Microscale Transport Processes
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Lecture No. # 14
Micro Heat Pipes (Contd.)

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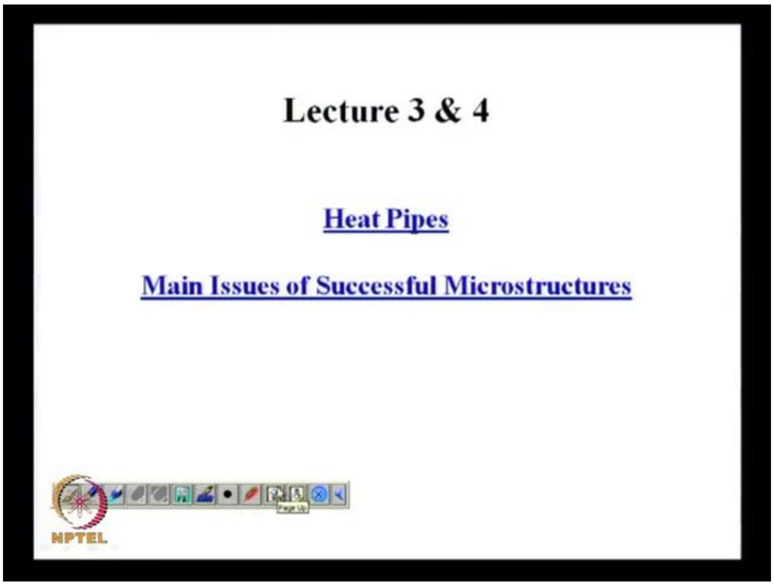

So, in today's class what we are going to do is to recapitulate on what we have covered in the last class? And then think about the components of pressure drop or the additional terms for pressure drop in micro fluid devices or micro scale devices that one has to incorporate in order to find out the exact pressure drop for such systems.

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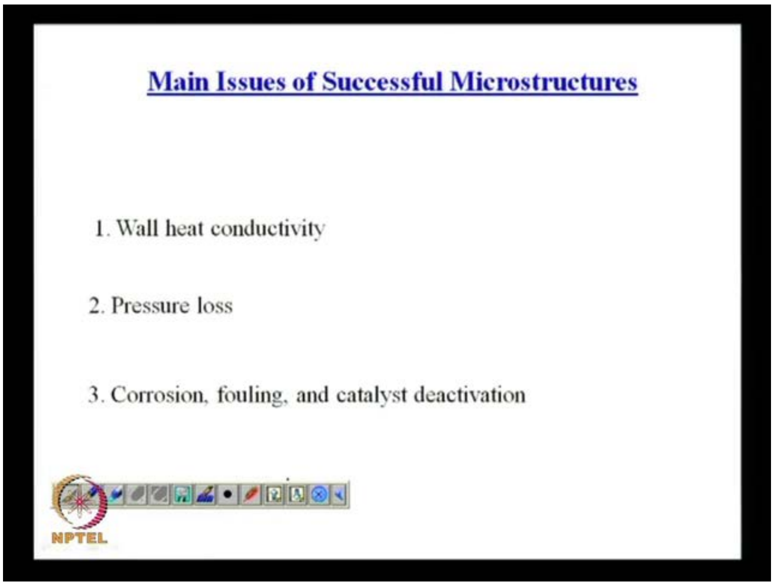

So, I will talk about heat pipes in relation to main issues of successful microstructure. And what we have seen in the last class? Is that the wall heat conductivity, can play a major detrimental role in heat transfer in micro scale devices and while discussing the wall heat conductivity we introduced the concept of, introduced the concept of heat pipes and there we saw that heat pipes are essentially devices, which are extremely efficient in transporting heat from one end from the hot end to the cold end and it works on capillary suction through the wicks, which are providing micro pores present in the system.

And through, the micro pores the through wick the liquid will flow from the cold towards the hot side, when the liquid reaches the hot side by suitably selecting the liquid it will evaporate, at that point and take the latent heat with it and the vapour formed will travel in the reverse direction towards the cold side and condensed the air releasing the latent heat. That so that is how the heat pipe will work? It is the passive device in the sense that there are no devices no external devices, which are used to make the liquid flow from one side to the other side everything is governed by capillary forces. Now, a variation of this heat pipe when specifically used for micro scale cooling is the micro heat pipe.

The genesis of micro heat pipe came while trying to cool the computer chips or the integrated circuits to within their operating range operating temperature, which is about 85 degree. The major bottle neck was how to reduce the size of the heat pipes? And the main contribution to the size of the heat pipes was the presence of considerably thick wick, which has to be provided to account for the capillary suction necessary for the fluid to flow. So, we have to get rid of the wicks and the methodology used was instead of wicks provide corners. So, if corners are provided then the liquid will fill partially, at one the partially the groove let us say at the corner at one end of the heat pipe and at the other end let us say towards the hot end as the liquid progresses, the film the meniscus will be depressed more and more towards, the corner towards the apex of that corner.

And this would result in a difference in curvature. So, this difference in curvature would in turn result in a difference in the liquid pressure. Because we know that the liquid pressure for a curved meniscus is governed by young Laplace equation. And the young Laplace equation simply tells us that p l which is the liquid pressure is equal to p v, which we can consider to be uniform throughout the throughout the heat pipe p v minus sigma k where k is the curvature. So, let us say we are discussing about two ends of the heat pipe in and these are connected and over here it is almost filled, with the liquid and towards the hot end it is depressed towards the vertex towards the apex of the groove. So, the p l and we will we will assume that the p v is about the same everywhere.

So, p l would simply be equal to p l at point 1 would be equal to p v minus sigma k sigma being the surface tension and k is the curvature, which is related to which is about 1 by r where r is the radius of curvature. Now, if we see in these two cases the curvature for case 1 is going to be substantially, smaller than curvature for the for location 2 so, this is my location 2 and location 1 and as a result of this we would see that p l pressure in the liquid phase at location one is going to be greater than p. The pressure of the liquid at location 2 and this delta p equal to p l 1 minus p l 2 this would be the driving force for liquid flow from the cold side towards the hot side, this is how the micro heat pipe will operate.

The additionally one we were also, discussing about I think we should go slightly go deeper into that in today's classes where exactly is the evaporation taking place. These sides are hot, let us say this side is hot so the entire solid is hot so I have there are possibility of evaporation is from here as well as from the thin film that extends along the walls of the micro heat pipe. So, if I if I blow this region up then I would see a situation which is something like this, so this goes towards the capillary meniscus part or the region where the curvature is constant that is this is called the macro part of the meniscus where the curvature is given by simply 1 by r, r being the radius of the curvature.

But as we move along the wall then we will come to a point where the liquid forms a very thin film, on the solid surface and the molecules of the liquid are attracted so strongly by the solid due to the Vander walls attractive forces that no evaporation is possible from here. Whereas, I am going to have substantial evaporation from a region, which is called the transition region and this transition region will account for most of the heat transfer, most of the phase change that is occurring in a micro heat pipe. So, essentially it is this region which will control how much heat is going to be transferred from such a system. And as we move towards the bulk part of the meniscus as, you can see the distance from the hot wall is substantial therefore, the conductive resistance is more and we do may not have enough evaporation or substantial evaporation from this. So, even though the entire interface is active in terms of heat and mass transfer.

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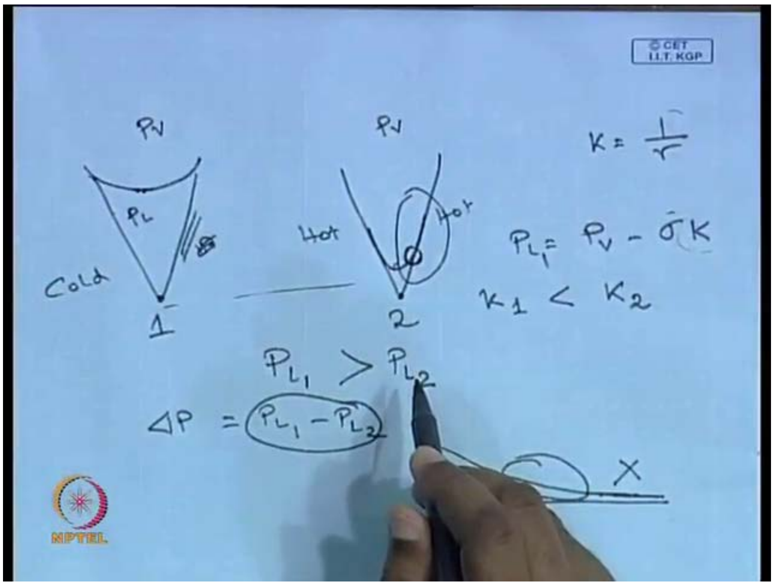

But ultimately the end process is controlled by what is happening in a region very close to the interface very close to the inter line.

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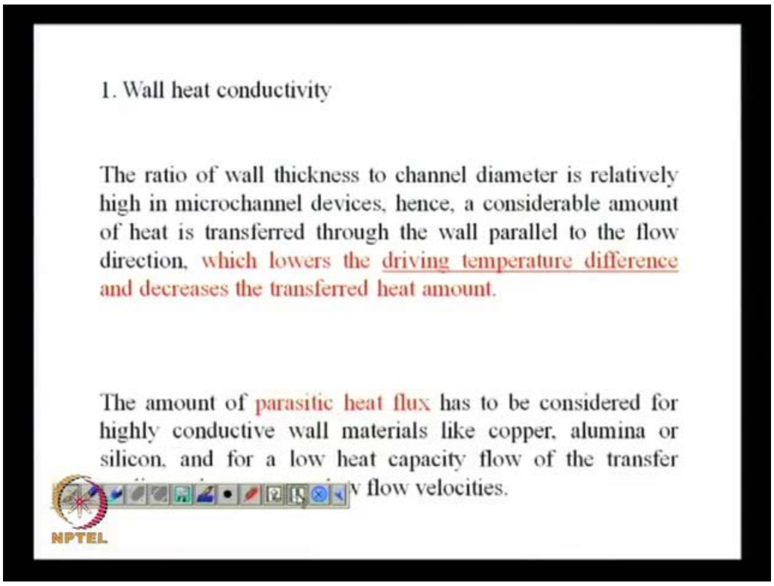

Which is the junction of this solid liquid and the wafer phase where the thicknesses are very small of the order of microns or even less so, it is this region, which one should scientifically, look at in order to enhance heat transfer from the region.

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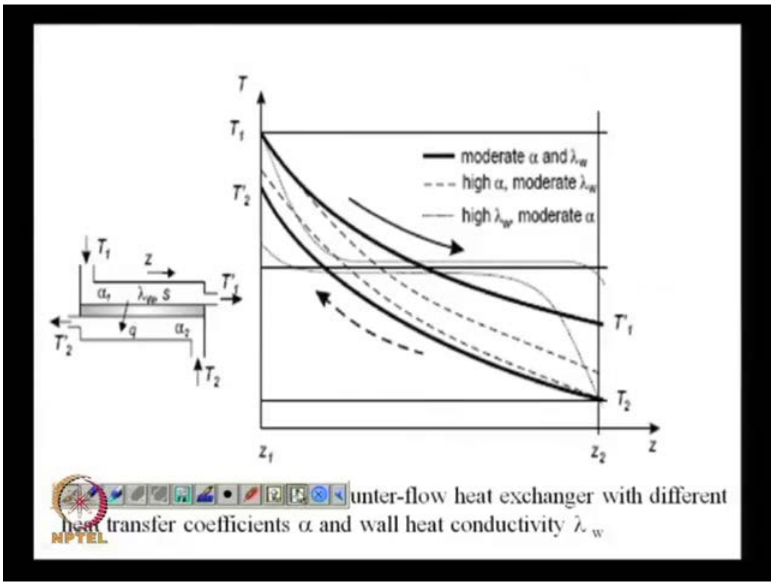

So, now we go into, we went into the modeling of a micro heat pipe, but before that I have added this few things in here.

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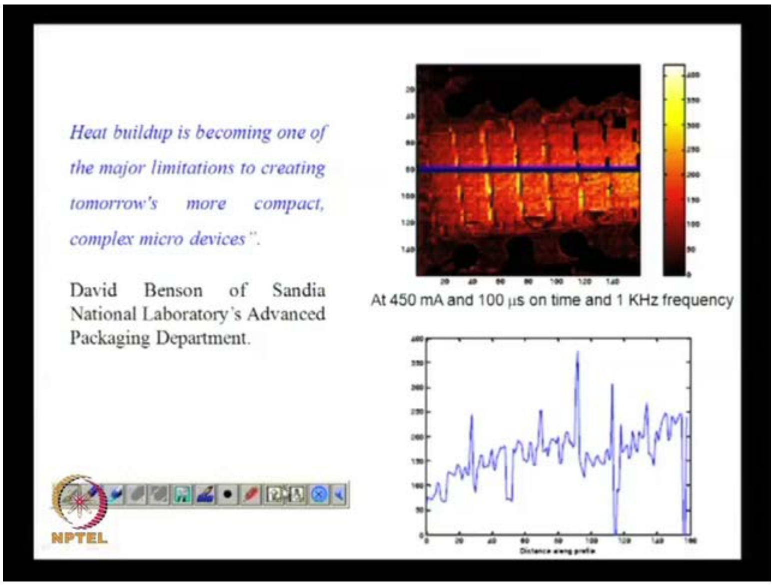

Which is about what is the classical definition of a micro heat pipe?

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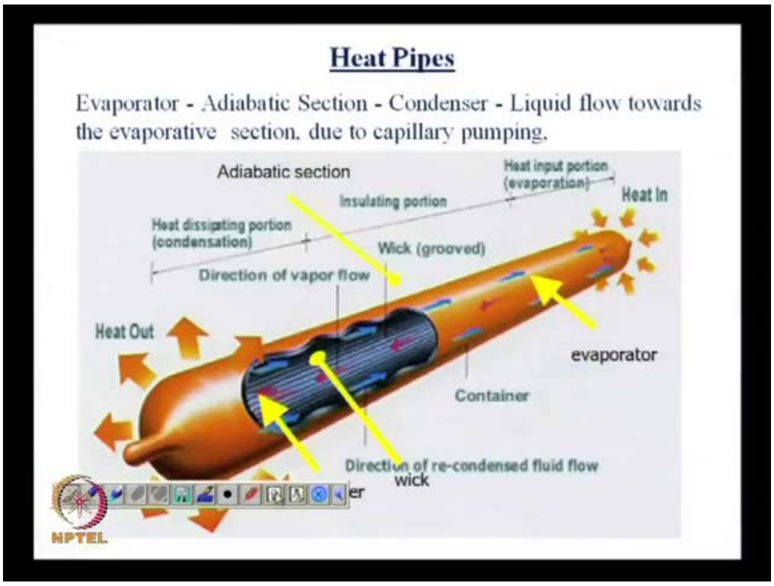

The concept of micro heat pipe came in 1984 by a researcher whose name is cotter and cotter proposed the, that the corners can provide substantialer enough suction.

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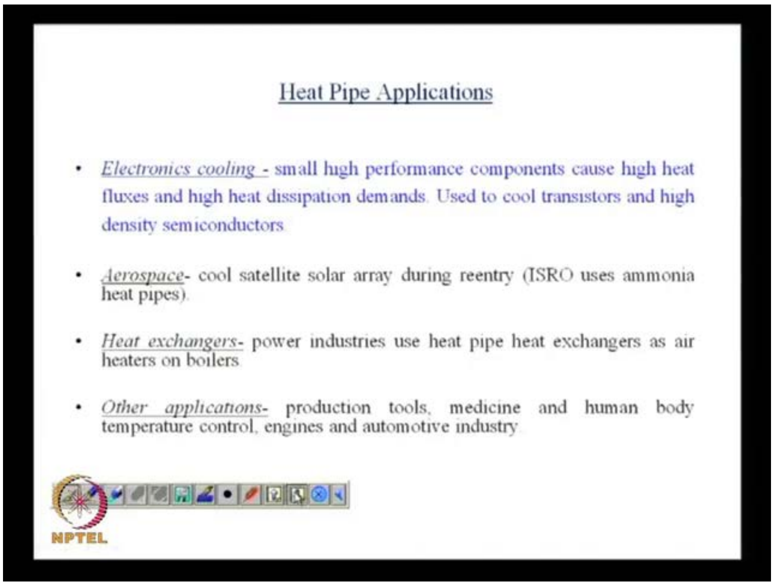

So, is to have flow of liquid over at least a small distance compared to a micro heat pipe.

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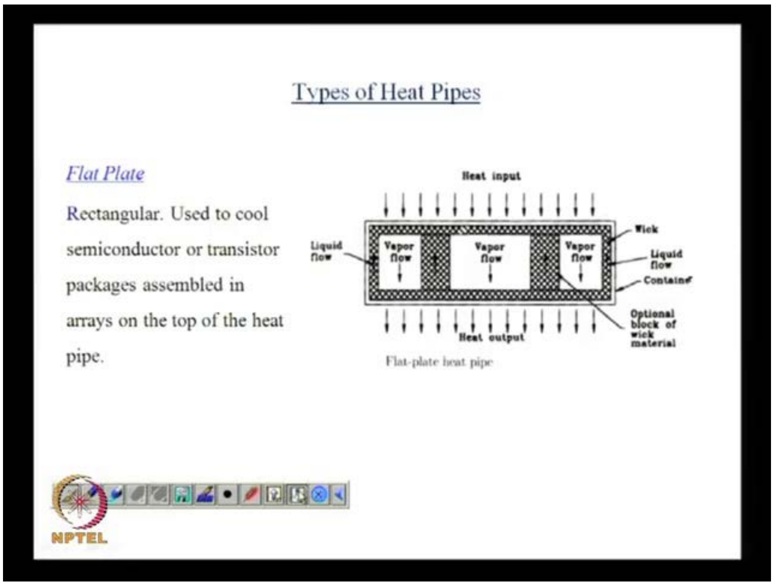

So, in we can have liquid delivered over a length scale of centimeters he has defined this is the statement, which is used for defining what is a micro heat pipe is where the curvature of the liquid wafer interface is comparable, to the reciprocal of the hydraulic radius of the total flow channel.

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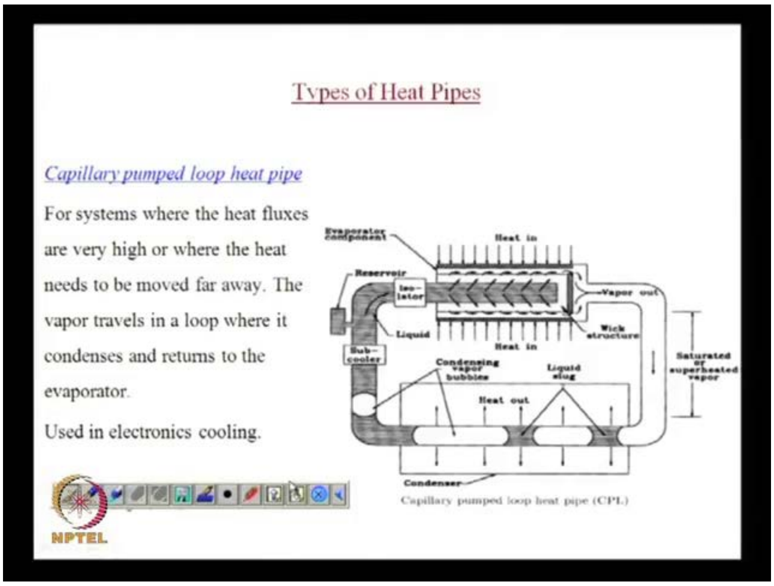

So, this is probably the closest scientific definition that we can think of, of a micro heat pipe.

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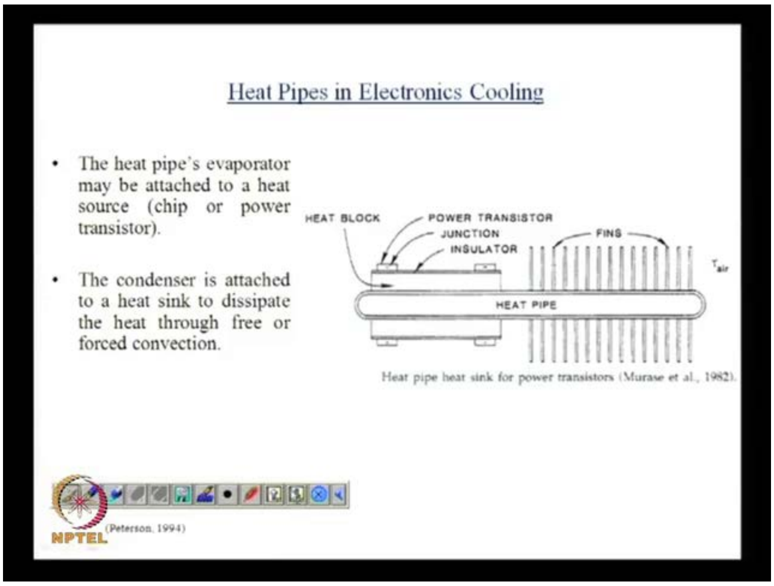

The dimension is comparable to the radius of curvature that is what is a definition of a micro heat pipe? And I already spoke about.

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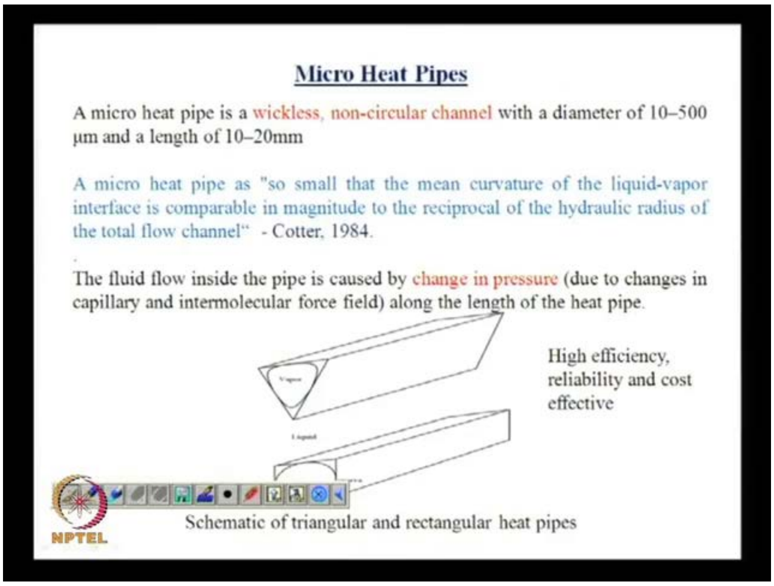

The basic mechanism of what is a heat pipe and this is another picture.

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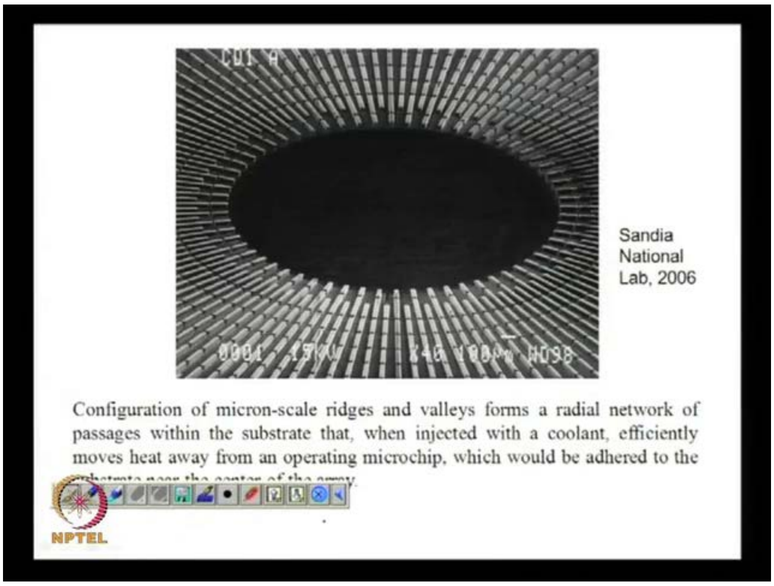

Which I have added to my last class is that this is a grooved a circularly, grooved wafer made in 2006 at this Sandia national laboratory. And what you can see there are channels, which will make the liquid flow from the outside from the periphery towards the center. And even in the next which you would see these, channels are not just unique single channels, in this channels there are other several channels which are also present.

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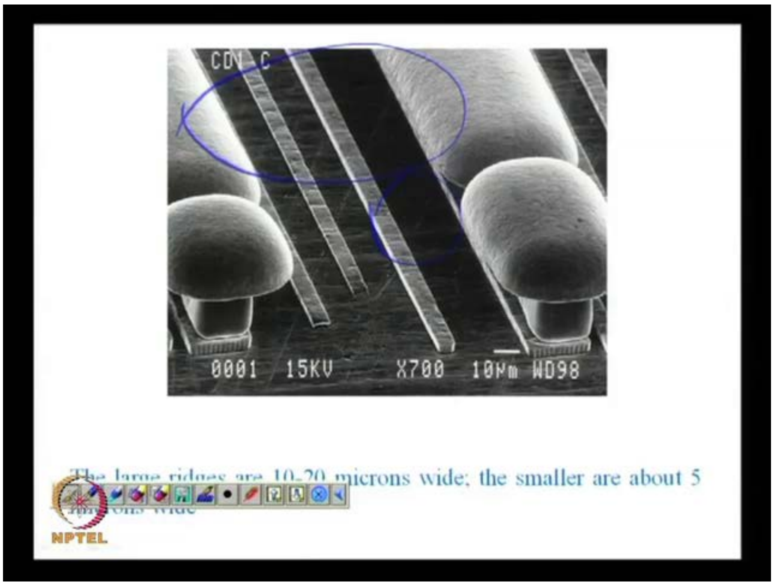

So, this is a large channel which you we were seeing in the previous picture and this is a smaller channel. So, there are three or four such channels embedded into the large channel the ridges provide more corners sufficient corners for the liquid to flow from the hot side to the cold side. So, the sizes are about 10 to 20 micron and the smaller ones could be as small as 5 micron in size. So, if we go back to the previous picture here what they have proposed is they placed the, I c or the heat generating component over here at the center.

And the when sufficient small amount of liquid is placed along the periphery the capillary section will draw the liquid, from the periphery towards the center and when it comes in contact with the heat producing I c it will evaporate. And another silicon wafer would be bonded would on top of this so, it is going to provide that will be that will not be grooved. So, that is going to create the closure for these grooves and through the grooves the liquid will flow and some portion of the grove, will be utilized for return of the vapor towards the cooler section.

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So, this is how the entire process will keep on extracting heat from the center and towards the periphery. This is something which we have made here this is also, based on similar concepts, the center that you see we are going to place a heat generating component in here and these are made at here itself, using reactive on etching. But we could not go that small channels we were able to get about 100 micron into 40 micron these are u shaped channels. So, through the u shaped channel the liquid will flow towards the center evaporate come back and so on? And this these channels are closed using a Pyrex glass bounded on the silicon wafer and the modeling part, which I have described in the last class basically, the pressure gradient is provided by is caused by a gradient.

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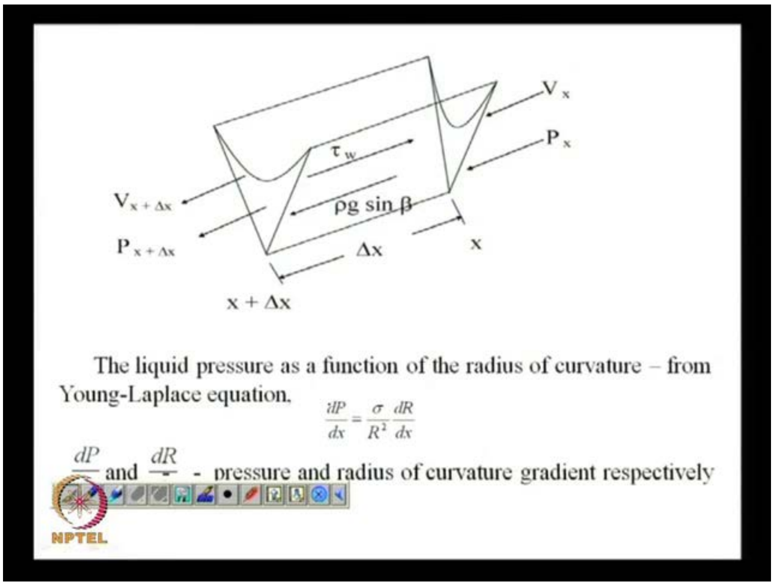

In the radius of curvature so, as long as we have a gradient in non zero gradient in the radius of curvature there will be some pressure gradient, which will cause the liquid to flow.

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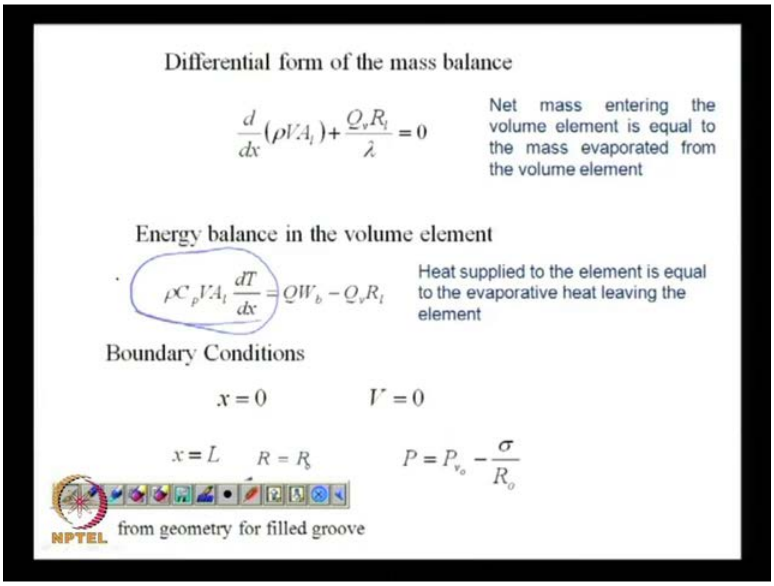

And this is the momentum balance equation we also, have the mass balance and the energy balance in the volume element compared to last class. I have added this term which is previously what we were doing is the heat supplying element is equal to the evaporative heat leaving the element. But as you can see that as the packet of liquid moves, towards the hot side it is going to encounter hotter environment. So, if that is the case then the substrate then the sensible heat content of the fluid packet will also, change. So, there should be a term which would account for this sensible heat gain by the moving packet of fluid while it is experiencing evaporation.

So, it is experiencing evaporation at the same time sensible heat change so, this term denotes the sensible heat change of the fluid packet, but what we have seen through numerical analysis is that the thus the order of magnitude of this term is quite small compared to the evaporative term which it should be. So, we can even make it equal to 0 without much loss of accuracy so, the boundary conditions we by what is happening in a region have discussed already. And this is some this is a figure where I would like to spend some more time. Now, these equations were solved numerically for two different geometries, experiencing, identical heat transfer conditions. That mean the amount of heat the evaporative the amount heat supplied to the hot end of such a micro heat pipe is fixed for rectangular, as well as for the triangular heat pipe.

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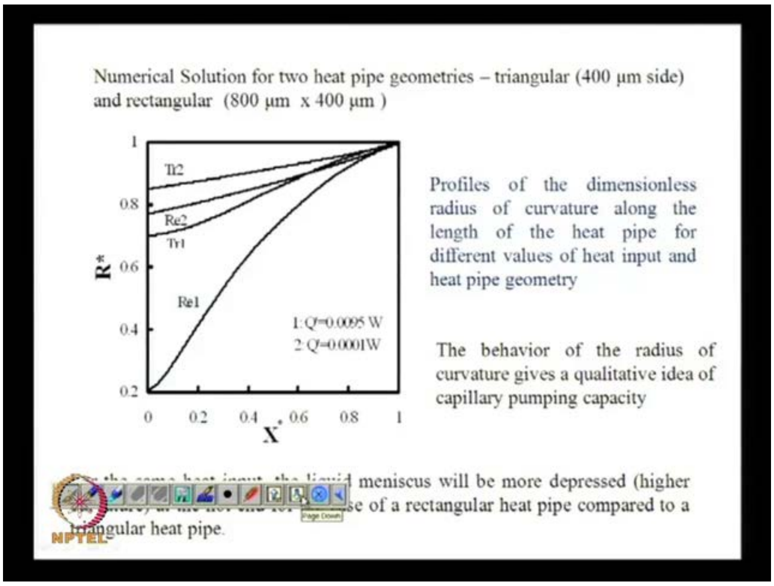

The sides are mentioned 400 and 800 into 400 and what we have done is the analysis is based on finding out the variation of radius of curvature with position. Because we saw that the pressure gradient is almost is connected with the radius of curvature gradient. So, as long as we have a radius of curvature gradient, we do have a pressure gradient and that pressure gradient will ensure that there will be some flow towards the hot side. But as we keep on increasing the evaporative heat flux the capillary suction necessary to replenish the evaporated amount will not be available anymore. And that can happen; when your radius of curvature becomes equal to zero there is no change of radius of curvature beyond that point.

So, when we do not have any radius of curvature that signifies that a dry spot has been generated is created at some point near the evaporator. The moment the dry spot starts to form on a surface the temperature, at that point will shoot up because there is no evaporative cooling available at that point. So, we do not have any liquid coverage on that section and if we go beyond that heat flux then that dry region will propagate. So, the critical heat flux of the meniscus is defined as the point or as the heat flux for, which we are going to have the formation of the first dry spot.

Now, the how much capillary suction a channel can provide would depend on among various other things the apex angle? Smaller the apex angle you had see that the meniscus will have greater chance to go deeper into the channel well still remaining a liquid coverage at that point. So, a triangular groove will work better than a rectangular groove since the since the angle is going to be less for a triangular case and this also, can be verified by looking at a numerical results is that for the same heat input the change in radius of curvature of let us say t r 1. The change in radius of curvature is relatively less compared to that of a triangular groove.

Now, what you can see I that for r e 1 for some value of the heat flux the radius of curvature has come down to a point about to a point was of about point two. Whereas, for the same heat input the radius of curvature even at the hot end is close to point seven. So, the triangular groove I can still increase the heat flux, to higher value and the triangular groove will resist the formation of dry spot to a to a higher value. So, that was the point, which I wanted to make in the in the last class is that just looking at the radius of curvature profile, would tell you how much heat? How much heat flux? Or what is the capacity of the heat pipe in terms of transporting heat from one point to other. And this is a plot of the critical heat input or rather the dimensionless dry out length, as a function of heat input.

So, here you can see that up to a heat input of point zero to what there is no dry spot for the case of triangular groove, triangular heat pipe. Whereas, let us say for about point one we could see that there is formation of dry spot and even with four corners compared to three corners of a triangular heat pipe. The rectangular heat pipe is not cannot be operated beyond a heat flux of point zero one watts. And the drug dimensionless dry out length increases, rapidly as I increase the heat flux and so, this is from the theoretical study and this is the definition of critical heat input where the flow resulting from curvature change is unable to meet the evaporation rate at that value of heat flux.

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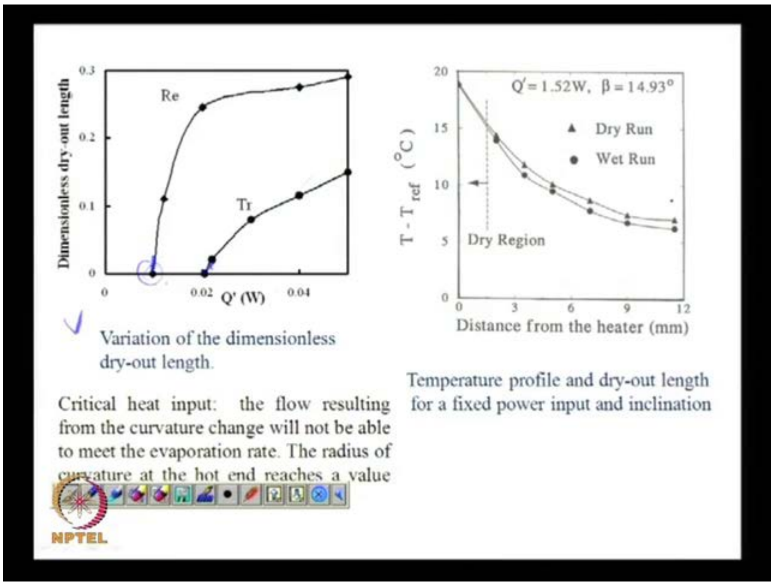

And here we see that some experimental results, where the temperature profile is used to predict the onset and the propagation of the dry out point. Where we see that the dry and wet temperature ratings are touching each other? We assume that it has reached a point where there is no liquid to the left hand side of that region and we call that as the dry region. So, these two results can be compared and, but that is something which we do not need to know now, and this is we would like to mention here, I had like to mention here is that even though the corners, would be such that there will be liquid evenly distributed at all corners. But inclination will still have a role to play because if you incline the heat pope then there would be a an opposing body force, which is acting on the flow. It is not going to affect the presence of the liquid at the corners, but it will affect the flow of liquid through the corners towards the hot side.

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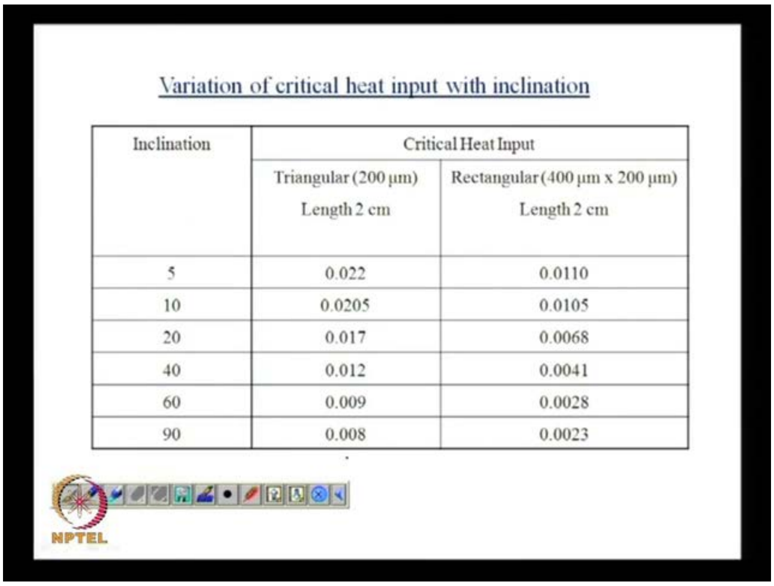

So, this is what shows is that? The with change in inclination how the critical heat input the heat input that the heat pipe can sustain keeps on decreasing drastically. And even here you would see the difference in amount of heat between, the rectangular and the triangular. So, the points that is needed to be made is that there will be liquids at all corners, but the critical heat input will still be a function of the inclination.

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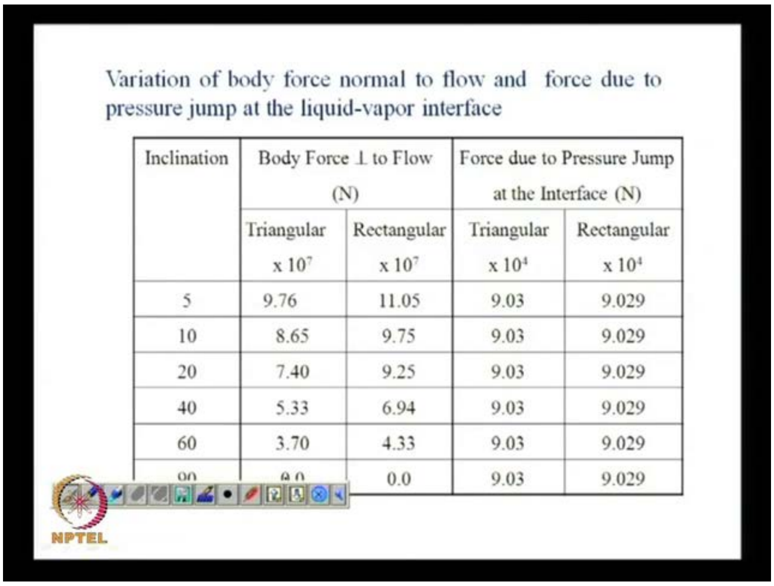

And we see in the next slide is how much is the body force with respect to the surface forces, we keep on talking in micro scale devices that the body force are rather unimportant it is the surface forces which govern the flow it is the surface forces, which are important. And that fact is verified here by looking at the values of body force and the values of the force due to pressure jump at the interface, which is can be evaluated by the young's equation and there is an orders of magnitude difference between the two.

So, the conclusions that we could make from this short presentation of a very complex phenomena is that the body forces are I mean their effects, are rather small in the liquid there will be liquid at all corners. But the liquid will start evaporating at the hot end and the liquid will be supplied by a capillary pressure gradient and a point would come where, the capillary pressure gradient would not be sufficient to make the liquid flow in the profile of the radius of curvature, can be used to predict the onset of the dry out point.

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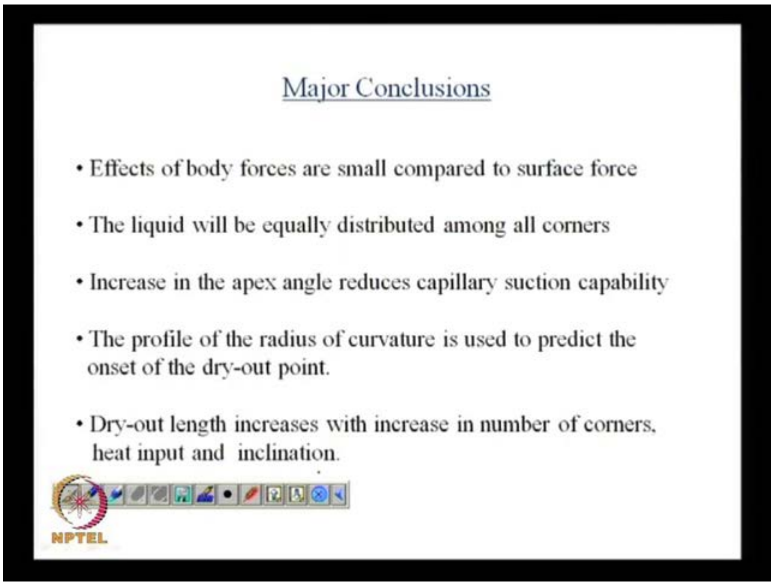

Now, if you think about the operating limits of a micro heat pipe there are essentially four or five different limits that you have to consider. And it may so happen is that the micro heat pipe is proton operating very well within the capillary limits, but it is not going to operate well at some other limits. So, the designer has to calculate all such limits, their possible and decide which one is going to going to lead to critical heat flux. The results that I have shown you before are assuming, that we only have capillary limit present in such a case.

So, we already know what is the capillary limit? Where the capillary pressure head is less than the sum of all pressure losses present in the system. So, the moment that happens you have reached your capillary limit, in the there are some approximate formulas, which would give you these are approximate relations I would say these are correlations, again proposed by the pioneer in this field called quarter, which tells us about what would the value of critical heat flux? Be and where these are available at preferences expressions for k l k v h L and so on.

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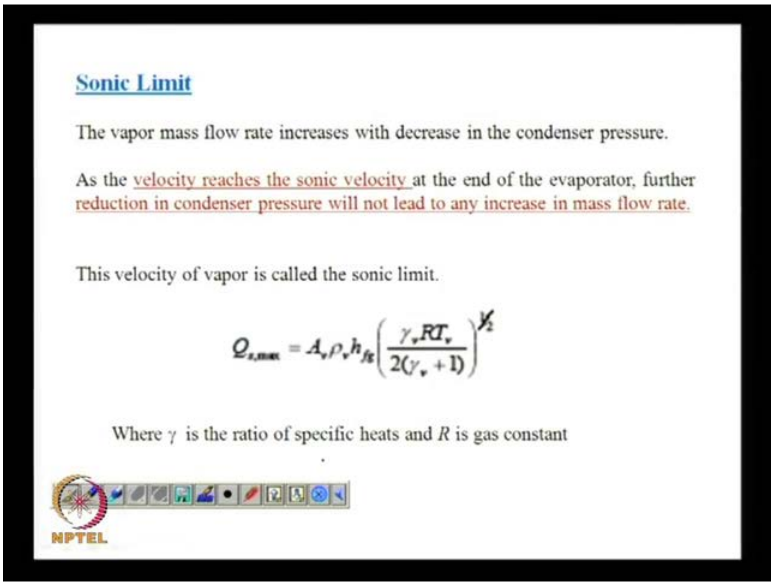

So, we already know what is capillary limit so let us go to the next limit that one can think of it is called sonic limit. Now, if you increase the heat flux to the system to the evaporator vapors are going to be generated the amount or the volume of vapor generated per unit volume of liquid evaporated is quite large it is very large. So, through the channel available for the vapor to flow towards, the condenser section it is going to travel at high speed towards, the condenser. The speed of the liquid the velocity of the liquid would be rather small, but the velocity of the vapor can be very high.

So, a point may reach at certain value of heat transfer is that where it has reached the sonic limit at the end of the evaporator channel evaporator section? So, the moment it reaches sonic limit then further addition of heat flux, will not increase the velocity of this and then this would lead to a clogging. And this clogging is known as, the sonic limit which could be possible for situations in, which you are dealing with very high heat flux cases. The second is entrainment limit now, if we think of let us say a solid and I have a liquid on top of it and I have some flow of vapor, the liquid flows in this direction and the vapor flows in the other reverse direction.

So, far what we consider is that? There is no momentum transfer across the liquid vapor interface, but that will not hold good if the vapor velocity increases so, if the vapor velocity increases the first thing that would happen to the interface is instead of a straight interface it is going to be a wavy interface. So, the waves are going to appear at certain point beyond the is the velocity of the vapor is increased beyond that point then the waves are going to be longer and at after some velocity the top of these, waves are going to be sheared off. And this sheared off liquid droplets will come into the vapor phase.

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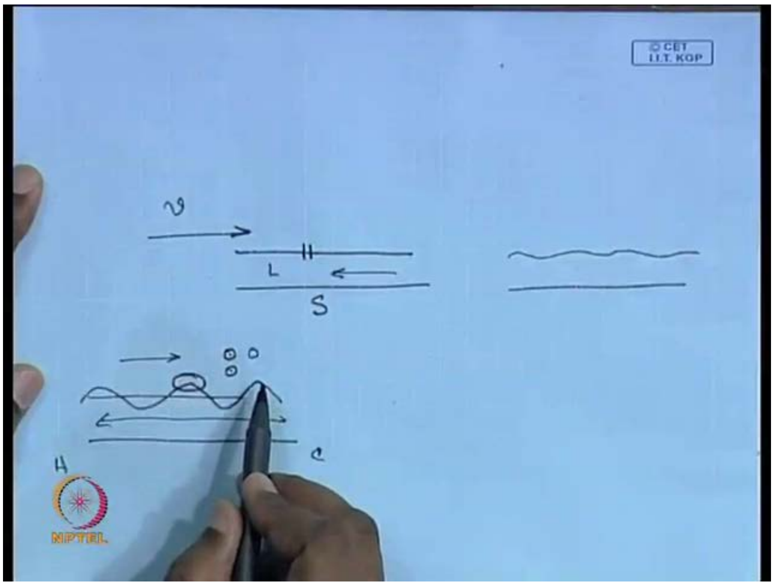

So, in these liquid droplets are going to be entrained by the vapor from the cold side I mean from the hot side to the cold side. So, liquid before it reaches the hot side I mean before it reaches the hot side part of it is going to go back to the cold side without undergoing a change in phase. So, when entrainment happens it is going to limit.

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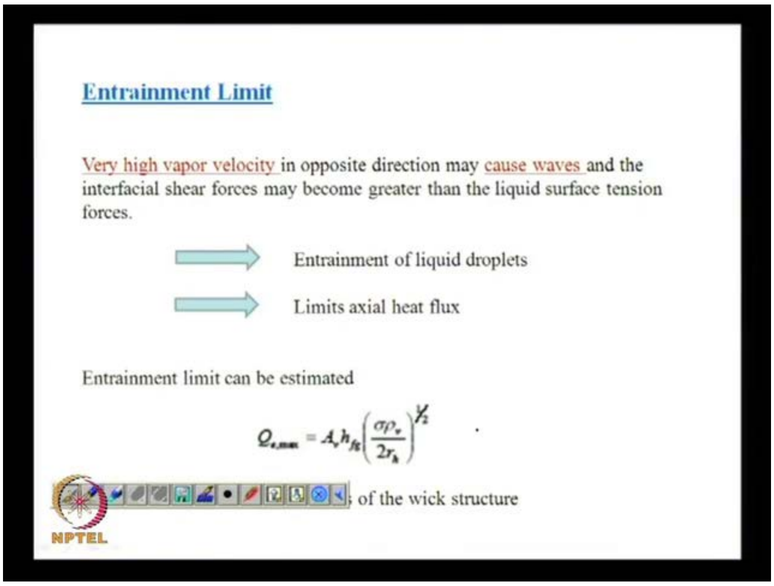

The heat flux that the heat pipe can handle and the entrainment limit again can be estimated by a rough formula also, this is something which would happen? Only at heat only for those heat pipes, which are operating at very high flux condition? So, entrainment and sonic limits you we do not encounter very often in micro heat pipes only for those heat pipes, which are operating at very high heat flux and those, are for standard or macro heat pipes. Mostly not micro heat pipes, but at the other end we have a situation where let us say the operating temperature is quite low. And we have a very small vapor pressure difference between the two sides so, the very small vapor pressure difference and the slow motion of the vapor molecules, from the hot side to the cold side.

So, it is there is going to be sufficient viscous losses and the viscous losses may exceed the vapor pressure difference that is provided in such a heat pipe. So, the viscous forces within the vapor region can be larger than the pressure gradient caused by the imposed temperature field. And there is going to be very it is applicable for cases where it is very slow moving. So, slow moving vapor towards the cooler side will give rise to viscous limits in this no flow or the low flow condition in a vapor region is called the viscous limitation. And as you can obviously see that this is the chances of viscous limit being the limiting phenomena in a heat pipe would appear only for cryogenic heat pipes, where the amount of vaporization are generally, is low and that is again a rough estimate of a viscous limit can be obtained by utilizing this formula this correlation.

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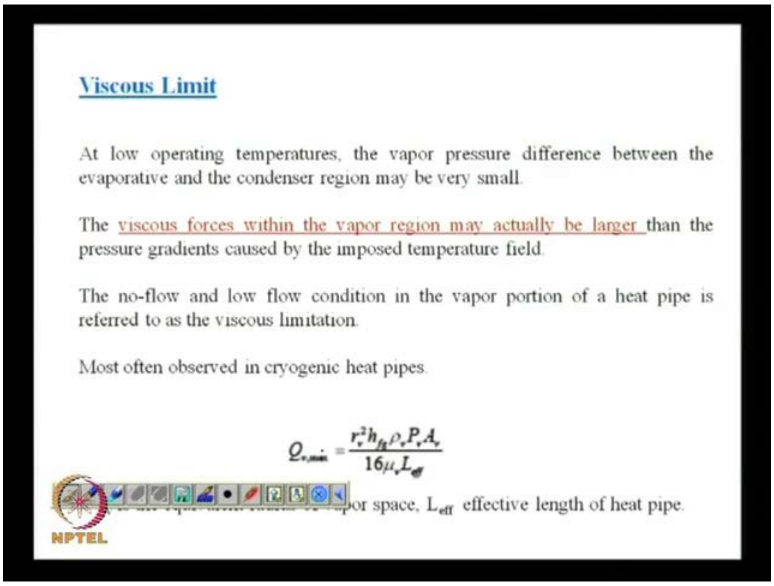

Now, the point I would like to make here is that one should calculate all these limitations while designing a micro heat pipe see, which one is the smallest or largest, which one is the smallest and change the design criteria in an appropriate manner. But for micro heat pipes it is a capillary limitation almost 90 percent of the cases it is the capillary limitation, which will govern the heat pipe the performance of the heat pipe. So, that is more or less that I wanted to cover in micro heat pipes it is a growing literature there are there is enough information available in the in several fantastic review papers, which you can read to know more about the operation, the design the fabrication the limitation and possible uses ongoing uses of micro heat pipes.

Now, I am going to talk about the pressure losses that one may encounter in a in at micro scale. Now, usually the flow inside a micro channel or a micro device is laminar so, we know very well how to calculate the pressure drop over a certain length of length of the heat or length of the of the of this channel. But there are at in some cases there are internals, which are provided in the flow path or there are bends in the channel and those bends and internals, can provide local can generate local vertices and then the flow becomes, turbulent or at the at close to turbulent.

So, it is not there so there should be two contributions to pressure drop in such a system one coming from the laminar flow and the other coming from the turbulent flow, with separate ways to separate methodologies to handle each of them. So, the equations that I am going to show to you are very straight forward, they are just simple Bernoulli's equation and nothing beyond that. So, me form of Bernoulli's equation can be used to predict what would be the or to calculate? What would be the pressure drop in a micro system? But by rearranging the equation in different ways one can clearly see the effect of smaller dimensions or effect of smaller length effect of viscosity and so on.

So, that is something which so I am rearranging the very well known equation in different ways to give you ideas about, the effect of size the effect of property and the effect of number of channels, being added to the flow path and how they would depend on Reynolds number volumetric flow rate and so on. So, this is very well known fact is that we are going to have high pressure losses due to high surface to volume ratio for the case of small channels. Since the surface area is more the frictional pressure drop in a small system will be more.

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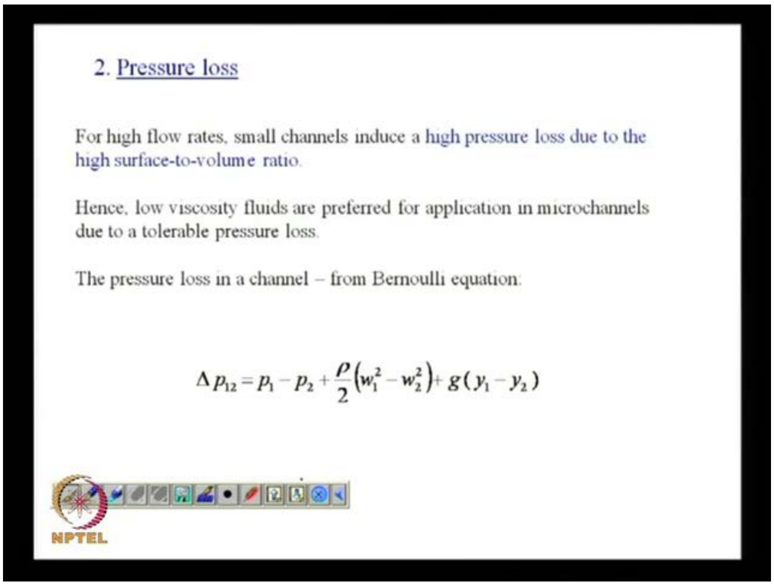

So, we would definitely prefer low viscosity fluids for utilizing flow in a micro channel so, suppose I am using a micro channel from heart transfer I will definitely prefer something with low viscosity. But at the same time I will also, be looking or a liquid which have high latent heat of vaporization. So, a balance has to and the high latent heat of vaporization fluids are also, high in viscosity for example, if you consider water, water has relatively high viscosity compare to glycerin, but the latent heat of vaporization of water is the highest among known fluids among the common fluid.

So, you would like to utilize water, but how would how do we deal with low viscosity so, one way as I was probably discussing in the last class is to add surfactants, to reduce the viscosity of the water and use it as a coolant fluid in such a system. In many of the micro scale heat transfer devices you would see that the use liquefied ammonia, because the liquefied ammonia has very low viscosity. So, a common liquid choice for these kind of devices is liquefied ammonia at high pressure.

But there would be cases in, which just flow in a micro channel with water in which reactions are taking and the reaction medium is water so, we have to handle we have to deal with water in micro channels or even viscosity fluids in micro channel. So, we write the standard equation the Bernoulli’s equation, the pressure head the kinetic head and the gravity head of these three heads obviously it do not need to consider the last term, where the effect of gravity is generally small negligible compare to other terms in micro devices so, we do not take that into account.

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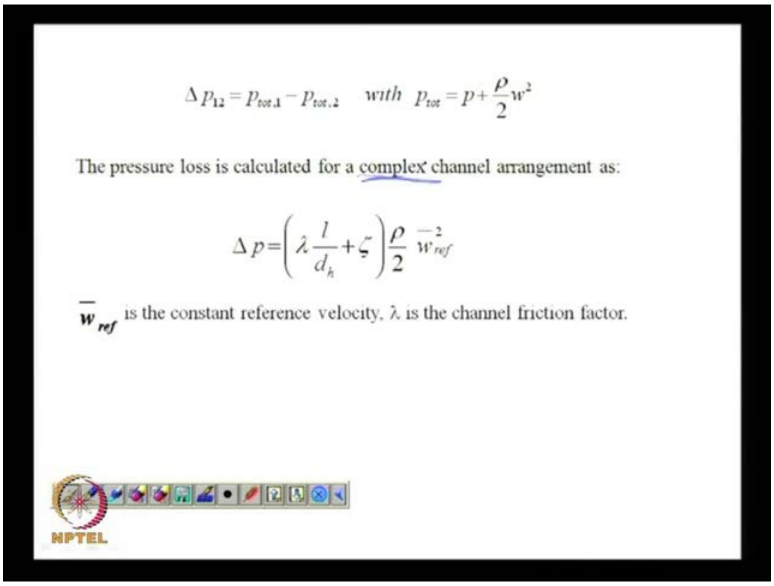

Now, the way the pressure drop in a complex the keyword here, is complex channel arrangement where you have let us say a t junction or where we have a just one micro channel which is getting divided into number of such channels. So, at this junction vortices are going to be formed suppose, you have a device in which a sensor is kept inside a flow so, we have liquid coming in or a fluid coming in and then it flows like this creating a low pressure side over here and the high pressure side over here.

So, these presences of these internals would create localized turbulence, which has to be taken into account. So, the standard formula for pressure drop can be enhanced by incorporating two terms, one which refers to standard laminar pressure drop so, lambda refers to the channel friction factor when the flow is laminar, when the flow is through a straight pipe whereas, this stands for presence of internals or wherever vortices are going to form wherever you have a bend in the channel or where wherever the channel is divided into a number of sub channels.

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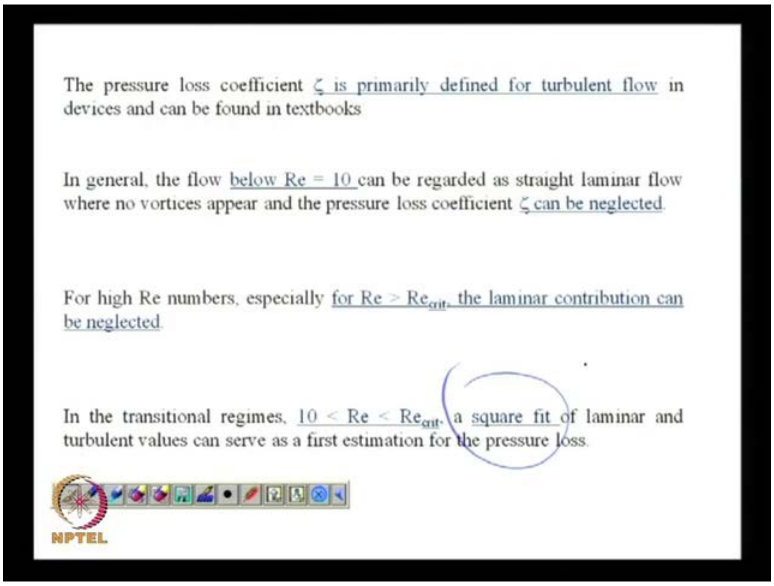

So, these two will have to be the relative importance of these two terms will have to be taken into account. And let us see how it can be done if we have low Reynolds number flow obviously the second term should not be there in the expression. If we have high Reynolds number obviously, the first term becomes unimportant though it is the chances of this happening is rather small. But the trick tricky part comes where the Reynolds number is greater than 10, but less than critical Reynolds number for that specific case.

So, the common estimate of the value of pressure drop is by a square feet between, the values of friction factors at laminar and turbulent flow which is commonly used for predating pressure drop in micro scale devices. Now, let us look at this value of this friction factor in terms of c f, the friction factor that we know and here, we would see that the channel friction factor is inversely proportional to the channel diameter. And this is the reason why you have substantially, high pressure drop in micro scale devices since your d h the d h influences the value of the friction factor to a great extend.

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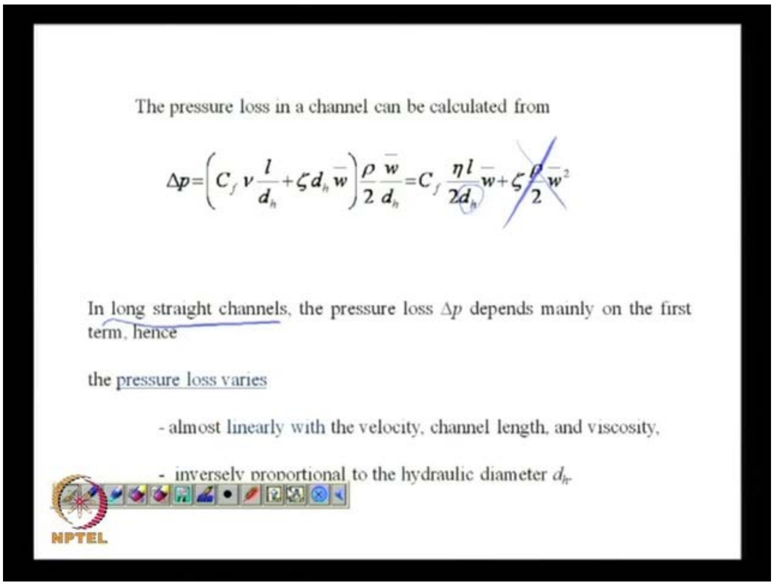

I would rewrite one can rewrite this expression and let us say that we have a situation in, which the flow is through long straight channels so, the effect of this term is negligible. And you can see that the pressure loss changes, almost linearly with velocity w linearly with viscosity and with the length, but inversely with d h. So, smaller the value of d h you are going to get higher pressure drop so, far at since that it is simply linearly proportional to d h, but if we look at this expression in a slightly modified form. What you would see is that? If I express everything in terms of Reynolds number there would be at first term, which is linearly dependent on Reynolds number, but a next term which is which depends on a Reynolds number square. So, for systems with curved internals or systems where you would expect Reynolds very high with turbulence a small change in Reynolds number can lead to a large change in pressure drop.

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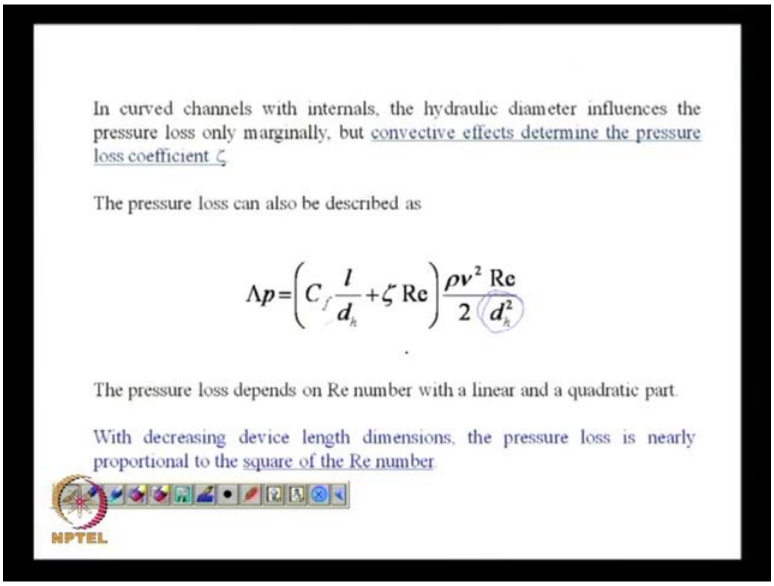

Similarly, if you look at the presence of d H Square over here this also, tells us that how sensitive delta p is to the size of the micro channel. Now, these are important parameters in the design of a micro channel, because by you can reduce the size of the micro channel with the available fabrication techniques that is with us currently a size below ten micron is not a big problem anymore. But how do force the liquid to move from one point to another in such a system? So, that what kind of a pump are you going to use to have such flow and prevent leakage at the same time so, there are different ways to fill the micro channel different ways to cause flow in a micro channel, flow in a micro channel where there are bends in the path.

So, you would see that electric field is applied the exotic applications exotic body forces, are being applied to make the liquid flow from one point to another. So, electric field is one example then, but that would give rise to interesting effects, such as electro kinetic effects. What happens to the viscosity when you use electric field to move a liquid from one side to the other? Because the electric field near the liquid solid interface would create ordered structure in the liquid molecules. So, the apparent viscosity of the liquid will be much more than the actual viscosity of the liquid.

So, you are dealing with glycerin, but near the thing, near the wall the liquid wall due to the presence of the due to the ordered structure of the electric field ordered effect of the electric field, the viscosity is going to be much more viscosity of glycerin will be much more near the surface. So, this apparent viscosity is going to give rise to very high pressure drop the pressure drop that you calculate using bulk property will no longer be applicable. So, these new sciences have come up when you have flow in a small system? And these equations or the equation that I am going to I am or the rearrangement of this equation simply magnifies the effects that one should consider while thinking about flow or how to make liquid flow in a micro channel.

So, with decreasing device length dimensions as I mention the pressure loss is square proportional to the square of the Reynolds number. The moment you start decreasing the device length dimensions the first part becomes unimportant it is the second part, which is going to govern, how much pressure you are going to have? If you have a number of internals, if you have number of n, number of rectangular parallel channels then the volumetric flow through such channels, can be expressed is going to be obviously proportional to this d h square will be the flow area w bar is the velocity.

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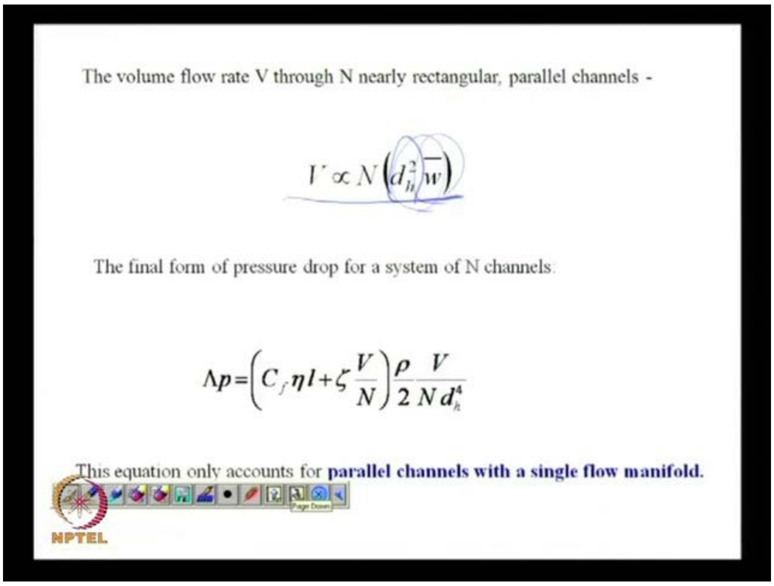

So, this is essentially the proportional to the volumetric flow rate multiply that with n and you get a total volumetric flow rate through a series of through a through a number of such channels connected parallel. But this expression that I am going to show is valid only when we have a single manifold, we have one manifold and then the liquid is going to get divided into n number of channels the subsequent equations are valid for that. So, you have a when you express it in terms of this in terms of this expression then interesting things, that you would see.

You look at the last term in the denominator d h to the power 4 so, any small change in hydraulic diameter of the system is going to increase the pressure many, many times. So, this is something the designer the fabricator will have to be very careful about. So, the if look at the number two the convective part the convective pressure losses depends on the square of the volume flow rate obviously, but part the hydraulic diameter it plays a very crucial role in because of the inverse dependency of the fourth order. So, one has to think about the higher pressures, which are possible and there are certain obvious facts or obvious observations.

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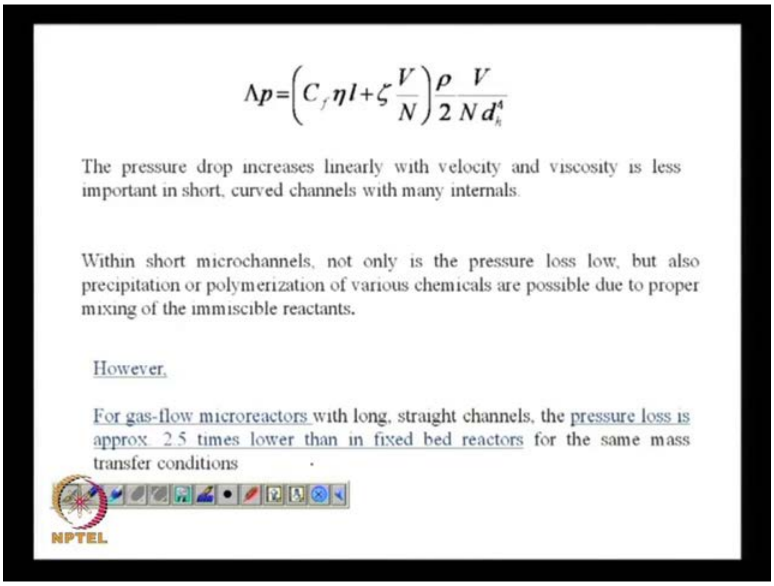

Which one can make is that when we have a very short micro channel the pressure loss maybe low, but the reduction in pressure loss can be more than offset by certain chemical reactions, which may take place in shorter micro channels. In shorter micro channels the mixing is going to be very good. So, if mixing is going to be good and if you have a reaction let us say a polymerization reaction that is taking place inside a micro channel. What may happen is that? The rate of polymerization will increase the formation of large molecules will be more the chances of precipitation will be more and the precipitated large molecules can clog the channel.

So, one has to the option of limiting the length of the micro channel when you are utilizing it for a polymerization reaction is one example, which leads or which points to the complexity of different processes, that one has to think of while designing such micro channel. So, simply by reducing the micro channel you may not may not get enough leverage you may get a some reduction in the pressure drop, but the resulting equation, resulting reaction and the deposition of particles can give rise to higher pressure drops. But with all these difficulties one I should also point out that for gas flow micro reactors not liquid flow it is for gas flow micro reactors, the pressure loss is small at least about three times smaller than that of macro reactors or fixed bed reactors with all.

The advantages of micro scale a process that is the conversion is going to be much more the yield is going to be much more and you can suppress undesirable equations by proper design of a micro reactor. So, that is why in recent days the micro reactors are gaining more and more importance compared to macro reactors, when essentially the flow in such devices are so complex that it is very, very difficult to control them. So, several things one has to keep in mind while designing a micro reactor.

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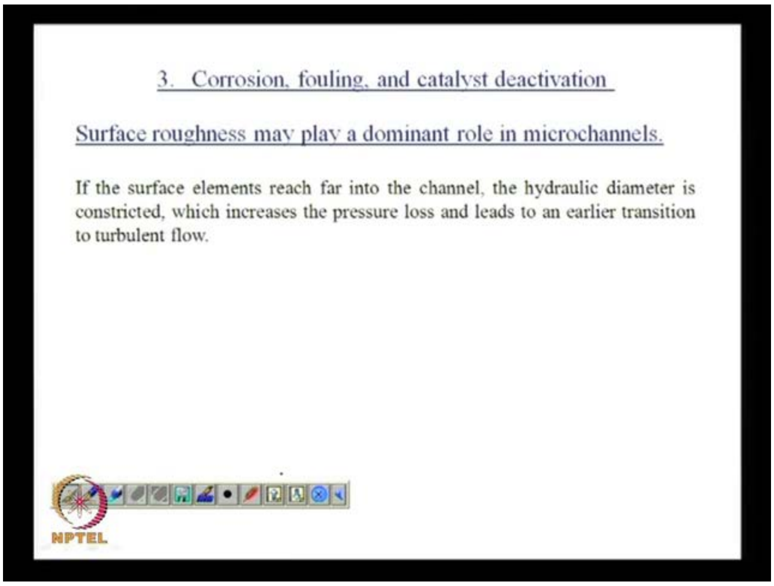

Now, the third point that I would like to discuss about it is pretty obvious straight forward is that surface roughness can play a very dominant role in micro channels. Any idea how much would be the surface roughness of a normal pipe orders angstrom millimeter microns? Just a pipe, which is carrying household water drinking water.

Microns (( )).

It could be microns so we are talking about a one inch pipe which is carrying water to us and the scales that form in or the surface roughness is that are even present in a very new pipe about hundred microns hundred microns for a smooth pipe. Now, hundred microns to one inch it is not comparable at all so, you are whether or not you have a whether or not you have roughness is can create can change the friction coefficient, but it is not going to change the flow area.

But suppose you have ten micron surface roughness on a micro channel that is going to substantially, alter the flow area available to you. I am not talking about friction factor I am only talking about flow area the friction factor will obviously be more when you have higher surface roughness. But the presence of surface roughness itself would should point to that the diameter that you choose diameter that you use for your calculation has to be substantially reduced. So, this is an additional consideration for micro scale for micro channels the corrosion, the fouling etcetera that one has to in order to take into account is that the surface roughness has to be incorporated into your calculation.

So, it is a some problem essentially let us say let us try to describe it is that. If I have a specific hydraulic diameter and epsilon being the surface roughness of such device so, we take the worst case in when you have it is a rectangular channel. And let us say we have surface roughness from the top and from the bottom. As well and we subtract the surface roughness the value of the surface roughness epsilon from the diameter in order to obtain the diameter to be used for actual for real calculations.

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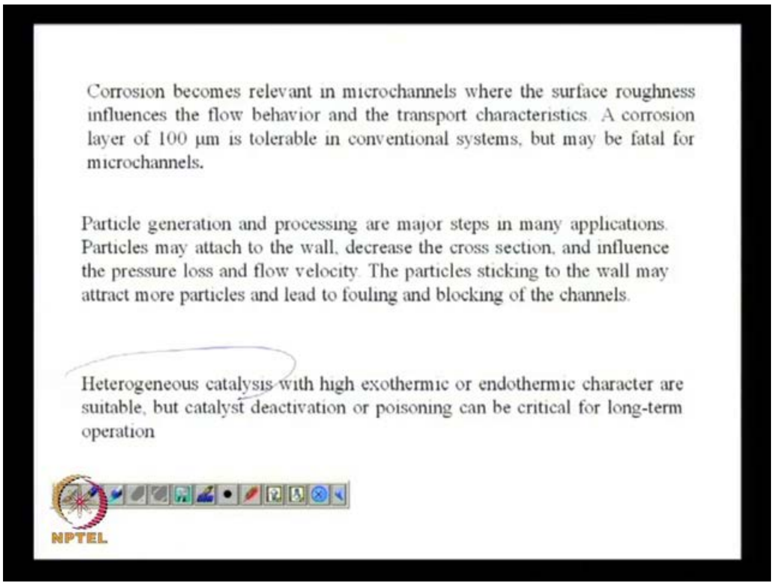

And corrosion also plays well fundamentally it basically, kills the flow through the micro channel. And there are several applications where you would see that the number of times a micro channel can be used is also limited. So, you do not you cannot use a micro channel for a reaction in which you have formation of particles may be nano particles and keep on using it without cleaning, because cleaning of a micro channel is extremely almost impossible.

How do you clean a micro channel? You cannot use a liquid jet to clean the micro channel you probably would not be useable to use a chemical to clean the micro channel in any kind of physical cleaning contact cleaning is impossible. So, your any corro[sion]- any material that you use for fabricating the micro channel you have to think about the corrosion issues, which in a in a totally different way than when you are dealing with a with a with a normal macro pipe.

And generation of particles if you have a reaction, which generates particles then you should think carefully you should think very you should be very careful before making a decision of using a micro channel for such cases. So, reactions in which generally you have catalyst catalytic reactions, where if you could line the sides of the micro channel with catalyst particles and you can keep them fixed at that point then probably it can be used. But situations in which solid particles are going to be generated, as a result of some reaction micro channel is not the candidate to be used for such cases.

And there are situations in which particle may stick to the wall and once they stick to the wall they act as the nucleation site and they attract more particles and they create a colony of particles around it. And thereby creating increasing the value of epsilon and thereby diminishing the value of d h even more. And the moment the value of d h diminishes the value of delta p is proportional to 1 by d h to the power 4 so for this if you keep everything else same even a very small change in d h can give rise to a very manifold increases in delta p.

So, the effects of corrosion the effects of particle generation the effects of particle deposition, which we were we could be a bit casual about it in macro flows it cannot be it do not have that liberty in micro channel flows. And the place, where this micro channel is going to be very effective is when I have heterogeneous catalysis with high exothermic or endothermic reactions. Since you can control the temperature so very well in micro channels they are the ideal candidates for to be used in such cases. So, to summarize I can see that these devices the micro scale devices the micro channels they provide presenters with many opportunities.

In terms of higher rates of reaction in terms of higher yields in terms of eliminating undesirable side reactions in terms of temperature homogenization, very well control about what would be the final product and so on. But it has disadvantages and special requirements the major disadvantage that one should think of is pressure drop. How do you control the pressure drop? What would be the effect of pressure drop? How do you ensure that you have the same amount of flow through all the channels?

That is the designing of manifold in these cases is extremely important. How do you distribute so the design of the distributor is extremely important? There are fabrication issues which we are now familiar with I think professor Ganguly is also teaching you extensively on the different fabrication techniques so how do you fabricate and not only fabricate. How do you make sure that you can have a repeatability in fabrication as you as you move along? And how do you ensure that the fabrication the fabricated micro channel is going to be very smooth?

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There are different ways a micro channel can be made for example, a lithography. Lithography can give you a relatively smooth channel, but if you use let us say a technique or reactive ion etching. These are different techniques which you would learn in part of this course in all of these cases the roughness is on the surface can be maybe one order of magnitude smaller than the dimension of the channel itself, which should give rise to tremendous amount increases in pressure drop. And the special requirements, about which are the processes that can take place in a micro channel a catalytic reaction possibly yes, a catalytic reaction where the catalyst particles can become loose from the side walls and start to move with the flow definitely not.

A reaction in which particles are solid there would be precipitation there would be formation of particles these are the reactions, which you will never try in a micro channel. But if you have let us say reaction of two reactions where there are diffusion controlled. So, two reactants coming in two liquid reactants coming in contact where their diffusion limited reaction, if you reduce the size of the micro channel then the diffusion length and the micro channel length when they become comparable, you eliminate a huge resistance for the mass transfer. And the entire process becomes much more effective so, another problem would be how do you make the liquid flow you use electric field you use normal pressu[re]- normal pump, syringe pump different types of fluid moving machinery.

But how do you control such a flow how do you ensure that you have amount of flow through such micro channels. So, that is something which needs to be looked into for it is successful application. So, in the next class we will deviate from micro channels and go into a system where we have a open surface on top of, which I would like to make something move. So, I would like to use electric force electric field to make certain amount of liquid to move from 1 point to another and the associated scientific issues. So, that electro wetting than digital micro fluidics that would be the subject of the next two lectures.

Thank you.