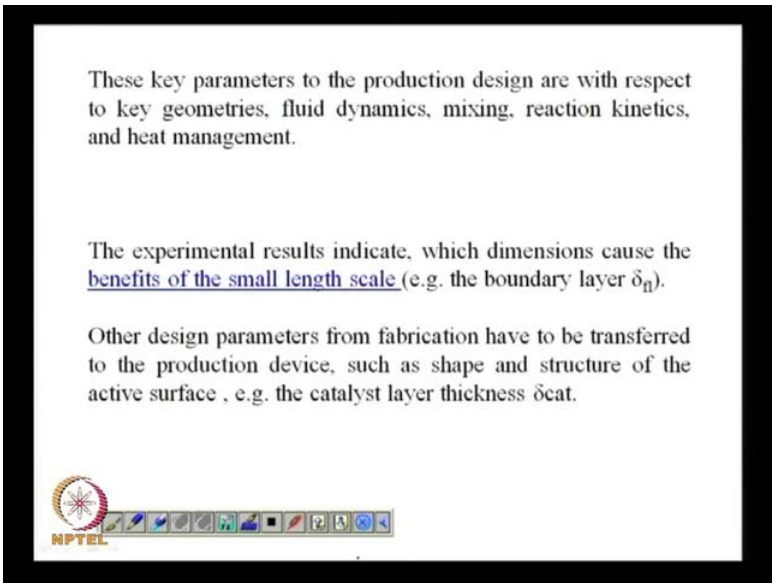
Soif you have the flow directed towards the entry of the micro channels, then the chances are that one of the channel is going to be highly indicatedcompared to the other channel. So, the flow jet is never directed to the micro channel,it is always directed to a side wall or a side plate.Such that you have very well mixed high pressure side at the inlet and then all the channels are hopefully fed with the same flow rate.

(Refer Slide Time: 31:24)



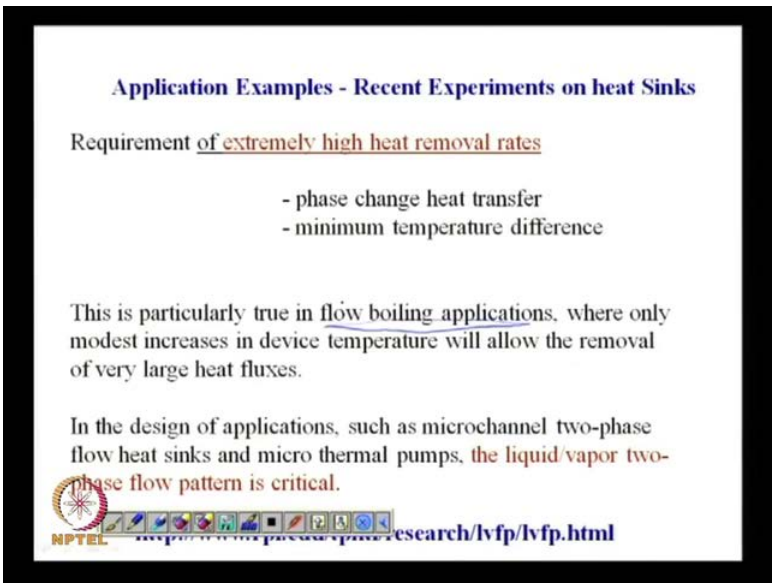
Sothe,you decide about the manifold; obviously, based on the number of channels that you have.And it is still not a complete science, where you can one can explain how to design such manifold. So, it is depends even now on experimental practice.

(Refer Slide Time: 31:50)



The key parameters are then flow the geometry, the fluid dynamics, mixing, kinetics, and heat management.Everything we would like tohappen at a length scale, which is let us say of the boundary layers.

(Refer Slide Time: 32:11)

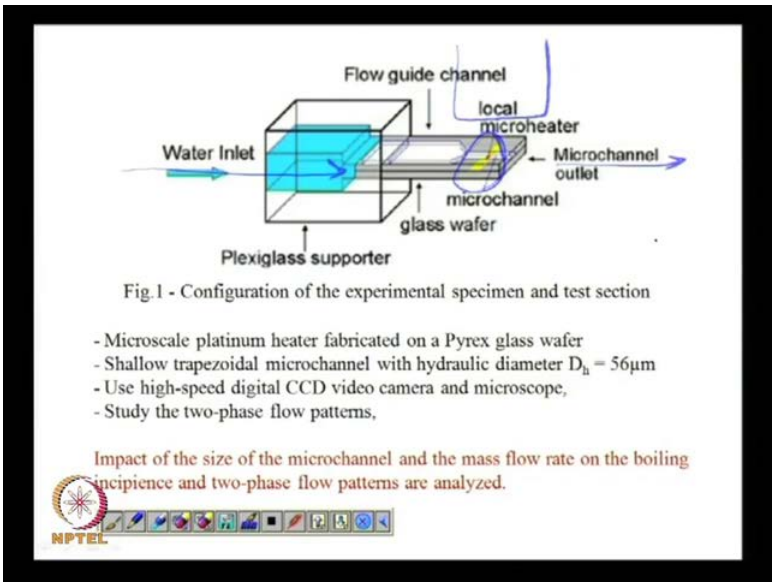


I willgo to an example right now.An example, where fabrication that we have discussedsofar;the top down approach has been used to design a heat sink.In this design of heat sink is necessitated by the requirement of high heat removal rates; and as I mentioned, it has to depend on phase change heat transfer,an another advantage of phase

change heat transfer is heat transfer takes place with the very small value of delta t.If you think of a heat exchanger, the delta t's could be of the order of 10's,20's, and 30 degree centigrade.Butwhen you have phase change heat transfer, you require very, very small delta t,soas to have a temperature;soas to have a phase change.

If you think of a thin liquid film, for the liquid film to evaporate across the liquid vapour interface, it has been calculated it has been shown that the temperature requirement could be as low as 10 to the power minus 3 degree Kelvin. Sowith that smaller heat that smaller temperature jump, you are going to have phase change from the liquid to the vapour or vice versa. So, any phase change heat transfer any heat pipe, soto say which is acting on phase change, can operate with smaller very small delta t compared to a normal heat exchanger. So, these are the experiments that I am going to describe would be very importantfor flow boiling applications. Applicationsin which I have flow and simultaneously there would be transfer of phase, in the form the bubble which is formed is going to depend and is going to flow is going tomove with the flow; and there by create two phase flow situations, which could be unique in nature.

(Refer Slide Time: 34:09)

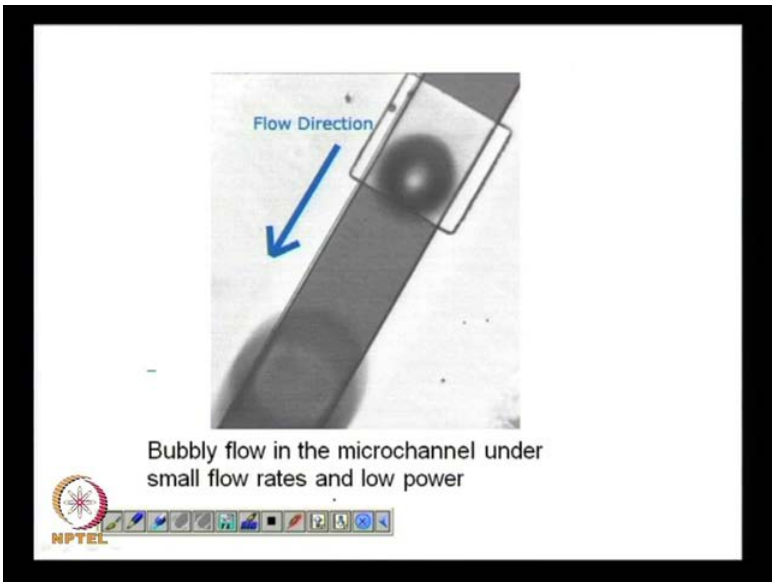


So, let us see what has been designed in this case. So we have a small micro channel, which is made by two glass plates bounded to each other.And there is a micro heater, the yellow part which is going to act as the hot spot and I am going to have flow of water from my left to the right.

So, the flow takes place over the micro reactor and there would be a microscope with a high camera, which would focus on the micro heater. So, initially when there the micro heater is off, then you are simply going to have single phase flow, just flow of water nothing else, you would not see anything.Butthe moment the micro heater is on and the heat flux to the micro heater is progressively increased, there will beinitiation of boiling. So, the initiation of boiling will create a vapour bubble and thewhen you supply enough heat this vapour bubble will detach from the surface and will come to the bulk flow; and it will be carried with the bulk flow towards the outlet.

So, this is the situation which is common at micro scale, but at the micro scale, we would like to seewhat are the factors, on which this boiling or the heat transfer would depend on.One obvious factor is the heat flux, the nature of the surface, and soon. So, the essentially the setup that we are describing is a Pyrex glass and with the hydraulic diameter about 56 micron, sowe are in the micro scale, definitely not in the nano scale. and we would like to see the impact of the size of the micro channel and mass flow rate on theboiling phenomena. So, let us see what we get.

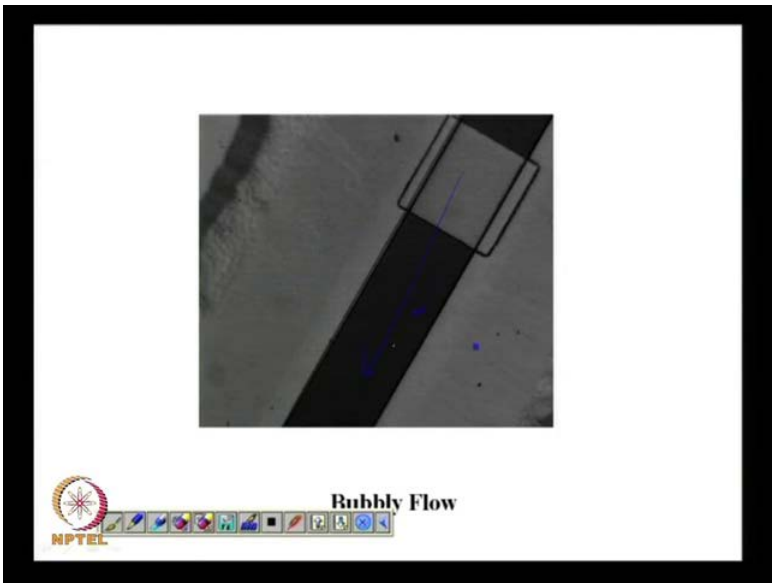
(Refer Slide Time: 36:03)



The first thing that you would get,some of you areprobably takingtwo phase slow in the semester as an elective course, there you know thatthe flow regime in two phase flow can be divided into a number ofdistinct categories.The simplest one is bubbly flow,you generate one bubble; and that bubble, will grow in size, at some point due to surface

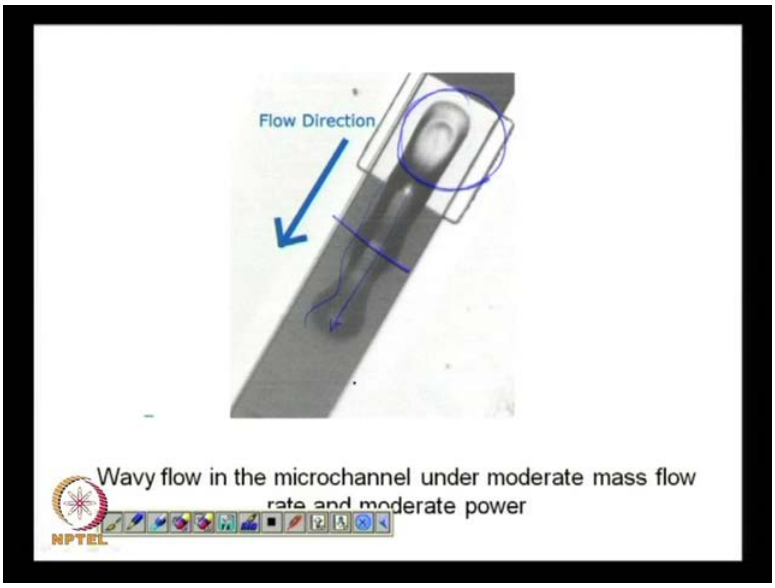
tension, it will detach from the surface and it will be carried with the flow downstream.This formation of bubble, essentially takes sufficient amount of heat form the hot spot, because of phase change, because of latent heat;so that is the simplest one can think of.

(Refer Slide Time: 36:49)



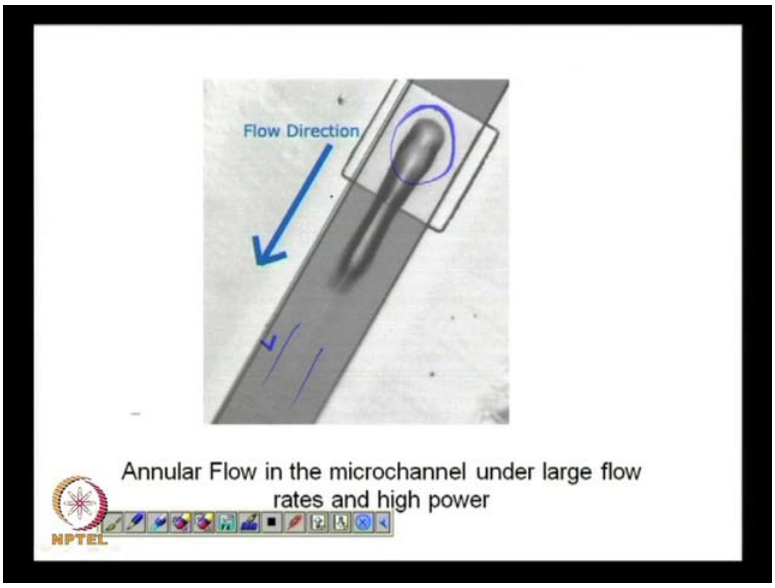
And this is the video of aof this bubbly flow which obviously itis not working.What you would see, if you would and you have to trust meis that the bubble will form the bubble will detach itself from the surface; and very quickly it will flow through the channelin the downstream direction. So, they have taken the picture of the bubble, they have measured the temperature, when the bubble forms, when the bubble detaches and soon.

(Refer Slide Time: 37:19)



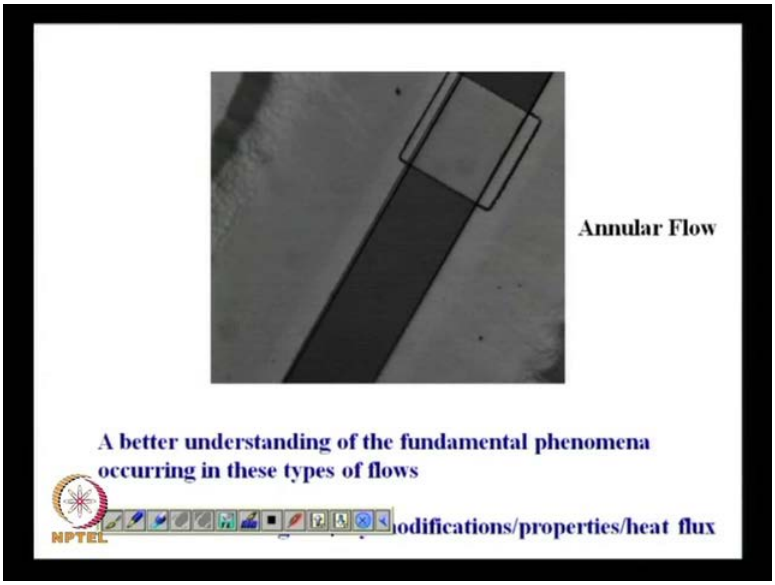
The next one,I will not show the video then I will describe it.If you increase the heat flux,soyou what you are going to see get is wavy flow of the bubble.The bubbles become elongated, they are larger in size and this some sort of there still attached as if by rots to the point, where the bubble has found and progresses in this direction.Obviously, after some time, they are that is going to be they are going to be shared of either from their base or it is going to be cut off from some point around the middle and will flow withthewater flowing downstream.The amount of heat that is transferred by this type of flow wavy flow is going to be more than that of the bubbly flow; and this is more difficult to handlemathematically.

(Refer Slide Time: 38:16)



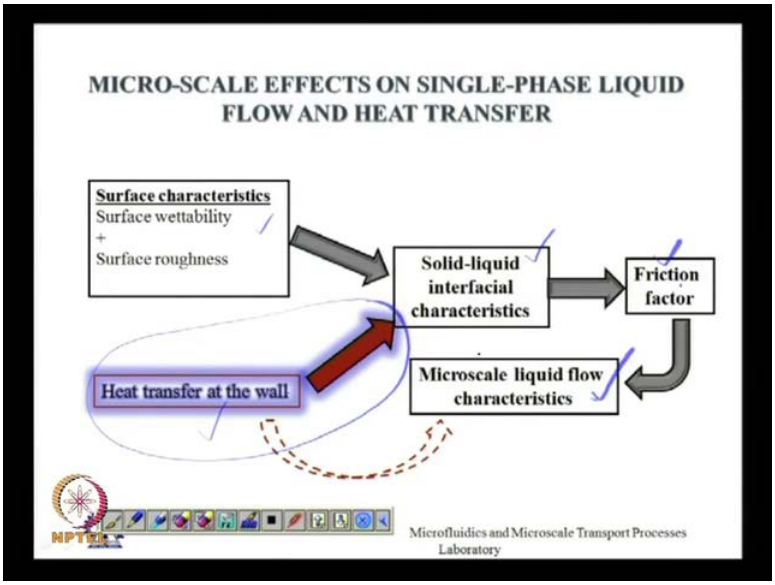
The next one is annular flow.An annular flow is similar to wavy flow, but here we are going to have a distinct flow pattern of two phases flowing simultaneously side by side, to a large length filling a large length of the pipe. Soyou are going to have a vapour core and a liquid which is flowing along the side. So, the heat transfer that if youcalculate the value of the heat transfer coefficient will be less than before, because this section is more or less going to be covered with a vapour film all the time. So, this annular flow is also going to be seenat some point.

(Refer Slide Time: 38:57)



Now, we need to have some ideas about wind and what type of bubble formation, you are going to get on the surface.Because you would like to create a surface, where it would be very easy to form a bubble,you would also like to see what would be the effect of different machining techniques; that means, whether or not this formation of bubbles are going to depend on the geometry and how they are going to affect heat transfer. So, the trained of research sofar was create a new surface of some roughness.Make it hydrophobic or hydrophilic,supply the some amount of heat flux, let the bubbles form, heat transfer takes place and try to see what is the optimum at which point you are going to get the maximum amount of heat transfer. So, the train is for different slow geometries, different structures, when you are goingto get the maximum heat transfer.

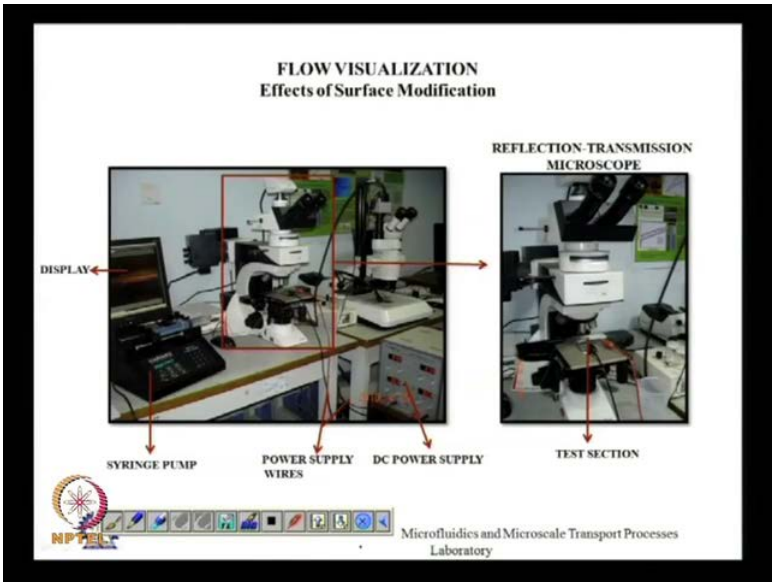
(Refer Slide Time: 40:02)



But something else could be thought of which I am going to show in the last few slides. We know that if we change the surface characteristics, the change the solid liquid interfacial characteristics, which intern changes friction factor, the pressure drop changes and that change is the liquid flow characteristics.This is if we if you forget about this part, the rate part this is a normal procedure what you have donesofar, what you have studiedsofar in fluid mechanics.Change the surface, change that socalled epsilon in the in the moody diagram, change your friction factor, find out what is the pressure drop and you get the different value of pressure drop.

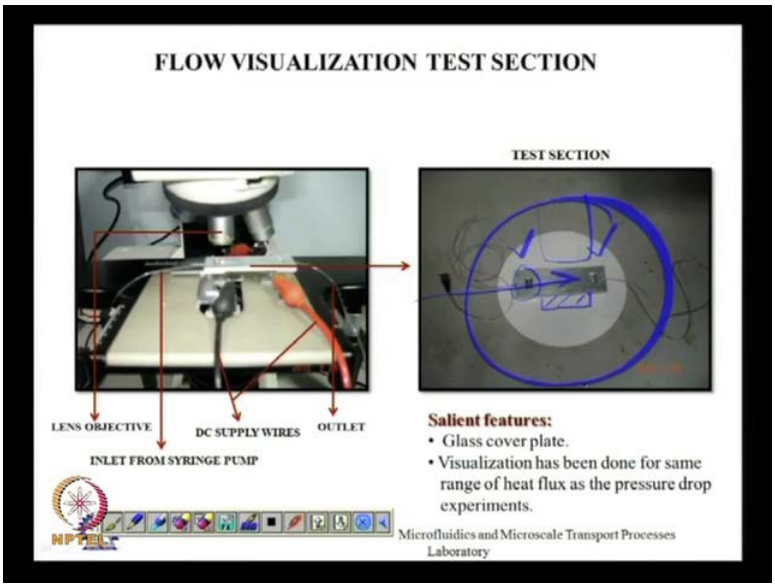
What if now we add the heat transfer at the wall, we create a bubble at the wall we create, we force a phase transfer at the wall and this heat transfer is going tochange the interfacial characteristics; and this heat transfer is going to affect the friction factor.So, it is not that fluid mechanics is controlling heat transfer, what we are trying to see is whether heat transfer can control fluid mechanics as well and how it is done?If you let us think of a simplest in a simplistic fashion, if we create bubbles a large number of bubbles on a solid surface, then the liquid a small fraction of the liquid will not see, will not know will that a solid exists at some point. So, the surface is going to be covered by nano bubbles and the fluid, the liquid in this case is going to slip over the nano bubblecovered surface. Sowhat happens to the friction factor?You are going to get a verysmaller a reduced value of friction factor. Sothat the concept, you wanted to see whether heat transfer by incorporatingheat transfer at the wall by creating very smallbubbles on the surface, whether or not the frictional pressure drop that we measure is going to be different or not.

(Refer Slide Time: 42:16)



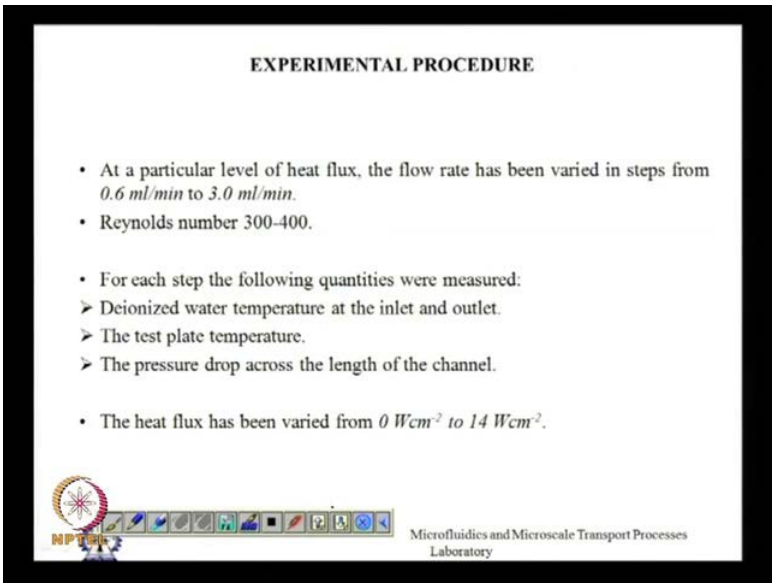
Sothat was the experimental plan for such thing, in for which we havedecided a flow visualization setup.

(Refer Slide Time: 42:25)



In fact, I think I will go to this first; this is the setup which was created.Analuminum channel and on the aluminum channel youusing milling process, you create thin channels.That channels are stillhundreds of micron in size about 75 to 150 micron would be their size.And the milling process was varied,so as to get different surface roughness.We wanted to see whether surface roughness, how surface roughness will help in the bubble formation.We are measuring pressure drop atsothe flow of liquid is from,let us say from one direction and we are measuring the pressure drop between these two points.And over here there would be some sort of heater attached, which is going to supply a known heat to the micro channels. So, we have flow of flow, constant flow, measured the pressure drop and start adding heat intry to measure the change in the pressure drop with increase in heat.And at the same time you put a microscope over here and focus really down inside the microchannel to see the formation of the bubble. So, your physical observation of the formation of bubbles, the number density of bubbles, the growth of the bubbles, how that process is linked to a change in pressure drop, a change in the friction factor; and whether or not you can say something about the heat transfer coefficientassociated in such a process. So the concept is use a heat transfer to change the surface and then thereby to change the pressure drop some of the examples which...

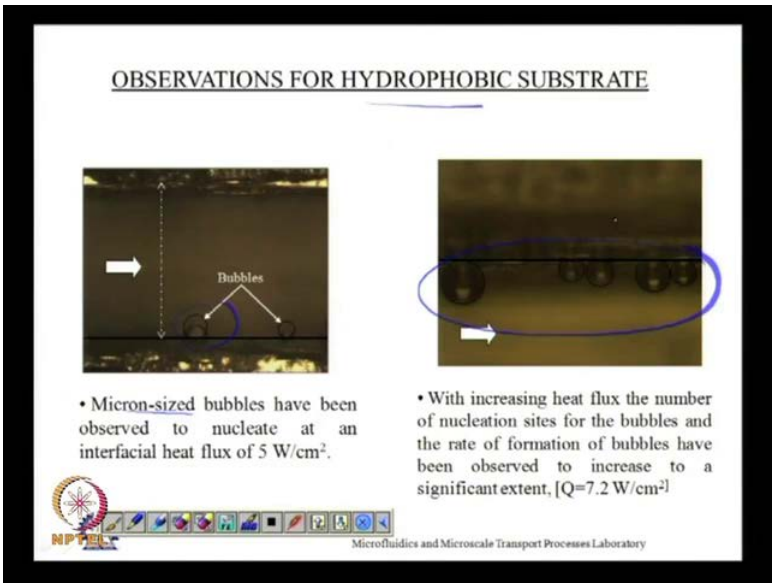
(Refer Slide Time: 44:11)



So this is the description of the experimental procedure;soyou maintain the heat flux, change the flow rate or you maintain the flow rate, change the heat flux.And at each step, you measure the temperature, you measure the pressure drop.And see whether, when you really see bubbles forming at the surface of the walls, whether or not you see a drastic change in the pressure drop, which obviously was observed in this case.

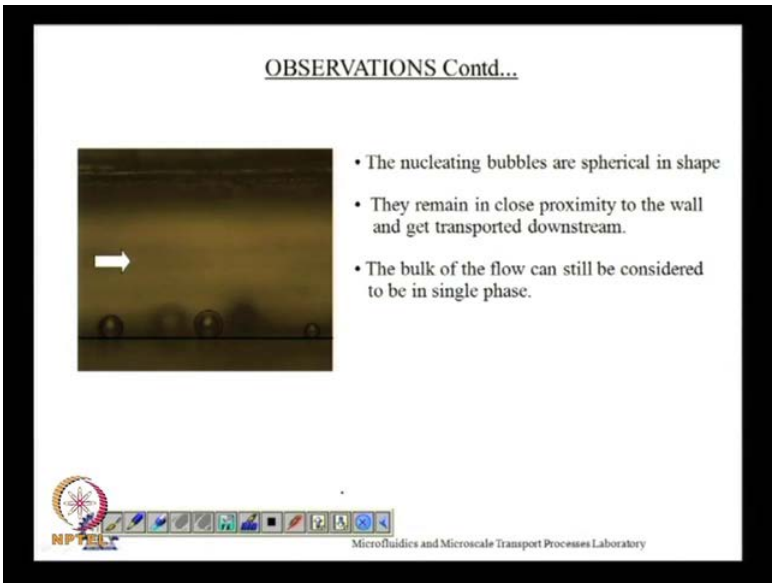
And when bubbles are formed, the pressure drop decreases, initially decreases then it starts to increase. So, one would like to knowthebackground for decrease in pressure drop with formation of bubbles is well known,there has beentheoretical papers published whichpredict that the formation a nano bubblecovered layer would give lesser values of pressure drop.What was observed was that, for higher roughness surfaces, if the surface roughness are quite large, then you would see that some of those protruded portion of this side wall may go beyond the bubble covered layer and then there by increase in the pressure drop.

(Refer Slide Time: 45:33)



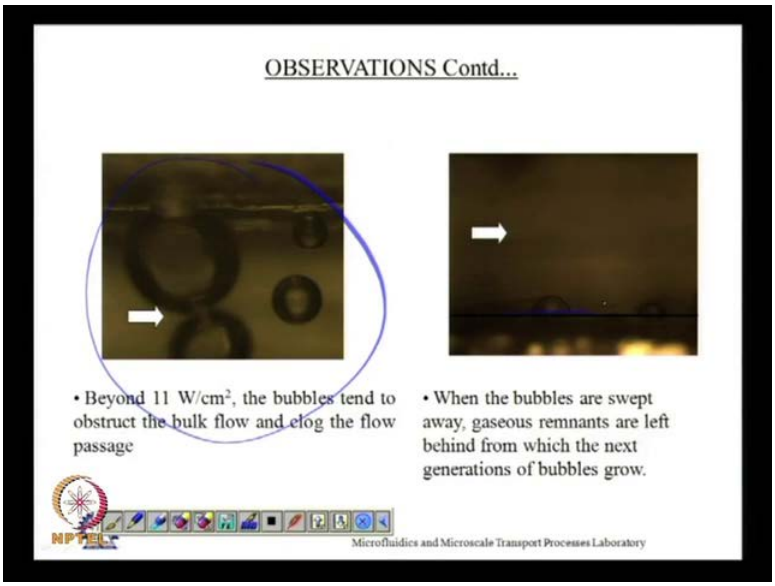
That is alsoto some extent obvious, but what would happen when you go from a high, when youmake a surface hydrophobic or make a surface hydrophilic. So, that is something which is which is going to be interesting.So, we focus on the microchannel and we see that micron size bubbles right over here I am not sure, whether you canyes you can still see itinon the screen, that micron size bubbles areformed.We obviouslycannot using a microscopic cannot really see a nano bubble, but we see micron size bubbles. So, you increase the heat, increase the energy and you can see that the number density of the micron size bubbles has increased ato some extent.Butthe bubbles are stillstuck to the surface; they do not leave the surface at this value of heat flux.Andwhat we what was seen is at the pressure drop has decreased, because now the liquid no longer sees the rough wall, it slides over the bubbles.

(Refer Slide Time: 46:38)



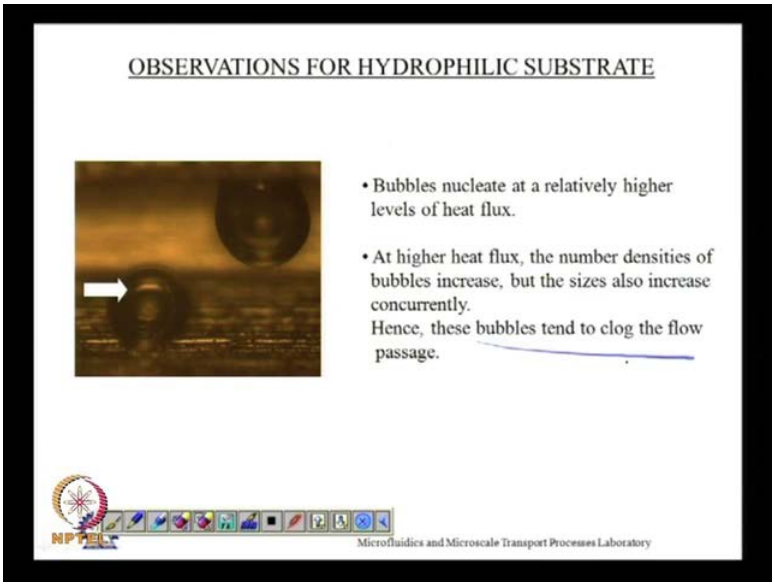
You increasethe heat flux to slightly higher value, but before that,just to mention the shape of the bubble will be spherical as expected; and they remain in close proximity to the wall, the moment they getdislaunch from the surface they do not they disappear.So initially,so it wasthought that it is due to that it they condense back, but using a first camera, one can see that the bubbles have simplyswept downstreams with the flow; well that has itsadvantages and disadvantages.The moment youstart to have bubbles, large number of bubbles flowing with the liquid through a micro channel, the question of clogging will appear.

(Refer Slide Time: 47:35)



If your number of bubbles found are quite large, the size of the bubble as they increase with heat flux are more, then you are going to a come to a situation, which is depicted in here is this, two bubbles almost touching each other.When two bubbles almost touch each other, then they clog the surface, they clog the entre channel and the flow becomes irregular first and the pressure drop increases bysubstantial amount. So, another interesting thing is when bubbles are swept away this is still yet to be explained, there would be some remenance of the bubble on the surface.And the remenance of the bubbles on the surface would act as nucleation sites for further for future bubbles; so the future bubbles will grow from that site only, from that site itself at the same heat flux.

(Refer Slide Time: 48:24)



Andfinally, we come to the hydrophilic surface. So here we see that the bubbles nucleate at relatively high levels of heat flux, which is expected. If you have a hydrophilic surface, then the molecular interactive interaction between the solid and liquid molecules will be smaller large, will be relatively large.So, if it is large, then you need super heat,extra super heat in order to nucleate the bubble, in order tomake change of phase.Andso thecomparatively larger heat fluxes are necessary, in order to havea bubble formed ata bubble formed on a hydrophilic surface.And at higher heat flux, the number densities of the bubbles will obviouslyincrease, but the size also increase concurrently. So, the bubbles will tend to clog the flow passage more in a hydrophilic surface than in a hydrophobic surface.And what also was observed, which is also intuitive in nature is that the pressure drop in a hydrophobic surface would it be high or would it be less.

If you think intuitively, the pressure dropas measured by the two points that too at the beginning, at the entry, and at the exit, the pressure drop would be.

Less.

For a.

Hydrophobic surface. .

For a hydrophobic surface, the pressure drop would be would be smaller.

So, the main points of this of this study, what was found is that, it is possible to use heat transfer to change a surface?You can make a surface, you can change a surface by manufacturing method, definitely yes,you can treat the surface chemicallysoas toimpart certain qualities to it make it hydrophobic or hydrophilic.And all of these would change the flow, wherever flow changes associated heat transfer also changes;that is we have knowsofar.Butthe novelty of this these set of experiments would be to use heat transfer and to use heat transferso as to create a condition, such that the flow changes. So, it is a reverse way of looking at things.And what was found is that it is really interesting is thatusing heat flux, you can change flow pattern.If you change flow pattern, they are inter connectedwhich intern changes the heat transfer.And the structure of the surface,the nature of the surface,they are very important for the formation of the bubbles and the overall heat transfer and pressure drop process.

So, if I would like to summarize the, what I covered in today's class isfirst is more like two different philosophies of manufacturing, a bottom of process and a top down process.Top down process is more common, bottom of process is fastly catching up,it is a new technique, new way of its paradigm shift in the thinking process of manufacturing something which is quite unique in nature.One is like almost atom by atom, you placed one atom on top of the other, as if and to create uscreate a structure; it is extremely difficult to control.In some cases for complex geometries, we still do not know how to create it.We can create a nanodot, but we do not know how to create a structure. Sowherever you create a structure we are still going to depend on thetop down process. Soyou start withletssilicon wafer, protect some areas, remove something and where by ultimately end up with a structure, it could be micro channel, it could be a transistor, it could be connecting wires in between, and soon.

Then we spoke about the number of numbering of strategies, the strategies of scale of in micro scales; the parameters that youneed to maintain constant in such cases and soon.And finally with two examples, onewhere you create bubbles, just create bubbles and see how the heat transfer is going to get affected; and look at the different regimes, in which you have flow, how the different regimesin different regimes, you can get different values of heat transfer.And second is an interesting way, to change the liquidsolid surface characteristics by using heat transfer. So, that is all for today’s class.

Thank you.