Microscale Transport Processes

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Lecture No. # 11

Micro Heat Pipes

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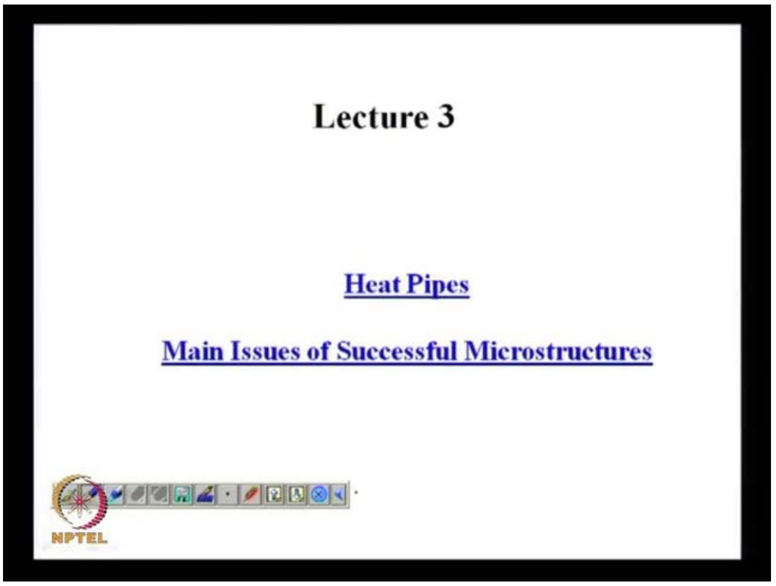

We are going to start with our discussion today on some of the issues involved in successful microstructure design. And to amplify our discussion or to bring more focus into our discussion, I am also going to discuss about heat pipes or more specifically micro heat pipes in the design, construction, modeling and possible use of micro heat pipes in different disciplines or in different, for different applications.

But if we start with issues of successful microstructures specifically for heat transfer, one has to keep in mind, that the heat in any heat exchange equipment, it is a temperature difference delta t between the hot and the cold fluid, which is, which is responsible for heat transfer. So, if because of certain reasons if the delta t between the two fluids decreases, then obviously, the performance of the device is going to be hampered. So, one has to be very careful about material of construction and the relative rates of heat transfer; that means, between the two fluids by convection and through the pipe walls by conduction.

Now, when we speak about macro heat pipes, the conduction effect is generally not going to be of any significance because you have a pipe, which is maybe couple of millimeter thick and through that thickness of the, of the pipe, the amount of conduction, that you are going to get is going to be very small compared to whatever you are getting across the pipe. So, the effect of thermal conductivity, effect of enhanced thermal conductivity of the wall does not play a significant role in reducing the temperature difference between the hot fluid and the cold fluid.

The situation becomes different when we come into micro heat pipes because in micro heat pipes or any heat pipe or any heat exchange, micro heat exchange, where the tube wall is thin, the diameter is small, the surface area is large and in many cases, these, these heat exchange equipments or micro heat exchange equipments are made of highly conductive materials, which are easy to fabricate. For example, silicon, silicon has a very high thermal conductivity. So, if you make a tube out of silicon and you have hot fluids, let us say, flowing through a tube side and you have a cold fluid on the, on the other side, on the, on the outside of the tube, then the amount of heat transferred by convection across the silicon tube and amount of heat, that is conducted through the silicon tube, both may become comparable and this would result in reduction of the delta t available for heat transfer. As a result of which this parasitic heat flux would decrease or would, would detect the heat transfer between the hot and the cold fluid, which is, which is quite common in micro devices.

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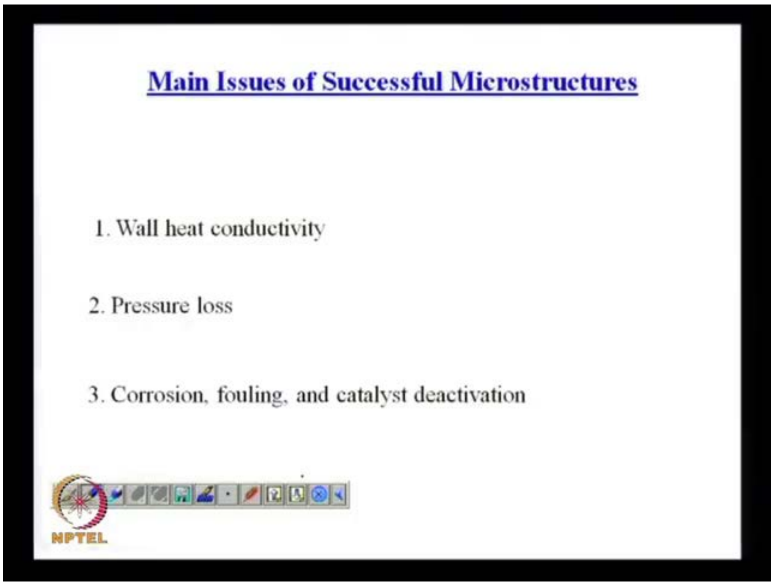

So, the first thing that we are going to look at is the wall heat conductivity, in the effect of wall heat conductivity in terms of heat transfer between phases. Secondly, another important thing, which is also important in macro scale heat exchange, is the pressure loss. We all calculate what is the pressure drop necessary or pressure drop required to have some flow through the shell side, as well as, through the tube side? In, in the case of macro devices, the type of flow, that we have, both in tube side, as well as, as well as in shell side are, will be turbulent in nature. Very rarely you will use a heat transfer equipment, heat exchange equipment, which is operating and the under the laminar flow condition. But the situation is going to be different for the case of micro scale devices where most likely the flow through the tube would be in the low Reynolds number zone.

Secondly, if you think of the shell side, the, the internals present in shell side provide additional sites for turbulence. So, you are going to have secondary flows and turbulence across the, around the internals and the baffles, which are present in macro devices. We may not have such cases in micro devices. In the micro devices we will mostly be working with long, long and narrow confinements through which the flow is taking place. But there would be some situations in which there would be internals in which there would be bends in the path. And how do those bends in the path can, can provide additional pressure loss in a system that is something, which we, we need to look at.

And finally, we are, we are, let us say we are working with a, with, with very small, very small diameter tube and due to some imperfections in the fabrication process or due to deposition of certain particles inside such a tube over, over a period of time. We may get corrosion or fouling or surface roughness whose order of magnitude could be comparable with the device dimensions, which was never the case in, in macro devices. You are, you are (( )), your, your surface irregularities in a macro device is essentially negligible compared to the diameter of the tube, but in this case it is not going to be that, it is not going to be the case. So, one has to think about catalyst deposition or corrosion or surface irregularities and they need to be taken into account.

So, these are the three issues that I would like to discuss in today's class with special emphasis on their applications or their relevance in micro heat pipes.

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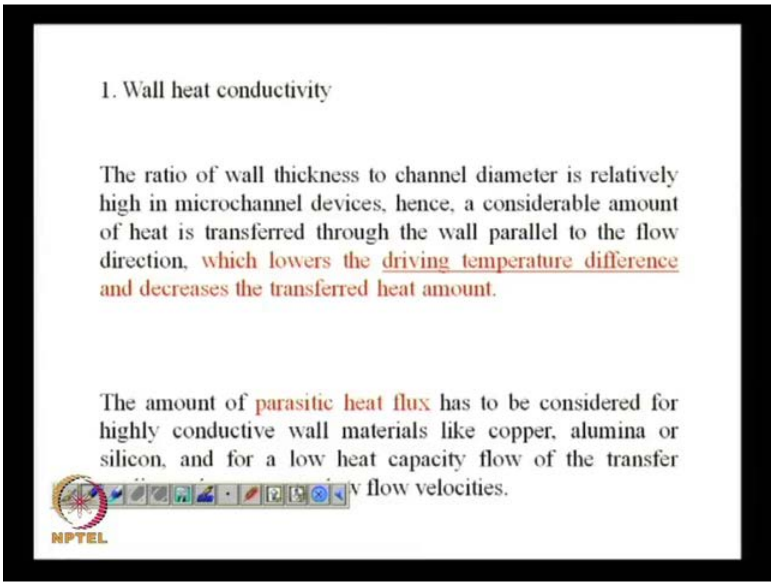

So, this is essentially what we, I have said so far, that we have some ratio of wall thickness to channel diameter is, is very, very high in micro channel devices, and so your driving temperature difference is going to be lowered by the conduction of heat through the walls of the micro channel. And this parasitic heat flux one need to consider, one need to take into account while designing such devices, when you are using such device to heat a fluid or to cool certain fluid stream.

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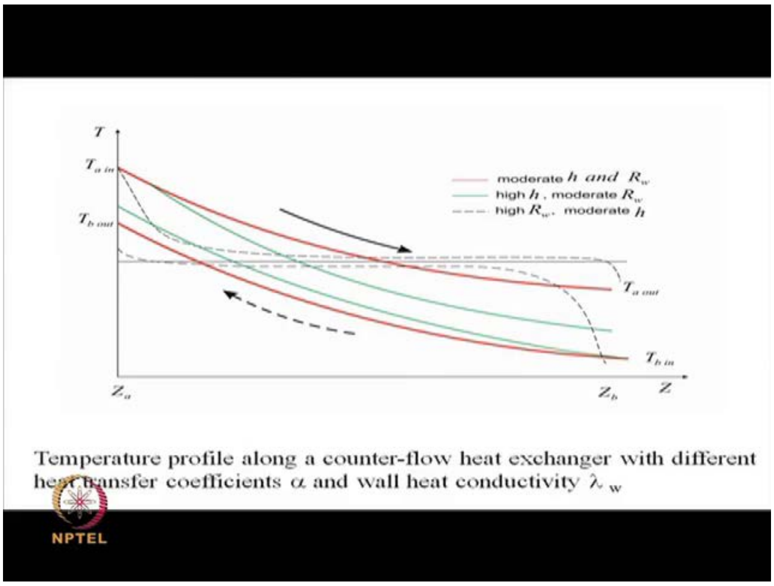

So, this picture essentially shows us what would be the effect of heat transfer coefficients and wall thermal conductivity. The dark, the bold one is what is commonly, what we commonly see in macro devices, and the dashed one is an intermediate, but the interesting phenomena or interesting observation, that you see is the lightest one, which is a typical chair shaped curve. So, it starts with some value over here, that is, the hot end and it ends at this point, which is a cold end and in between it sharply drops. But this region is important where the temperature of the two fluids will more or less not change with time. So, you can think of this region as if it is an adiabatic region in which no transfer of heat is taking place.

So, this happens when you have high conductivity, high effective conductivity and some for certain values of heat transfer coefficients. So, if you, if you are designing a heat exchange equipment, this is the region, which is not participating in the heat transfer, so one has to be careful especially in micro structure design to see whether or not their entire length is utilized for heat transfer. So, this is something one has to look at.

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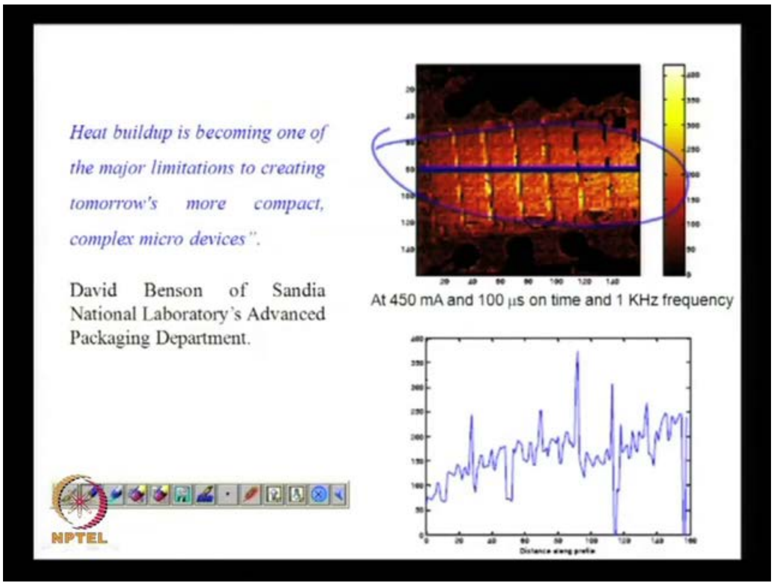

Now, say, now we come to a specific problem, which is common to many applications. It is, it is an emerging area, active research is going on how to cool a microchip or how to cool a semiconductor device. What you see at the, right, left, rightmost corner is a thermal image of a microchip while it is in operation. So, you can see, that the temperature varies and you would see occasional spots where the temperature could be very, very high and the bottom picture is nothing, but a, the, a plot of the, plot of the temperature along this blue line and you can see, that there are spikes, which are present where the temperature can be as high as 200 degree centigrade.

Most likely, in all microchips you would like the operating temperature to be within about 85 to 90 degree centigrade because if it crosses that, then you are going to encounter thermal diffusion of the dopant material, dopant ion, ions and so on. And the entire performance of the chip of the device will degrade very fast. And it is extremely important, that the temperature of this is to be maintained within certain limits and this specific problem is known as the thermal packaging of chips.

And how do we package the chips, so as to have the most efficient heat transfer possible is is something that chip engineers are increasingly become, increasingly become aware of. Now, if you think of the, this as the chip, then while designing such a chip you have to make sure where exactly you are going to put the heat generating components. Now, all the components are not going to generate heat all the time, there would be, sometime they are in between the two. So, when this one is in operation, the other one may be switched of and so on. So, it is a complex transient problem that 1 has to look at.

Additionally, we are not going to have just one layer or one level of chips, there will be several circuits embedded one or sandwiched or put on top of each other. So, it is not just a two-dimensional problem. It is a two-dimensional problem plus there would be variation with time and there could be transistors or chips at different level, circuits at different levels, which are producing heat at different rates. So, it is a complex three-dimensional problem and how you place them is a major concern of VLSI design.

Now, we, we, we are presently working with some sort of rule of thumb. It is more of an art than science. We know that, which is going to be the most heat generating component and we would like to place it somewhat separated from, from the others, but you, you see, that the drive now is towards more and more dense formation of chips. So, how do you place them? Would you place a heat generating component on top of another? And you also have to think that, which one is to be connected electrically to the other? And the mode the length of this connectors, these connectors, then your, your chip is going to act slow. So, your, you, you do not have much choice in terms of putting those pieces together.

So, how do you cool such complex geometry, which could be just few millimeters by few millimeters in size? And your, it is very difficult to reach because it is going to be embedded somewhere inside your computer. The problem is even more acute for the case of laptops. All of you who have used laptops, you would, you would notice, that the bottom or the, the, the base of the laptop becomes uncomfortably hot, it is difficult to place it on your lap and work, work like that. So, the trend is in order to please the customers. The trend now is, how do we keep the base of the laptop cool, not just the circuit cool. The base of the laptop has to be cooled and if you have seen inside the laptop, it is, it is an extremely complex and dense object where just to reach the hot spot is a challenge.

So, how do you reach the hot spot? So, in the three classes, that we are going to deal in today’s class, I am going to talk about a chip, which is to be cooled, but where access is relatively easy, and in the next classes I am going to talk about chips, which needs to be cooled chips, which needs to be cooled, but where access is very difficult. So, entirely different physics, branch of physics has been evolved in order to make liquid move from one point to another, where conventional ways of moving fluid would not be possible, additional body forces need to be added to the system in the form of, let us say, electrical forces.

How do we use electric field in order to make a drop move from one point to another; that is what we are going to discuss in the subsequent two classes. But in today's class we will assume, that this is a chip where, where we have access or we have the provision, we have the option of adding something on top of this chip and how do we cool such a device.

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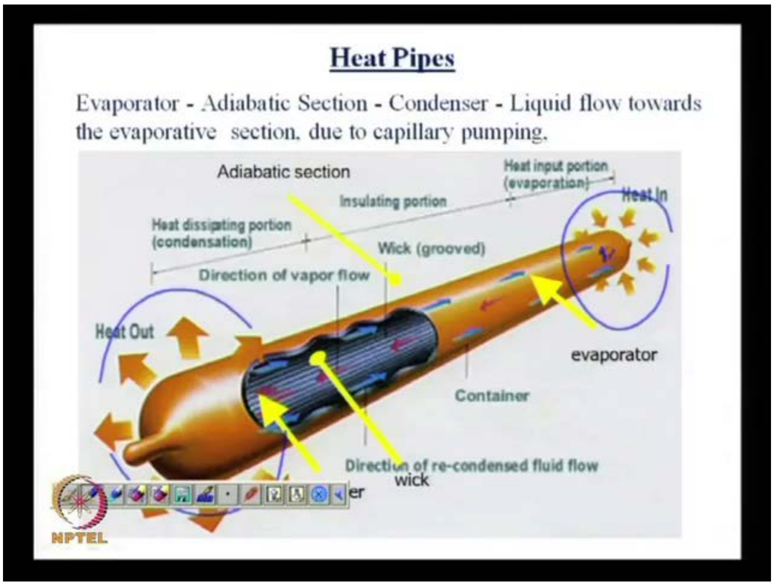

This is what a traditional heat pipe would look like. I am, I am not sure how many of you know about a heat pipe, but it is a unique piece of equipment, that has come up, maybe, 30, 40 years back, wherein you have a hot side, you could see the hot side, where heat is going to be added. And heat would somehow travel through this and it is going to be dissipated at the other end. So, I have an evaporator where the liquid is going to evaporate and the vapor is going to travel this, this end, the hot end. And the cold end are connected by wicks, so the liquid will flow by capillary suction from the, from the cold end towards the hot end.

So, there will be a continuous flow of liquid from the hot end towards the cold, I mean, from the cold end towards the hot end. The moment it reaches the hot end, it will start to evaporate and as it evaporates it is going to take the latent heat with it and the phase transform mechanism is, by far, the best possible heat transform mechanism, that you can think of. It is better than anything else, so we would like to utilize the phase transform mechanism to cool certain points. So, you have a heat source near the, near this evaporator region and once a liquid comes it evaporates the vapor troubles in the reverse direction, reaches the condenser and condenses, and lets us the heat out. So, I have a cold end and the hot end, from the cold end the vapor will condense, releases the heat, which can be removed by conventional means.

For example, by, by convection the liquid now will travel due to capillary section to, towards the hot spot. When it comes to the hot spot it evaporates and the vapor travels in the reverse direction. So, it acts like a thermosiphon, where without the addition of any external power source you are going to have continuous supply as long you as you have a delta t between the hot and the cold side and you have chosen the liquid, which will evaporate or which will boil, which will evaporate at that temperature.

So, there are many examples of heat pipes in exotic uses apart from, apart from just standard cooling. Now, the best, I mean, the most weird example is that of an ice cream scoop. Those of you who you have tried to scoop out an ice cream from a block, which is, which has been in the freezer for a very long time, it is very difficult and if you are using plastic scoop, that most likely result would be, that you are going to break it. So, what if, if I make a heat pipe out of the plastic scoop? So, where, where you are touching the scoop, that is your evaporator, that is your heat source. So, the liquid will evaporate at, whatever liquid that you chose, you have to choose the liquid in that way, the liquid will evaporate, it will travel through the scoop, which will have wicking material inside, it, it will come over here, it will condense, it is in contact with the ice cream it will release latent heat and that will locally melt the ice cream, and you would be able to scoop it out; so, an example of heat pipe.

The 2nd example of heat pipe is when you see a bridge in, in very cold climates, the bridge is not in contact with, with the earth, which is at a relatively high temperature even at winters. So, since the bridge overhangs earth and it is exposed to weather, exposed to air, very cold air from both sides, any water, which is on the bridge is going to freeze, freeze fast and that would be dangerous for driving. So, some driver who is driving on the road and not experiencing any slit on the road, any ice on the road, when he comes over the bridge, immediately he experiences ice and the car skids.

So, we have to think of some ways, so that is, so as to have water, at least water all the time on, on, on the bridge. The way, one way to do it is to use salt; that is still prevalent now. If you use salt the water will remain water, not freeze within certain temperature range, but it is, it is going to corrode the inner side or under side of the car. So, you have pillars, which are supporting the bridge. So, one idea is what happens if I make the pillars, some portion of the pillars work as heat pipe. So, your, your, your earth, it is going to be embedded in earth, the earth is going to provide the heat. This is going to be the evaporator section, this is going to be the condenser section, so the liquid will travel through the, I mean, the vapor will travel, it will condense, release the heat and that heat will keep the surface of the, of the, of the bridge warm enough, so as not to freeze the water on it; another example of it.

So, you, you would see, that the material of, material of the liquid, that is used are, it could be water, most likely it is going to be ammonia. So, ammonia under high pressure, so liquid ammonia is another material, another liquid, which is commonly used for heat pipe, for heat pipes and so on. The examples of heat pipes are also in during the reentry of the spacecrafts. In fact, I have, last year I had visited ISRO or last-to-last year and I had seen, that they have called the panels of the, they are making the making the skin of the spacecraft, which is going to go outside and will reenter at certain point of time and they are embedding ammonia heat pipes on, on the skin itself. So, the heat pipe will not only help in reducing the temperature, they are also going to homogenize the temperature of the entire structure, thereby reducing the chance of thermal stresses.

So, many applications of heat pipes, but if you want to use the heat pipe for electronic device cooling, the first thing, the major problem and chip engineer even will not even listen to me is because of the size, because of the presence of the wicking material the size of the heat pipe is in macro scale and even it would be like this. And how we will not, we are going to add this to a chip, so that it can it can act and your, this is going to be attached to the chip side and this is probably the condenser side where convection, convective flow would be used to cool this. So, I have to reduce it and the moment I tried to reduce it the only option left to me is should get rid of the wick material. I cannot use wicking action to drive liquid from the cold side to the hot side.

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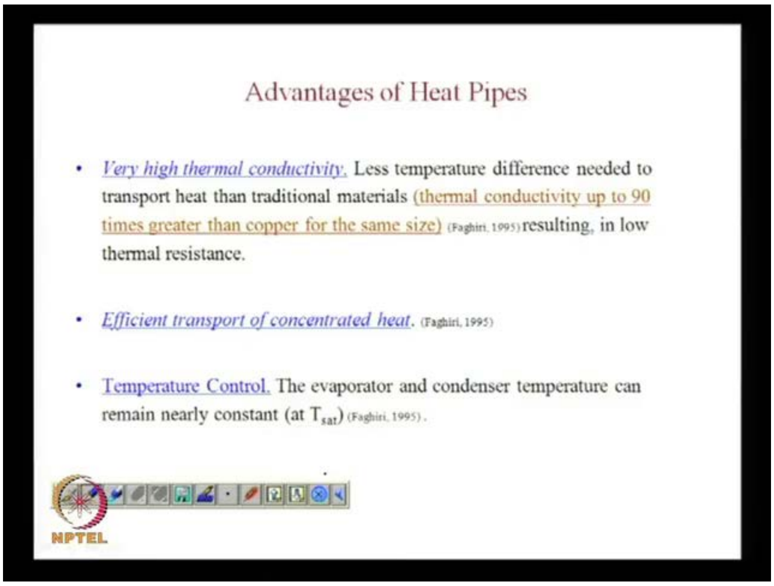

So, the option, that is available to me has led to heat pipe, but before that just this quick slide about advantage of heat pipe is, it is the first thing, that one should concentrate is its very low thermal, very high thermal conductivity. The effective thermal conductivity of a, of a heat pipe is about two orders of magnitude higher than a copper block of the same dimension. So, if I have a solid copper block acting as a fin and a heat pipe of this same dimension with a proper liquid, this is going to be about hundred times more effective in terms of heat transfer compared to a copper pipe. So, that is a big, big advantage, and we, we transport heat in a very efficient way. And we, we, as a result, we can control the temperature of the base in such a way, that it not only reduces the temperature, it, it also homogenizes the temperature around the heat pipe. So, those are the advantages.

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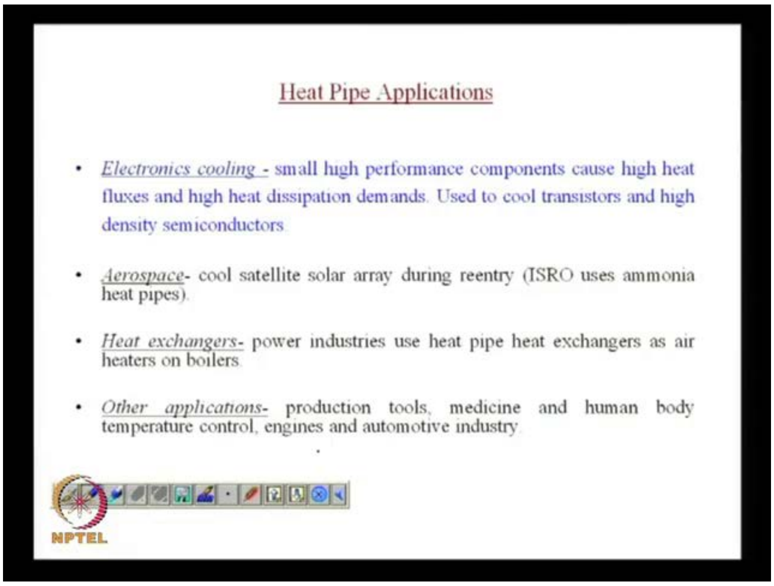

But the big disadvantage is the bulky nature of it. So, obviously, heat pipe applications I have covered in electronics cooling, in aerospace, in some heat exchangers and there are certain other applications, including in biomedical applications where if you would like to burn certain cells inside your body, heat pipe is an effective method because you cannot have a very hot tip getting into a human body. What happens, if we use a heat pipe, an insulated heat pipe where the tip of the heat pipe is going to be such that the temperature is going to be beyond some temperature, some required temperature? So, with a very small delta t you would be able to deliver, delver heat at a precise location inside upper, inside a patient’s body. So, those are possible applications in biomedical.

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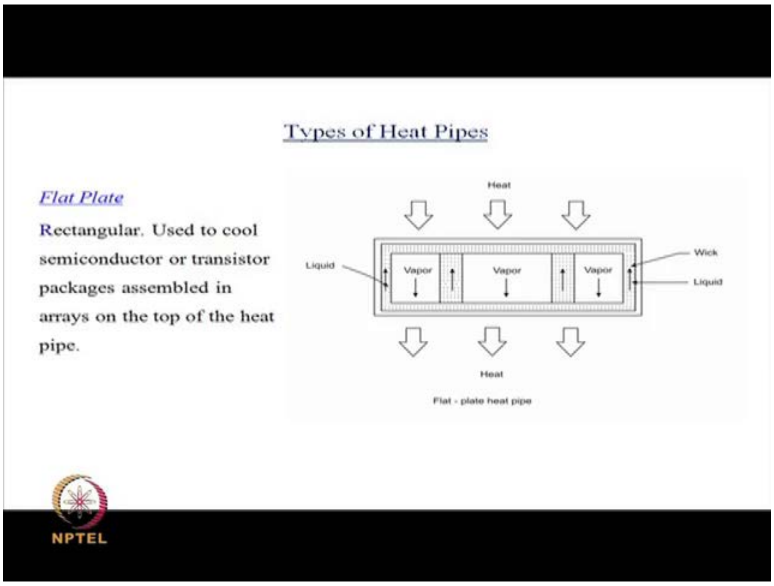

So, some of the types of heat pipe, that you see, I am still on in the wicking part of it, so you have vapor flow, which you have heat input.

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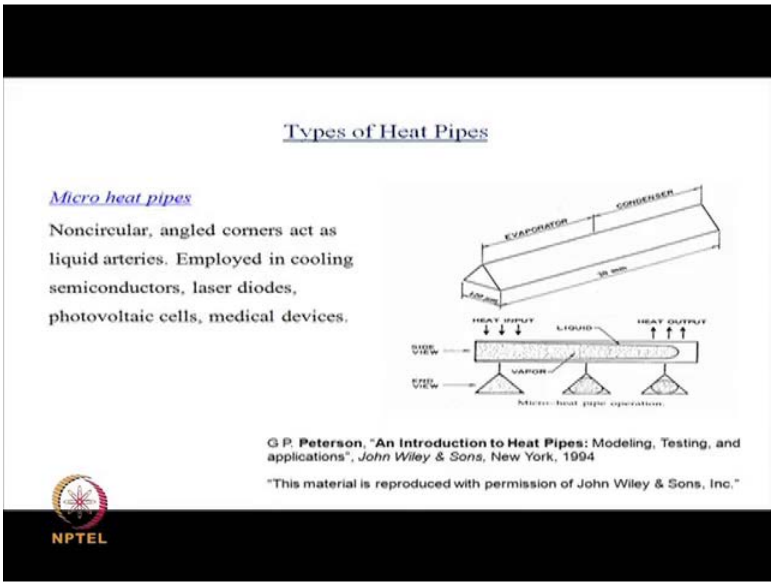

And suppose, you have transistor, a series of power transistors, which are bulky in size where you can still use wicks, you, you can keep them at the top and the heat is going to be let out from the bottom. So, the vapor from the top, vapor will flow from the top to the bottom and through the wicking action liquid will move in the reverse direction. So, against gravity it will go up, come in contact with the hotspot, evaporate and the vapor will come down and condense at the other spot. So, these would be possible for slightly larger applications.

But the heat pipe, that too I am going to discuss, which is consistent with the objective of present course is micro heat pipe. So, a micro heat pipe has to be non-linear, I am sorry, non, non-circular because the corners are going to provide the capillary suction necessary to drive the liquid, from the hot, from the cold to the hot side. We will see how it looks later on, but let us say I am looking at a triangular heat pipe over here.

This is the hot side and this is the cold side, so at the cold side what you would expect is that the liquid is going to fill almost all the corners of it, so there will be liquid at the corners in, when we come towards the cold, cold region, whereas this, I come towards the hot region, it is going to be, the liquid will be depressed far towards the apex of the corners. So, towards the, towards the cold side I have liquid everywhere, on the hot side I may have traces of liquid left only at the very deep recess of the, of the, of the apex. This, this is going to result in a difference curvature. As you can see, in, in the cold side the radius of curvature is relatively large and since the radius of curvature is large your curvature is going to be small. So, I have a small curvature towards the colder end and a very small radius of curvature and therefore, a very high curvature at the hot end. So, this difference in curvature is going to drive fluid from the cold side towards the hot side. We will see how, how that happens.

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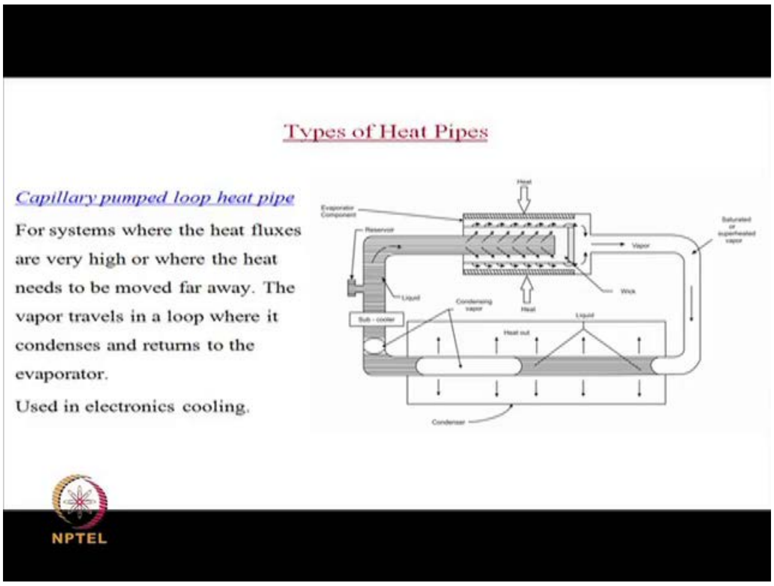

If we have very high heat requirement, that removal rate is very high, then there would be a capillary pumped heat pipe and these applications you can read in, read in a, any, any book on heat pipes and you would see, that these type of capillary heat pumps are also in use.

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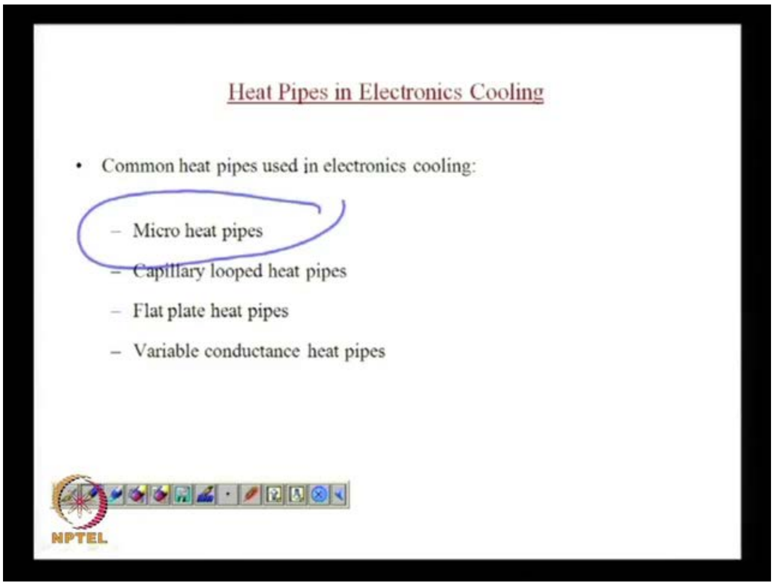

So, these are the 4 types of heat pipes, which are in use for electronics cooling, but in this course I am going to concentrate on the micro heat pipe only.

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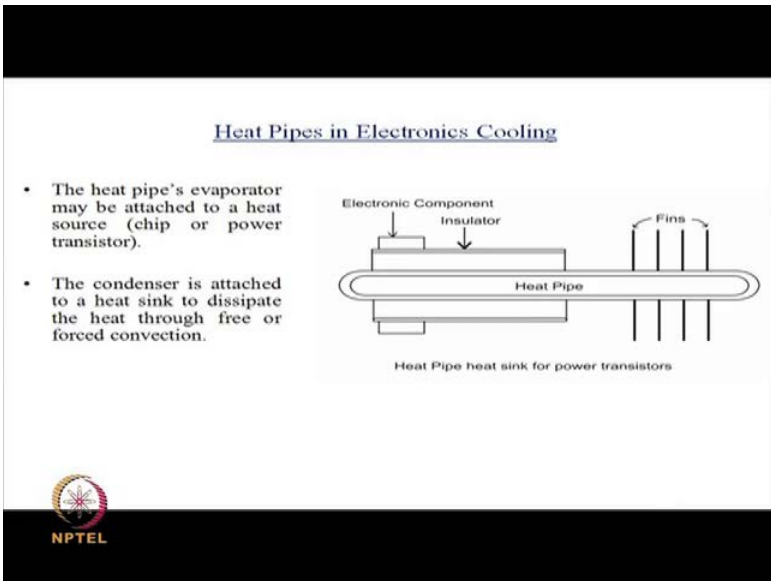

So, this, this is another example of heat pipe where this is going to be the cold, this is going to be the hot side and the heat pipe is embedded deep into it, and there are fins attached to the, to the cold side. And through convective cooling the temperature, or the heat temperature can be controlled.

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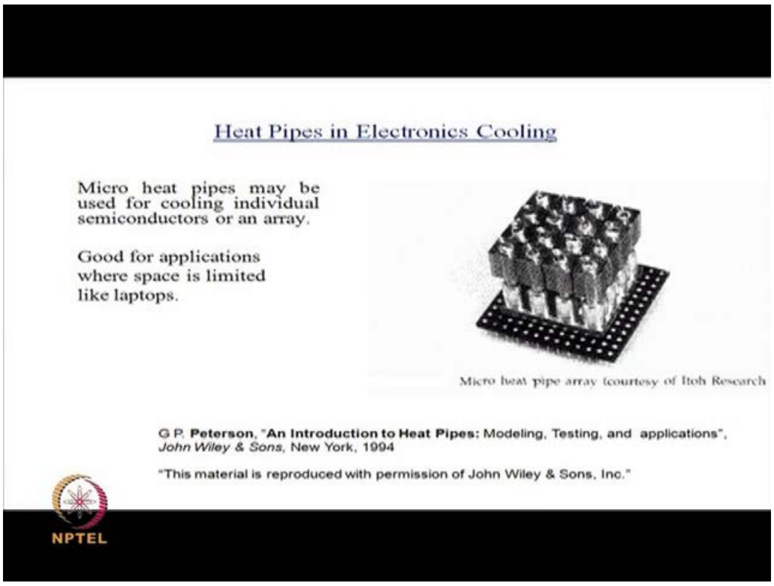

This is an array of heat pipe, which has been made for electronics applications and these are arrays of heat pipe where one side is going to be cold, the other side is going to be hot.

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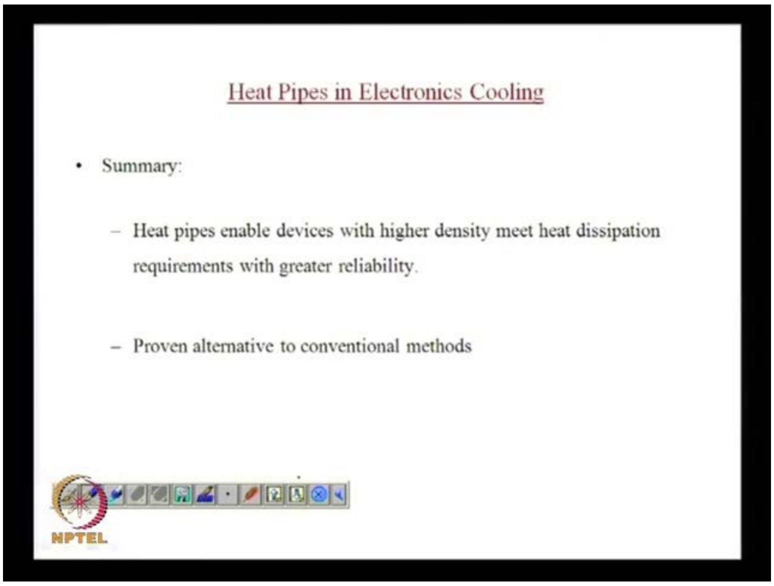

So, if I would like to summarize this section before going into the modeling part of it is that we have heat pipes, which are going to, which will probably meet the higher energy removal density necessary for keeping the substrate cold.

And secondly, it is, it is definitely a proven alternative to the conventional methods that are in use and which are slowly coming towards it's, towards its end. I mean, you cannot, you cannot remove heat anymore. We would, with the increasing circuit density, the requirement for heat removal keeps on increasing every day.

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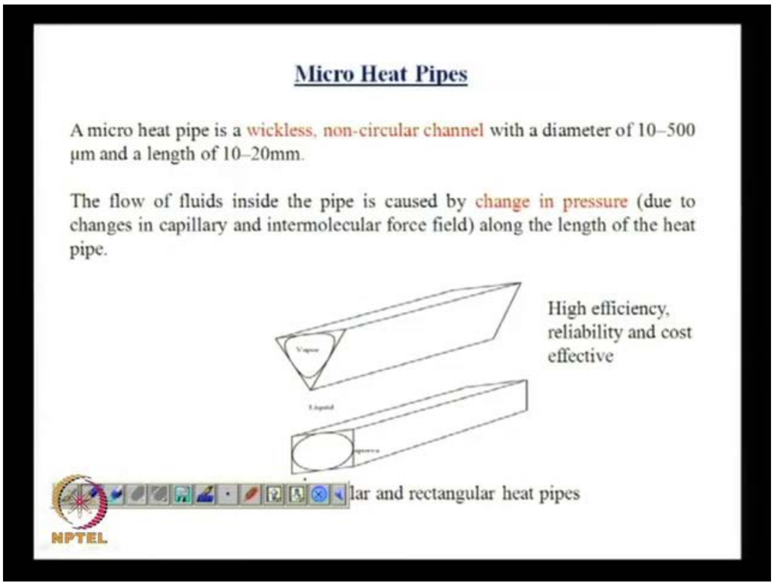

So, now, let us see what is a micro heat pipe? So, it does not have wick, it is a non-circular channel. In fact, you have to provide corners where you would let the liquid undergo, let the liquid undergo a change in the radius of curvature. The diameters are between 10 to 500 micron and the length could be a few centimeters and the flow inside the heat pipe is caused by a change in the radius of curvature. In fact, a change in pressure caused either by a change in curvature or by an intermolecular force gradients. If the size of the device is very small, then you would probably be able to use intermolecular force gradients to drive fluid from one side, from one point to another point.

And all of you are probably aware of Laplace equation, Young-Laplace equation, it is simply, P L minus P V, pressure on the liquid side of a curved interface minus P V, pressure on the vapor side is equal to minus sigma K, where sigma is the surface tension and K is the curvature.

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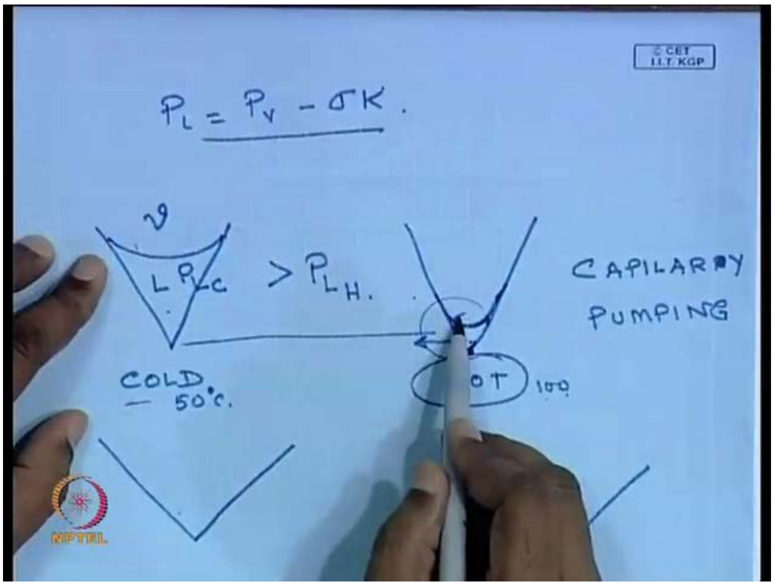

So, I can simply write Young equation, P L is equal to P V minus sigma K. Now, if this is the view of one of the apex of the groove and let us say, this is the cold side, so this is the cold side and I have, this is the, as the hot side, this is the liquid, this is the vapor and this is the solid wall. And at the hot end, this liquid meniscus is going to be depressed more towards the apex of the groove. So, when we, when we, and these two are connected, I could not write properly, but these two are connected, so the pressure in the liquid side at the cold end, due to this equation is going to be more than the pressure of the liquid at the hot end, since the curvature at this end is going to be much smaller compared to the curvature of this end. So, this capillary pressure, which is generated by the geometry of the groove and the nature of the liquid meniscus inside the groove at the cold and the hot end, is the driving force for liquid flow from the cold side to the hot side.

So, obviously, you can see, that the performance of this triangular groove is going to be better than this triangular groove where the apex angle is much more because I, I, I do here from a large value of radius of curvature, it can go to a very small value of curvature, whereas with increase in apex angle, the amount of change, that the liquid will undergo will decrease. So, a sharp corner will provide more capillary suction compared to, compared to an angle, which is, which is larger in size. So, this is something one has to keep in mind (( )) or well, fabricating such a device. So, this, so this capillary, this is also called capillary pumping, I am not sure of this. So, this capillary pumping one has to, one has to characterize, one has to evaluate, one has to predict model in order to predict the performance and to design an effective device.

Now, what happens, suppose this temperature is at 100 degree centigrade and this temperature is at 50 centigrade or you are adding some amount of heat, so that the temperature is 100 and this is the shape of the, shape of the meniscus. If you increase the heat input at this end the root come a point where there would not be any liquid left that is called the initiation of the dry-out point in such a device. And the moment dry out takes place the heat pipe loses its efficiency because it do not, it do not have any phase transfer, phase transfer mechanism, that is in operation right now. So, this is dry, you increase the heat flux beyond that and the dry part will start to propagate in this direction. So, part of the heat pipe is going to be dry, part of it is going to be irrigated by the liquid, which is definitely something, that you do not want because the temperature of this end will, will increase dramatically and inter device would fail. So, this is known as the capillary, capillary suction failure of such a device, capillary limitation of such a device. There are other limitations of, of heat pipes as well.

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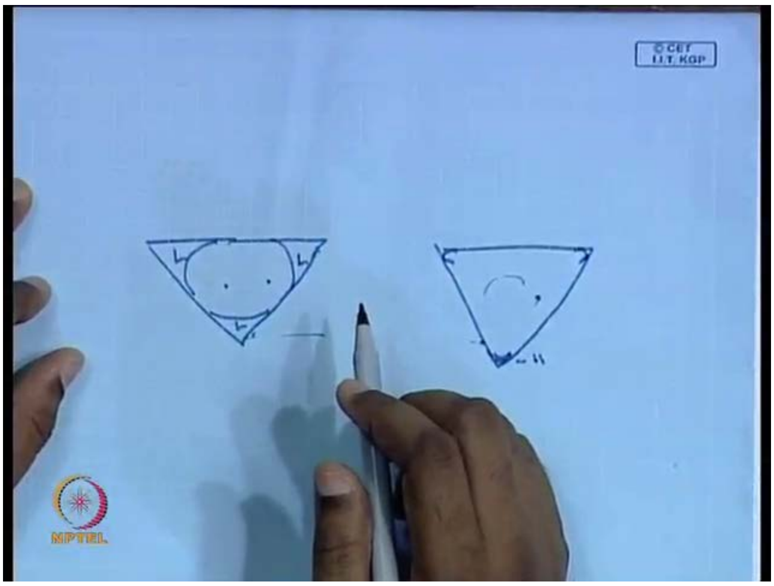

Now, if you think of, if you think of, let us say, the heat pipe in, in the hot and the cold zone. In the cold zone, the heat pipe is like this with this portion filled up with liquid; in the hot side, only the corners has some liquid left in it. But what happens to the vapor? The vapor is going to be generated in this region, which will flow through the core towards the cold side. And if you consider the amount of evaporation and the difference in densities between the liquid and the vapor, the, the velocity with which the vapor has to flow will be very large compared to the liquid velocity. Is that part clear?

The velocity of the liquid, small amount of liquid coming towards the hot side and getting evaporated, will generate large quantities, large volume of, volume of, of, of the, of the vapor, which has to traverse in the reverse direction. And in, in transport phenomena we have so far handled cases, analyzed cases, considered cases when there is no shear at the liquid-vapor interface; that is a very standard boundary condition, which we have used, that whenever we have a liquid-vapor interface, there is no shear. Whenever we have a liquid-solid interface, in most of the general cases we have no slip condition. But if we have a very high velocity vapor flow in the reverse direction, then the nosier at the liquid-vapor interface will not be, will not be valid and the flow, reverse flow of vapor will start to retard the flow of liquid towards the hotspot. And this is another limitation, which can happen in the case of heat pipes, especially micro heat pipes, especially as its direction will become smaller, dimensions will become smaller and smaller and the vapor core available would be very small.

One also would have to think, like what would happen if I tilt a micro heat pipe if I have a body force, which is acting against a heat pipe? So, you, we, there have been a lot of numerical work, theoretical work done on these and it has been shown, that the gravity forces are rather unimportant or less important for the case of liquid distribution at the corners in a micro heat pipe. They, they, so the effects of body forces are generally small. It is the surface forces, which are going to create a, which are going to create all sorts of flow in, in, in micro heat pipes.

Secondly, since we have the temperature also drastically different between the hot side and the cold side, the surface tension will also change. The surface tension of the liquid, which is at 50 degree and over a distance of 1 centimeter, the surface, the temperature is 100 degree. So, the large change in surface, large change in temperature will cause substantial changes in surface tension and the moment surface tension changes, additional flow, which is known as Marangoni flow will start to take into effect. So, surface tension driven flows, which were unimportant in at macro scale may become, may play an important role in the case of micro devices. So, this is another, another thing one has to…

Another limitation of micro heat pipe, that one has to take into account, so most likely one would encounter capillary limitation, that is, you do not have enough capillary suction to sustain the evaporation rate to replenish the amount of liquid, which has been evaporated.

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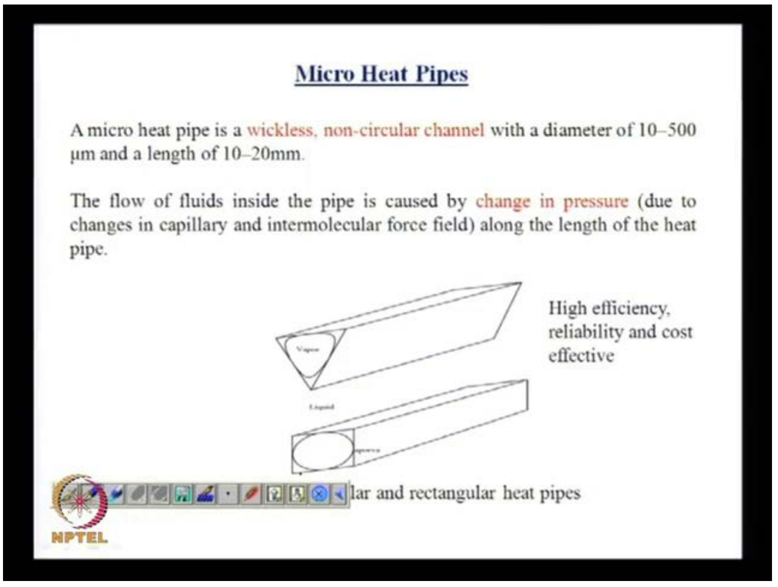

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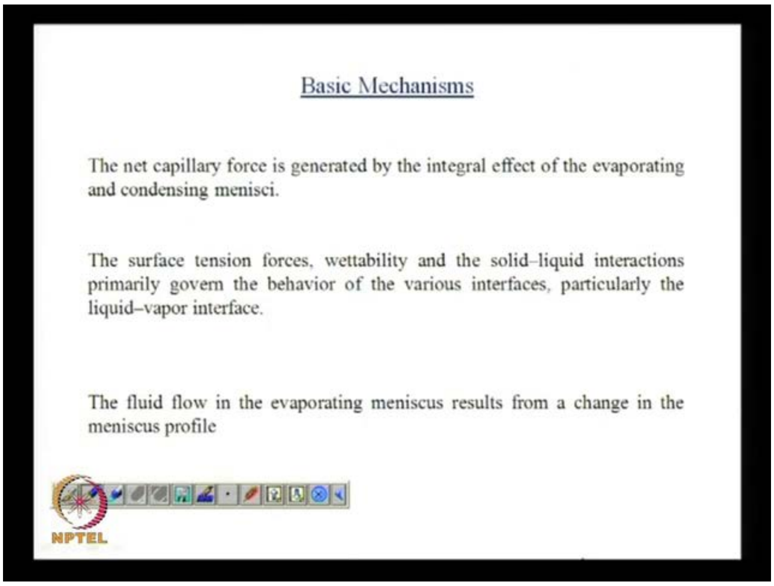

So, the, these are two pictures of a rectangular heat pipe and a triangular, equilateral triangular heat pipe and we will look at a, the, the, the basic mechanisms only in which they operate, which I have already described, that it is a capillary force and the surface tension force, which play an important role. And in also the other engineering parameters of interests is the wettability. Would you like the liquid to wet the solid through, over which it flows or you would you want a non-wetting surface? What, how do you model the liquid-solid interactions?

And when we talk about liquid film, which is becoming thinner and thinner as we progress towards the hotspot, then additional forces will come into play. For example, when we think about a meniscus, the, in the, at the, at the macro meniscus where it is thick, the effect of intermolecular forces will never come into play. But the moment the meniscus starts to become thin, additional forces such as long range Van der Waals forces will become, will become increasingly important.

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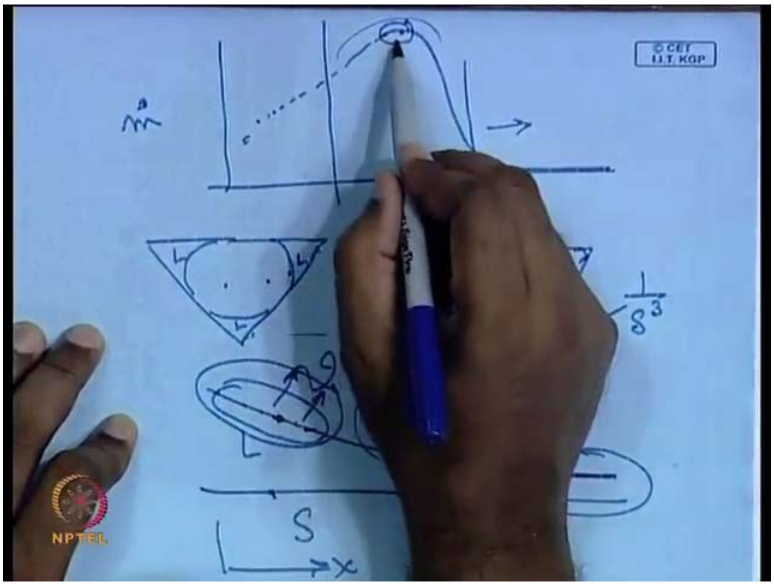

Let us think of liquid film, which behaves in this fashion. So, I have a liquid, its vapor and have a solid. So, over this region, the liquid molecules are far from the solid. So, the liquid molecules here do not face any attractive force, attractive Van der Waals force provided by the solid to the liquid. But the moment it becomes very thin, the liquid molecules are going to be strongly bound by Van der Waals forces to the solid, solid object. So, therefore, if I heat the, this solid, there is definitely evaporation possible from here, but over here the molecules are so strongly bound, that I will not have any evaporation from this region. So, this is called the adsorbed thin film region, which could be about 100s of angstroms thick, but it is going to play an extremely important role to define or to govern, whether or not you have a wetting system or non-wetting system.

As I move towards this direction, the thickness of the film starts to increase and the conductive resistance provided by the increasing thickness of the film will reduce the amount of evaporation from this zone. So, there exists something in between this zone where capillary forces predominate and this zone where intermolecular forces predominate. This is known as the transition region and this transition region where both, capillary denoted by sigma k and intermolecular Van der Waals attractive forces, which are proportional to 1 by delta to the power 3, delta being the film thickness in this transition region, both are important and you would expect the maximum evaporation, which is possible.

So, if I, if I draw an evaporation profile, it would, if this is, let us say this is the amount of mass of liquid, which is evaporated as a function of x where x is from this point, then it is going to be 0 in the very thin part, ultrathin part. Adsorbed part of the film increased drastically, reach a maximum, somewhere near the transition region and then, slowly start to fall as we enter into the capillary region. So, this is the so called macro part of the meniscus. This is the ultrathin part of the meniscus and this is a transition region. The reason I am introducing this to you is that to show, that there exists a maximum, which is orders of magnitude higher than the evaporation, which is possible from the macro part of the meniscus.

So, as I move towards thinner and thinner film, the area available for heat transfer, area available for phase change decreases, but the rate of evaporation will increase due to the less attractive long range intermolecular forces acting between the solid and the liquid molecules. So, you have very high rate of evaporation possible in the thinner region of the film and this is something, which is, which is exploited in micro devices, so as to obtain higher rates of evaporation or higher rates of transport. So, a micro device, a micro heat pipe will work very well because there is a possibility, that you are working in the transition region as I move towards the thinner part of the film, and therefore, have a very high heat transfer.

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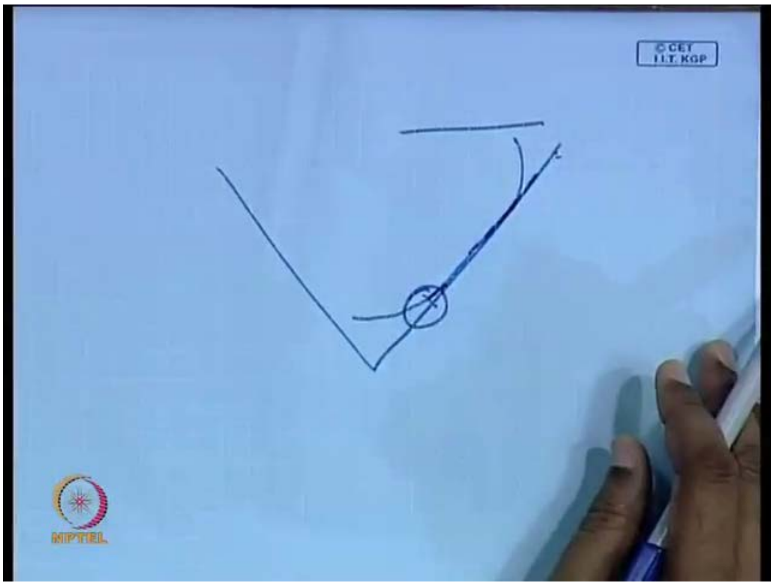

In any case, when we think about the shape of the film, the shape of the film will be probably like this. The adsorbed part will extend all the way up the, up this, this size till it reaches, till it meets the other, other meniscus at the other corner. So, this is the region, which is responsible for the enhanced heat transfer utilizing thin films.

So, it is a difference in curvature, which provides the, provides the driving force for fluid flow, but it is an evaporating meniscus profile at the micro scale, which not only governs the efficiency of the process, it also governs whether or not you are going to have a wetting system, a partially wetting system or a non-wetting system, because it is, it is ultimately the, the contact angle at where the liquid meets the solid, the equilibrium contact angle, which will govern and the motion of the contact line, that I will discuss later later. The motion of this region is going to govern the entire heat transfer process.

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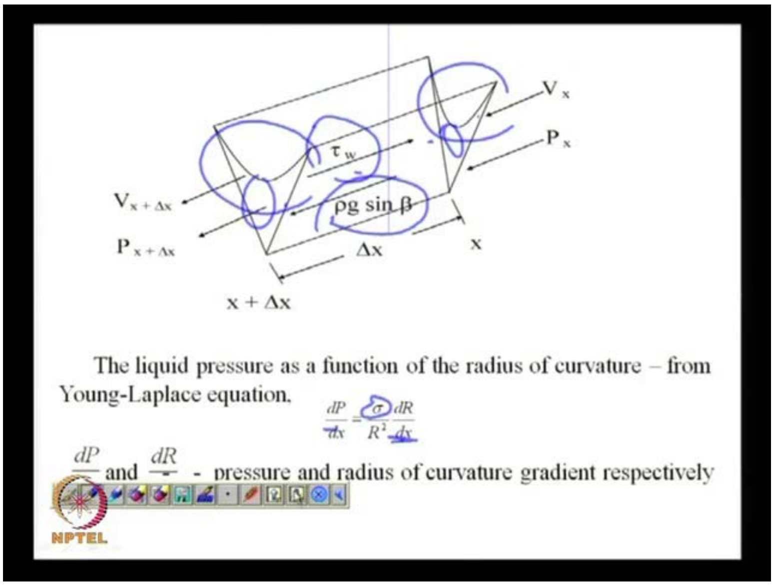

This is a very simple model of fluid flow in a, in a V-shaped micro channel and those of you who have done, all of you have done transport phenomena, just a simple shell momentum balance type of approach can be used to model the flow of liquid through a micro chip, through a micro channel in between two points where there is substantial difference in curvature.

So, let us say this is the cooler side, this is the hot side, this is the delta x, that is, the control volume size and I have flow, whichever way V could be negative in this figure, it is shown as if, that is, I have flow from the hot side to the cold side. Basically, the value of V that you are going to get out of it should be negative. There would be flow from, from the cold side to the hot side.

And I have a body force and since there is flow in from, from the, to the left, the shear stress acts in the opposite direction and at the same time, since you have a difference in curvature, that is going, going to give rise to an additional pressure gradient in the system. So, if I just have this system without anything and if I have flow due to gravity, then there would not be any imposed pressure, but the reason, that the surface, that the, that the curvature is changing, and since the curvature is changing, the pressure at this point is going to be different from the pressure at this point. So, there would be a pressure gradient acting on the flow.

So, I have several factors, which are governing the fluid, the transport process here. I have some convective momentum, which is coming into the system, some sort of surface force, which is acting on it, some body force, which is, which, which is also acting on it and there would be other forces. As I move along, I will, I will show you as it goes.

So, the Young equation can give what is a pressure gradient as a, due to the, due to the presence of sigma, which is the surface tension and a change in the radius of curvature. So, r here denotes the radius of curvature, which I understand is a function of the axial location. As I move into x the value of r changes. Since the value of r changes the value of curvature changes, as the value of curvature changes the pressure of the liquid will keep on changing. So, the difference in the radius of curvature will create a pressure gradient for flow from the hot towards the cold side, I am sorry, from the cold towards the hot side, that is, the essence of this modeling.

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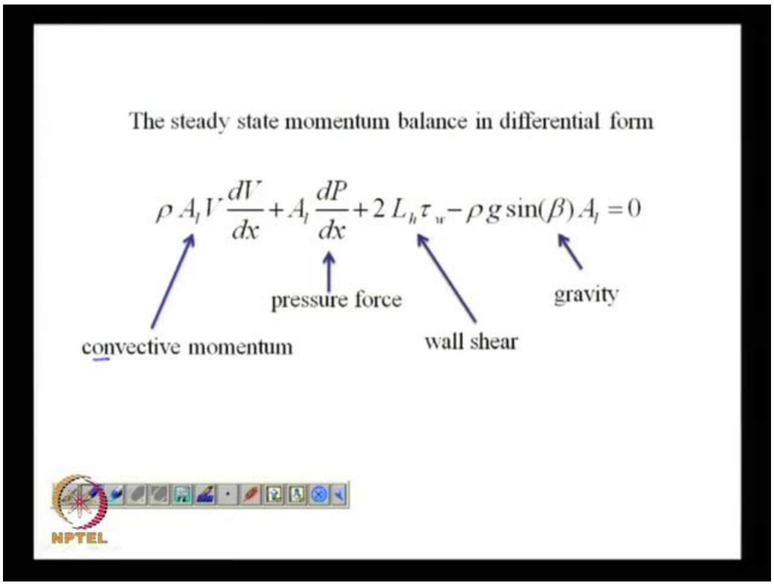

So, we, if we, so if we, if we, if we write the momentum balance using the differential element, that I have shown is, that the, it is going to be balanced at steady state, it is going to be a balance between the convective momentum transport process because of the presence of this v. The pressure force, where dP dx arises due to the change in curvature and the change in curvature is going to create a pressure gradient, I am going to have a wall shear, where tau w is the, the wall shear, which is acting on the fluid opposing the flow. And I have some sort of gravity body force, which is acting on it. So, this is the steady state momentum balance equation, that one can obtain by the, from the shell balance of the previous picture.

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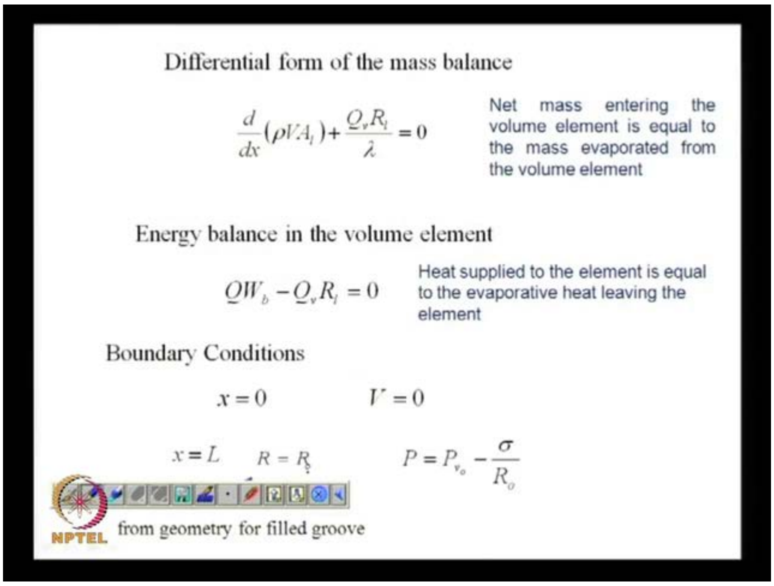

Now, if I, if I also write the mass balance, now, so we have some amount of mass, which is entering, that control volume and from the surface, from the top surface, from the surface where the liquid and vapor are in contact. I am also having evaporation, so when I am talking about evaporative part of the heat pipe, I am going to have evaporation from the top. When I am talking about the condensing part of the heat pipe, I am going to have condensation of vapor on the liquid film. So, depending on where I am operating, I could have either evaporation or condensation and thereby, I am going to either lose some mass or gain some mass. So, your Q v divided by lambda, this essentially tells us how, what is the mass, which is being added or subtracted from the, from the flowing film as a result of heat transfer. So, this is essentially a, a balance of mass between the amount of mass, which is net amount of mass, which is entering the volume element and the amount, which is evaporated or condensed.

We also can write an energy balance in the evolved element. So, this is the amount of energy, which is amount of heat, which is being added to the liquid film through the base. And this is the amount of, amount of energy, which is being taken out by, as evaporative heat flux, or in the case of condensation it would simply be the opposite. So, this is the energy balance of the volume element.

The boundary conditions are simple one is that at the hot end it do not have any flow. When you are at the hot end, you have reached the end of the heat pipe. So, at x if I call, that as x equal to 0, at x equal to 0, I do not have any velocity of liquid and at the other end, at x equal to L, that is, at the cold end, I will assume, that the liquid has filled the groove in such a way, that through geometry, by geometry I would be able to know what is the value of the radius of curvature at that point.

So, essentially, what I am saying is that if this is the, this is the V groove, then at the filled state, this is basically tangent, whatever circle, that I have is tangent to the surface. So, if it is tangent to, tangent to the surface, if it is like this, so at the filled up stage the liquid, this is going to be, whatever would be the circle, this is going to be tangent to that and the value of this r can be, can be obtained by the apex angle and the length. So, this is, by simple geometry you would be able to obtain what is the value of this r naught. At the other end and if I know the value of the r naught, at the other end, I would know what is the pressure of the liquid at the other end using simple Young's equation.

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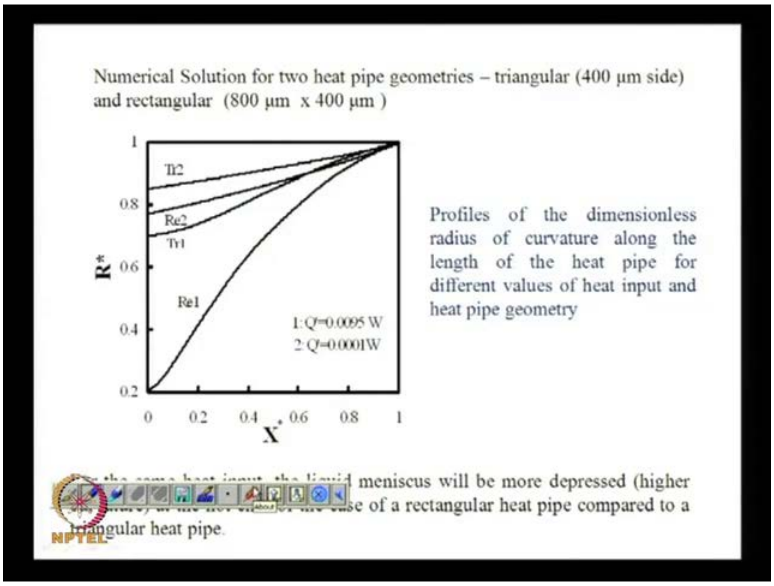

Now, this equation has been, these series of equations have, they have been non-dimensionalised and from the, they have been solved numerically, I will skip that part, numerical solution part is not important. This is some representative result that I would like you to see, one is for a triangular groove, which is for equilateral triangle, which is 400 micron side and the second is a rectangular micro heat pipe, 800 micron into 400micron and I believe the length of this micro heat pipe is about 2 centimeter.

Now, here you can see that it is a profile of the dimensionless radius of curvature as with x star, which is a dimensionless distance. So, the value of R star equal to 1 is that at the cold end. So, at the cold end, whatever be the radius of curvature that has been used as the non-dimensionalising factor, for non-dimensionalising R. So, R star is equal to R, local R divided by R at the cold end. So, obviously at the cold end the value of R star should be equal to 1, but this figure shows how the radius of curvature changes with location as I move towards the hotspot. So, let us say I have, I am comparing between Tr1, which is one specific dimension and the specific dimension is 400 micron. And when Re1, which is rectangular at two values of heat input, so you have two values of heat input, you could see, that the change in R star, necessary for the case of triangular groove is relatively less, substantially less than that are of a rectangular, rectangular heat pipe.

So, I am providing four corners for a rectangular heat pipe, whereas three corners for a triangular heat pipe. But the angle provided for the rectangular heat pipe is 90, whereas in the other case it is 60. So, angle has a, has a greater role to, pay, play than the number of, number of corners, that you provide. So, obviously you can think of some sort of optimization between the number of corners, that you can provide for a specific application and what is the effect of the angle. So, I can see, that the effect of the angle is much more pronounced than the number of the angles, at least between 3 and 4. I do not know what would be happen between 4 and 6, let us say, but in between these two, that observation one can see.

And see, the more important point is change in R star, is essentially causing the fluid to flow from the hot side to the cold side. So, the moment you see, that R star has come close to 0, you understand, that you are operating very close to the limit of your device because the moment R star become 0, that physically means you do not have any liquid left at that point. So, you can run a device, you can keep on increasing the value of Q star to see when are you, when and where you are going to hit the value of R star equal to 0.

So, that means the dry spot has generated, you can go beyond, you can increase beyond that value and you would see, that it is going to be like this. So, this is the region, which is a dry region. So, using the models, relatively simple modeling approach, you could see the propagation of the dry region with increase in heat flux, or keeping the heat flux at certain value you can, you can tilt the grooves, you can tilt the heat pipe and add additional opposing body force and see the effect of body force on the propagation of the dry region. So, theoretical prediction of dry-out region or dry spot is extremely important for the design and performance of a micro heat pipe and this model. Since it is very simple, I thought, that you would be able to appreciate the rather simple application of transport phenomena fundamentals into this.

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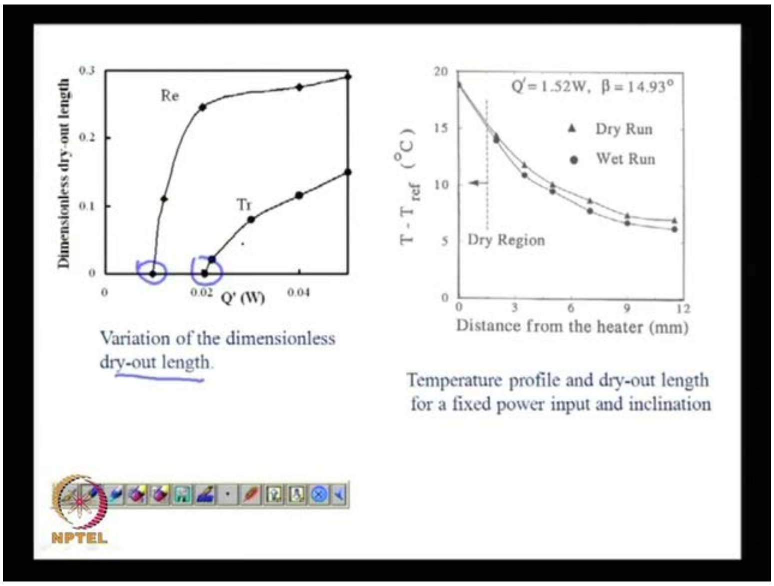

This is what I have, I have described just now is that with increase in variation of the dimensionless, dry, dry-out length with heat. So, this is the dimensionless dry out length. So, you see, that this is the point where for this value of Q's, the dry spots first appear into, into, into the micro heat pipe. And you can see that for the case of rectangular heat pipes, the formation of dry, dry spot is at a lower value of Q. So, if you are using the same Q, for similar dimensions of micro heat pipes one is rectangular, one is triangular. The rectangular is the one, which is going to fail first and this numerical result simply show how the dry, how the dry region, the dry length is increasing or changing with, with applied heat, that is the heat duty of the system for different geometries.

And these are the right hand figure shows the experimental data between for, for, for an, for an actual micro heat pipe. It is not, I would not say it is a micro heat pipe, it is a grooved surface, it is a micro grooved surface on silicon vapor, made on micro groves, made on silicon. And you can see, that the, the top one represents the temperature profile for the case of dry, dry run when there is no liquid; the bottom one when there is liquid.

So, because of the presence of the, the presence of the liquid, the temperature is slightly below than that of the dry, but if you keep on increasing the value of heat flux or keep on increasing the value of inclination, which provides an opposing force, there would be some region where these two will overlap.

The reason or the conclusion one can draw from this part of the figure is that this must be the dry region, otherwise why would these two coincide with each other. And I can see that there is still some gap between the two. And what I would do now is keeping, let us say, the heat flux constant, I will increase the inclination angle even more and I see, that this line will slowly propagate in towards this side. And now I have a model equation to predict and I have experimental data to compare with.

So, a simple model would, so this, this experimental result can be used to validate the model to see whether the model is predicting correctly or not, but more importantly, the model equation can be used as if it is a design equation, a parametric equation by which you can vary several things, including the number, the length, the liquid, that is, the physical properties of the liquid, the heat duty and you would see how much heat you can actually extract till you reach the capillary limit.

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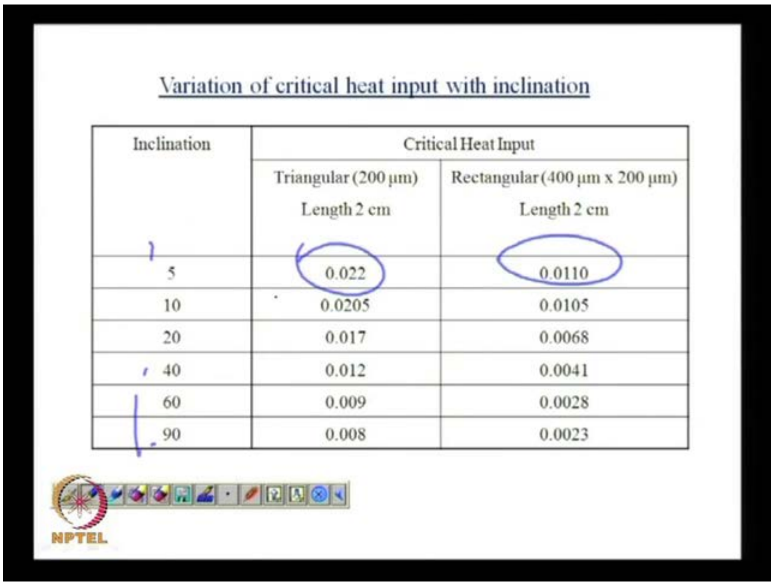
Variation of critical heat input with inclination

Inclination	Critical Heat Input	
	Triangular (200 μm) Length 2 cm	Rectangular (400 μm x 200 μm) Length 2 cm
5	0.022	0.0110
10	0.0205	0.0105
20	0.017	0.0068
40	0.012	0.0041
60	0.009	0.0028
90	0.008	0.0023

And these are, again as I said, that the critical heat input, you could see, that the critical heat input is large before dry out occurs for triangular compared to that of a rectangular. And the effect of inclination, obviously as the opposing inclination increases, the triangular, I mean, the dry out length, the critical heat input decreases, that means, the dry out occurs faster.

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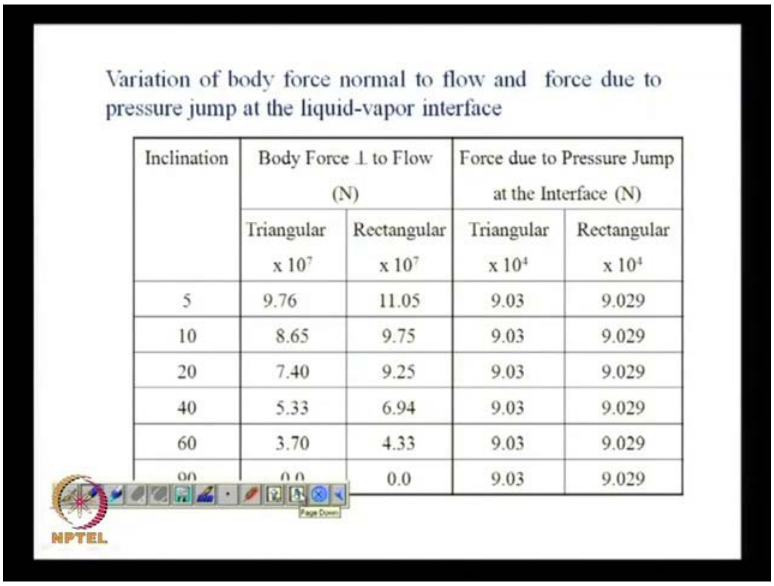

Variation of body force normal to flow and force due to pressure jump at the liquid-vapor interface

Inclination	Body Force ⊥ to Flow (N)		Force due to Pressure Jump at the Interface (N)	
	Triangular x 10^7	Rectangular x 10^7	Triangular x 10^4	Rectangular x 10^4
5	9.76	11.05	9.03	9.029
10	8.65	9.75	9.03	9.029
20	7.40	9.25	9.03	9.029
40	5.33	6.94	9.03	9.029
60	3.70	4.33	9.03	9.029
90	0.0	0.0	9.03	9.029

This is probably the last slide or the last, but one slide. It, we, we could also calculate using the same, same modeled equations is what is the body force perpendicular to the flow. What is the body force and what is the surface force? Force due to the pressure jump at the interface. You can see there are three orders of magnitude difference, there is, the surface force is 1000 times more important than the body force because this is another proof, that the gravity force is rather unimportant. As you reduce the dimension of the system, is the surface forces, forces due to pressure jump at the interface, which is, which is due to the curvature and due to the surface tension, which will govern the flow and associated heat and mass transfer for micro grooved heat pipes or flow through micro groves.

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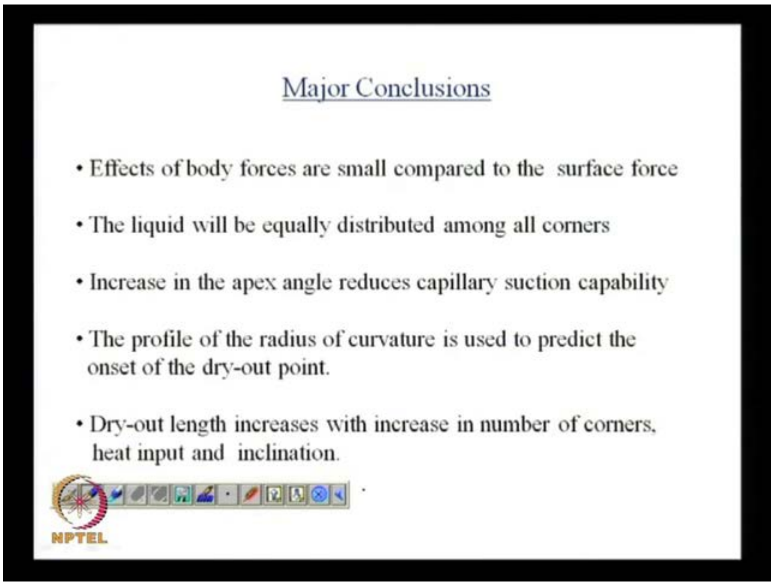

And finally, before I end, this is the summary of what we have studied so far is that we, obviously, the body force is rather unimportant compared to surface forces, and since the body force is unimportant, the liquid is going to be equally distributed, almost equally distributed at all corners, which is something you definitely want. You do not want only part of your heat pipe to be operational when the top half is not going to take part into the heat transfer process. And we, if we increase the apex angle, you reduce the performance of such device. And you have to think about whether you would like to provide more corners or short corners? That is a bottom line, whether or not you provide more corners to the heat pipe or very short corners to the heat pipe. And the profile with the radius of curvature is used to predict the onset of the dry-out point and the propagation of the dry-out point in the obviously, dry-out length increases as you increase the heat, as you increase the inclination and as you increase the number of corners. So, that is all we, I wanted to discuss today about micro heat pipes.

And in the next class, I will talk about the associated, but more important problem, which is how to calculate the pressure drop in such situations.