Micro and Nanoscale Energy Transport
Prof. Dr. Arvind Pattamatta
Department of Mechanical Engineering
Indian Institute of Technology, Madras

Lecture - 41
Measurement techniques in Micro and Nano Scale Heat transfer, Part 1

Good Morning. Now, the remaining couple of classes, we will look at the very important aspect of how do we measure, whatever we have talked about in macro Nano scale energy transport. Measurement is a very very important step. We have looked at so many theoretical models to understand heat transport in flow transport and so on. When you finally, have to prove that this theory works. You have to do a measurement you have to compare it with a theory and then show that the theory really predicts the measurement very well.

Therefore, I think in terms of priority I think measurement gets the highest priority, followed by theory you know the theoretical modeling is always supporting the measurement and therefore, you know we have to always perform experiments even at small scales you know it may be; however, very very difficult to do experiments to build small experimental set up to take measurements of temperature pressure flow at micro Nano scales.

However I think without doing that the theoretical part becomes incomplete. As with even the macro scale, unless you show your good agreement of your theory with experiments, nobody is going to buy your theory. This is same thing has to be also valid at micro Nano scale without doubt with only the exception that the experiments are far more difficult and you have to become use more sophisticated techniques to probe into the smaller scales.

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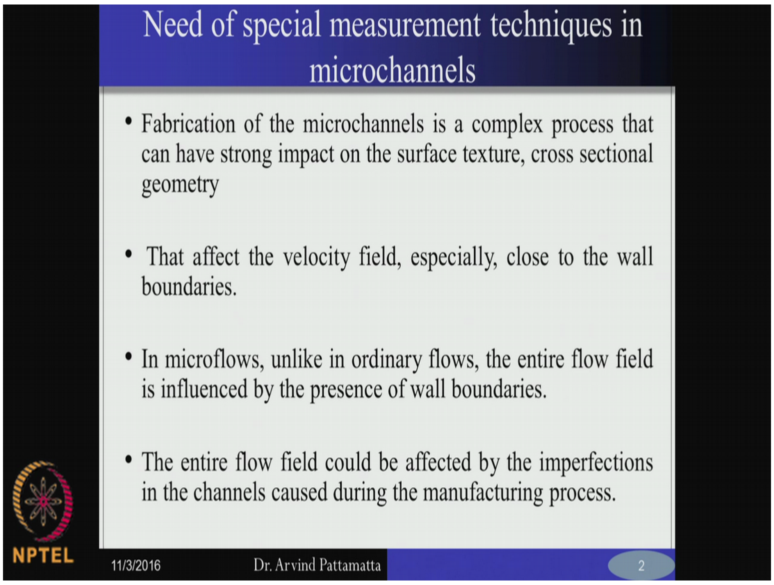

I think we will discuss a few aspects of measurement techniques. Will start with some micro scale measurement techniques and then we will end with the Nano scale part, Nano scale in thermo physical properties.

I think in the und under Nano fluids we already saw the thermal conductivity and viscosity measurement techniques using hotwire transient hotwire pro and Viscometer.

Those are not specific to anything in the Nano or micro, but they are generic equipment. You can also use them for Nano fluids, that I have not put that in this particular section because this is only pertaining to measurements at the micro or Nano scale. Now 1 of the first things that you want to start with the micro scale, this once we fabricate the micro channel for example, you want to calibrate the diameter or dimension of these micro channel. Now, let us assume that this micro channel is fabricated in such a way that you have a certain roughness, you cannot avoid surface roughness. With a certain surface roughness with which could be of the order of few microns and also the diameter of this channel or the depth of the channel could be of the order of few arranging from few 10s of microns to 10s of microns.

Therefore, this is the order of magnitude of micro channels that currently exist that you can fabricate, but once 1 is the fabrication technique or manufacturing technique the other is how do you check these dimensions? How do you check once you make a micro channel of diameter 100 microns, that this is exactly 100 microns and what is accuracy of such a measurement process. This is the most basic thing; that means, given that you have a micro channel fabricated to you given to you, you have to estimate, what is the dimension of this and similarly the roughness. You have to characterize what is the average roughness? We have seen that when we apply the reduced diameter theory. In that case, you have to know, what is the order of roughness size? In order to calculate the reduced diameter, in such a case you have to have a measurement device to accurately calibrate sense there are surface roughness and also measure the roughness to reasonably good accuracy.

Therefore, how are we going to do this? The issues that are required you know when you talk about measurement techniques are there are few of them. 1 is that fabrication of this micro channels you know is a already a complex process. You have to either use are we are not actually talking about those things. People working in manufacturing have to deal with the special issues in in manufacturing or fabrication of micro Nano scale materials. We are not talking about that, we are only looking at. Generally I mean if you take any manufacturing process at micro Nano scale, you have to have very strict quality controls.

It is not just making as channel with this size, you have to also make sure that if we need a surface which is smooth or surface which is of defined roughness, you have to make sure that the surface structure is properly made and the dimensions are more or less measured satisfactorily you know to I mean to the desired accuracy and then this is what is going to be having a biggest impact to you do the flow measurement process. For example, we all know that I mean as far as micro channels are concerned, if it is a gas flow then you have a slip depending on the order of the dimension.

If your Knudsen number is approaching close to point 1, you will have a slip at the wall and this slip is very much affected by the kind of roughness. As we have talked about the accommodation coefficients. You can have either a diffuse reflection of these molecules at the surface or you have can have a specular reflection and according the accommodation coefficients will change and this will decide what is the kind of slip that you happen to have at the wall.

Therefore, the surface roughness quality of this surface structure becomes very important in micro channels and again in micro flows the entire flow is now influenced by the presence of the wall boundaries. Therefore, any imperfections in the manufacturing processes, is now going to impact the fluid flow phenomena itself. You might have a theory for a certain approximation, now when you make this particular channel. It will not be confirming to that and therefore, it becomes even more difficult to validate your theory if your experimental set up is not well made. These are some techniques I would say coming from the manufacturing process itself.

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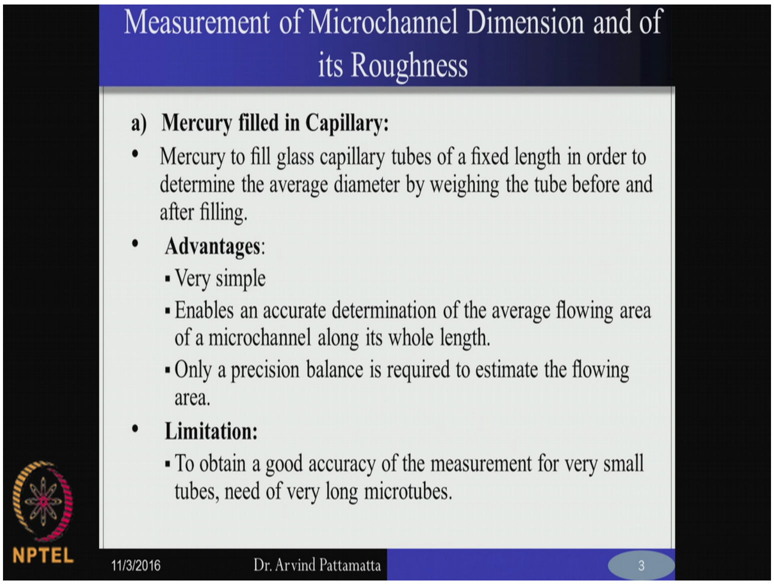

Therefore, very important first step process in measurement is the measurement of the micro channel dimension and its roughness. If you are given a micro channel from the manufacturing section, what you have to do is first may ensure that if you are asked for 100 micron channel you get it, 100 micron plus off course there is always tolerance manufacturing tolerance which has to be accounted.

But you have to have a method to ensure this dimension is in the reasonable limits. What are what the different ways of measuring the dimension are? It is not like you take a small scale you know or Vernier calipers then directly and go on check this because the order of magnitude of these dimensions are smaller then what you can sense through Vernier calipers or screw gauge. You cannot resolve say it 10 microns and 20 microns in a screw gauge. Therefore, what is what the practical methods to do this are? So, 1 is what is called by filling this particular channel or capillary with denser liquid like mercury. Generally if you are talking about a capillary tube, capillary tube maybe of dimension less than the millimeter and the order of few microns is a micro channel. What do we do is we simply weigh the tube first the empty weight, now if we fill it with mercury.

Once you fully fill this you again weight re weight, correct, and then you take the difference. Now, you know what is the volume? You know the density of mercury. You know the mass. Therefore, you can calculate simply the difference between this filled weight and the empty weight multiplied by the corresponding density should give the volume, divided by the corresponding density should give you the volume. Therefore, this volume gives you the total volume of this capillary tube inside section. Since you know the length in the much more precious manner than the diameter because the length will be usually of the order of centimeters compare to the diameter which will be in the micron range.

Therefore, now with this method you can estimate, what is the diameter of this channel. The diameter that you get here will be accounting also for the surface roughness because this is actually what the fluid is filling. For example, if there are some you know some small defects in the surface of the tube some cavities. The liquid can also fill that and it will also tell you I mean the volume based on that small cavity. Therefore, this is although not very perfect tool with the reasonable accuracy you can estimate what will be the diameter of tubes. Therefore, from the advantage point of view, this method is 1 of the simplest you can think about. You do not have to invest in any equipment all we have to do is fill with a you know either water or mercury because more denser it is better you can sense the you know the mass difference much better way and also it enables a very accurate determination of the flowing area along the whole length and what you need is only a precision balance.

Balance should be fairly sensitive may be to the third or fourth decimal point, you should be able to resolve the mass of this. Generally to auto the limitation of this method is to obtain good accuracy of measurement for a very very small tubes, suppose you are now going to the order of tens of microns. If you want to use this method, in order to have a significant volume. You have to have very very long tubes only then the difference between the initial and final weight will be somewhat resolvable. If this is of the order of fourth or fifth decimal point, again your precision balance may need to be more precise or more accurate. Therefore, this can be used to a certain range of diameters, but if this falls short, you know of say by the diameter is of the order of 10 microns then yeah you have to have very very long tubes in order to fill the mercury throughout and get a good estimate of diameter.

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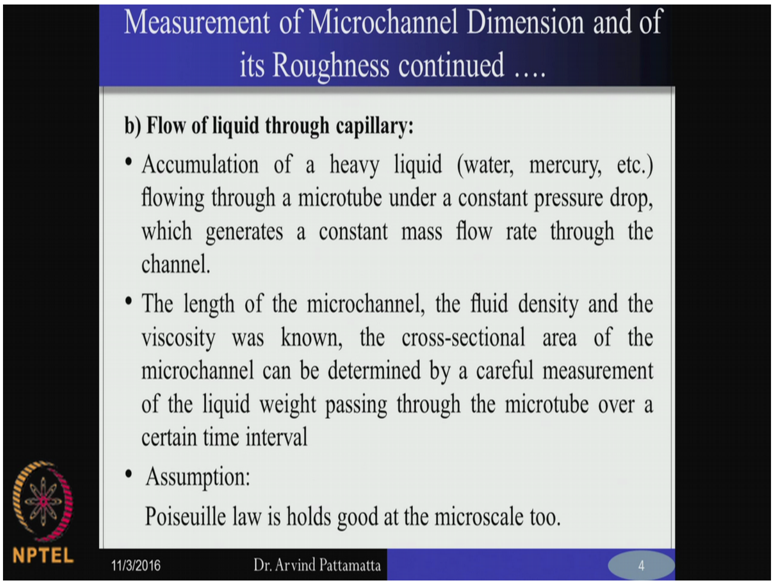

This is any way 1 of the simplest methods. The other method is how we do it is by flowing liquid through capillary.

This flow now this case mercury filling is just does not require any pump or anything. You just have to fill it manually and then weigh and check the difference. The other case, you are going to actually pump liquid and it could be water or mercury again and you are going to pump it through the capillary, now the way you are going to pump it is that since you know that in a capillary tube. You can actually use the Poiseuille law. If you are especially using liquids, there is no problem with a slip boundary condition. Therefore, everything is continuum. Whatever fully developed flow for the micro channel or micro capillary is same thing can be applied here. The Poisuille law is still valid; that means, if you measure the pressure difference across the tube. You will be able to measure what is the flow rate. Average velocity and therefore, you will know the flow rate and from which you can actually again estimate the mass because you know till what time what is the amount of time that this flow was happening through this tube and therefore, from this you can calculate the mass.

This is an indirect way of calculating mass. You do not have a balance precision balance because sometimes if the diameter is too small then even a in a precision balance may not be able to do the good job. Therefore, the general processes we flow either water or mercury. Now mostly since you have very tiny capillaries you will you can achieve constant pressure drop, which will generate a constant flow rate through the channel. And we know from the Poiseuille law, we can relate the flow rate as a function of pressure drop. Therefore, we if you measure the pressure drop use using differential pressure transducer and you know what is the amount of time for which this liquid is been flowing. You can actually calculate the mass flow rate and therefore, mass the exact amount of mass of the liquid filling the tube.

Once you fill the tube. You do not completely fill the tube you pass the fluid because if you have reasonably long tube. You can count enough few milliseconds or maybe a second and then at maybe a smaller pressure drops you can laid the flow go through at fairly low flow rates and then by the time the flow reaches the other end, you stop it you know how much time you have filled it. Calculate the mass and again this is used you know taking the difference between the initial and the final mass and you should be able to estimate again the diameter based on that. The only difference here been from the previous case, the previous case is a static 1 you completely fill it and then you weight it. In this case you flow the liquid by means by using a pump and then you do not use a precision balance now, but you use Poiseuille law to estimate the mass.

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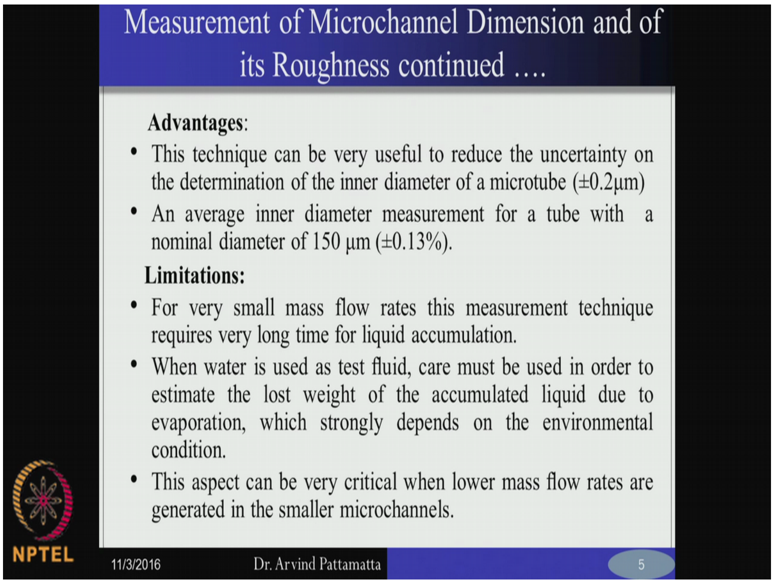

What is the advantage of this technique over the other? Since you are avoiding precision balance, therefore, the least count and therefore, the precision of the balance is not going to play a big role in determining the size of the tube to a great accuracy. It is only going to be the pressure, pressure drop that you will measure and usually you know these tubes, the smaller the tubes the larger is the pressure drop. The pressure drop is resolved fairly accurately without any big problem and you also know the Poiseuilles law is very accurate. Therefore, the accuracy of this method is usually much much better than simply weighing it.

The technique can be therefore, useful to reduce the uncertainty in the determination of the inner diameter to about up to the order of plus or minus 0.2 microns; that means, you can actually determine it with the very very high precision the precision can be plus or minus 0.2 microns and the inner diameter for a tube with the for example, a nominal diameter of 150 micron could be of the order of plus or minus 0.113 percent. This is the order of accuracy we are talking about with this particular method.

Only thing what are the limitations is that for very small flow rates; that means, if you have very low pressure you know pumping power the pump, and you maintain a very small flow rate. This might take actually take a very long time for liquid accumulation especially if your tubes are quite lengthy. And again depending on the working fluid, you assume that there is no evaporation all this is you know adiabatic case, but in reality if you use water for example, depending on this surrounding humidity. There could be some losses due to evaporation. In that case you know will be some actually water vapor that could be accumulated inside or there could be loss of water. Again that will be causing some errors in the difference in the weight. Especially when you are talking about smaller micro channel, these loses due to evaporation and so on. It might affect the diameter measurement you know fairly to great extent, but nevertheless this is better method than simply weighing the channel itself.

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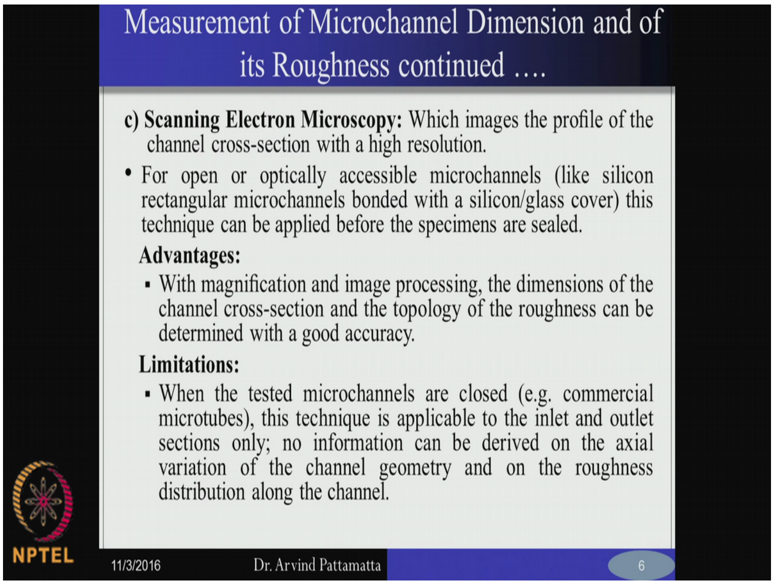

If you want to go to a more detailed descriptive method; that means, I want to look at this micro structure of the surface, how the surface roughness is there? What is the profile of the surface roughness? And how it varies? None of the previous 2 methods will work because all it tells you only the wetted diameter. Wetted diameter can come out of that particular theory, but if I want to go further into the nature of the surface roughness and I want to maybe make tubes of the order of few microns 2 or 3 or 4 microns then those 2 methods again will have serious problems. Therefore, in such a case, we use make use of the scanning electron microscope S E M. The scanning electron microscopy is usually available if you go to the chemistry lab, physics lab or materials engineering.

Usually they use this when they kind of synthesize a new material at the Nano scale and they immediately have to characterize this material. They do use different techniques for characterization, 1 they have to first identify, what is the size of size distribution and how it is actually appearing. The physical appearance that is done by using the scanning electron microscope, then they also look at the chemical nature of the constituent of this particulars.

They do spectroscopy in a X-ray diffraction, Raman spectroscopy, all this to tell what is the chemical nature of this particular material that they synthesize and to confirm whether this is this suppose I make grapheme I want to make sure how do I make sure that what I get out of my procedure is grapheme. For that they have to run through the

Raman spectroscopy for example, and they have to detect a peak at a particular wave length, that confirms that is a signature of grapheme.

But before doing that, we have to understand how this grapheme looks. What is the size distribution? How they appear? So, to do this this kind of an optical imaging, since we cannot do this under a normal micro scope. You use the scanning electron microscope to do that. Now the same scanning electron microscope can also be used to look at the surface roughness and also to measure the diameter of this kind of capillary tubes or micro channels, but; however, you should remember, this can be possible only either the existing channel, you cut cross section small portion and put it under the micro scope and have a look at it or it should be optically accessible. You make rectangular micro channel with an optical access on the top. That you can probe into it, but if it is completely you know Pake from all directions and you synthesize a micro channel which you simply cannot cut. How will you then determine the diameter? Then it becomes difficult to use even this method.

But the till this once you take a section or you make an optical axis. The profile of the channel cross section can be determined with a very high resolution. This is an off course because you are now able to resolve to the order of few Nano meters with a S E M, few Nano meter. Therefore, any small you know tiny blur that appears on the surface even of the range of Nano meters can be easily resolved. The advantages yeah, if you are doing using this method the dimensions of the channel cross section and topology of the roughness can be determined with a very good accuracy; however, what are the limitations? When you are talking about closed micro channels which are not optically accessible that is their Opec to many cases, you are having metallic micro channels. Which are close from all the sides? In that case you cannot simply cut it or you cannot put it under the microscope and get it. So, you cannot get any information from such cases.

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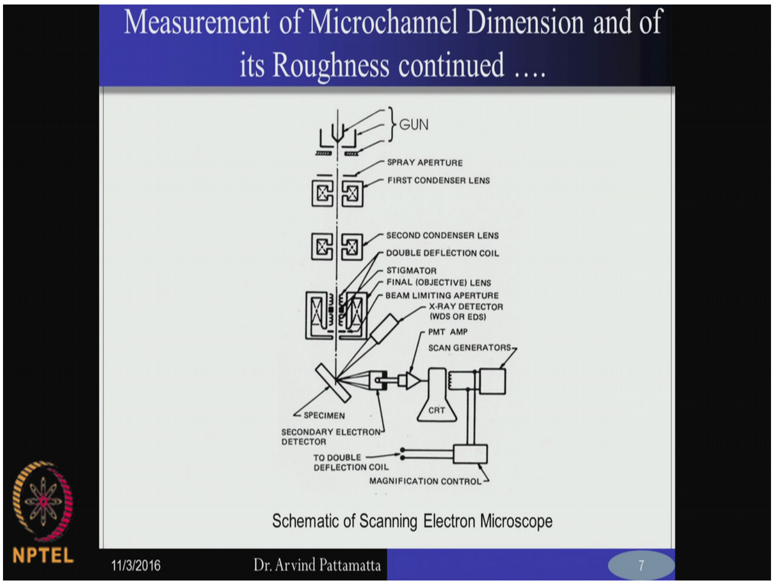

Just to show a schematic of how the scanning electron microscope looks. This is there is a separate theory for this and again the setup is not fairly that large, but also it is ya, it is reasonably its reasonably large, you need to have dedicated, I mean facility for that, room for that and you know you have to maintain the ambient conditions you know at constant temperature and humidity. Yeah you have to invest certain amount of money in maintaining this kind of microscopes.

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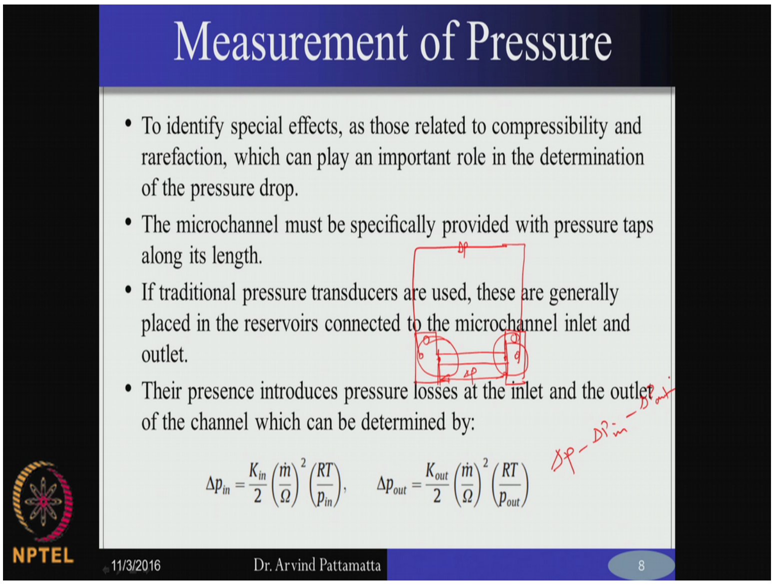

Therefore, the first part was concerned with respect to the measurement of dimensions. Depending on the access that you have, if you do not have access to S E M, then definitely you have to resolve to 1 of the first 2 methods, but if you have an optically accessible micro channel and also an access to S E M; obviously, I will go for the third method which will give you a more detail picture of about the surface as well as the dimensions, correct? Now, the next important quantity of measurement is pressure.

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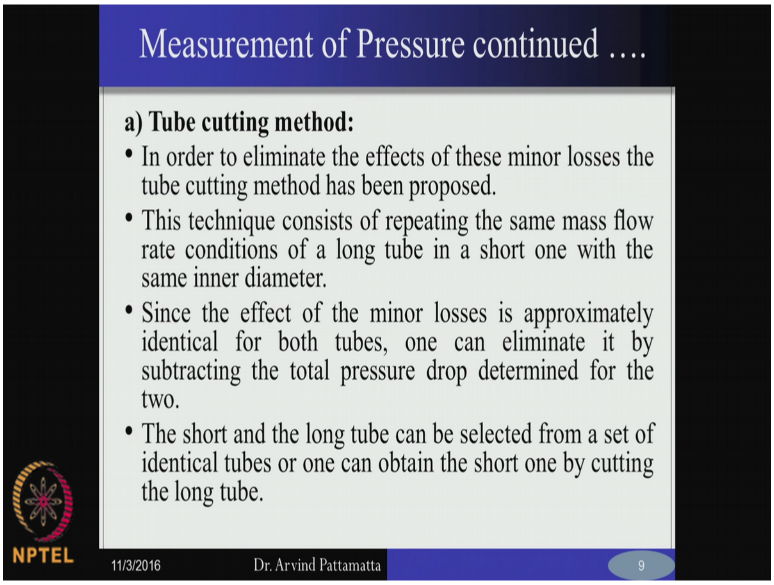

Of course you know when we are talking about you know pressure measurements; we are talking about generally pressure drop here. It is not just the absolute pressure that we are interested in. In micro channel, we are always interested in, what is a pressure drop across this micro channel and usually the good thing is this special drop values are not very small like the value of the dimension itself. There is nothing really specifically problematic with using and existing differential pressure transmitter which can measure the pressure drop for a bigger channel and using it for micro channel.

Usually only the range has to be customized the ranges should be higher when you are going for a micro channel, but; however, there are other issues, which make this measurement process a little bit more uncertain. So, for example, for 1 thing you know the entry and exit loses that is the contraction and expansion loses, are very significant in a micro channel compared to a larger channel. Therefore, when you it depends to a great extent where you put this pressure tapings. Just to give an example. If you are making a fabricating micro channel like this, you usually have an inlet manifold through which you have a flow of liquid and you have an outlet manifold to which you take out.

Now, you, where do you put the pressure tapings; obviously, you now you have to put the pressure tapings where you have a sufficient contact area. Generally we put it somewhere here. Therefore, the differential pressure that you measure is actually not within only the micro channel, but from the manifold. Therefore, the actual pressure difference that your measuring also includes the contraction loses here and the expansion loses here the entry and exit loses. This is usually the problem and if these are not very small values which you can ignore. Therefore, if you want to really only measure the exact delta P from here to here, this is a very difficult process because you cannot put a pressure tap here and here, this is the flow path the flow path itself is very small. You cannot simply put a pressure tap their and you can you cannot disturb the flow.

But you are interested in only delta P across this tube and not across the manifolds. Therefore, you have to find a method to eliminate the contraction and expansion loses. 1 simple way is of course theoretically you might know from the correlations. What is the value of delta P at the inlet? What is the value of delta p at the outlet? From the entrance and exit loses so, but these are approximate things they are not applicable to all kinds of micro channel shapes, therefore, but you can probably use that and you can reduce the delta P. You will be measuring the overall delta P and you will be subtracting delta P in and delta P out using theory, but this is a very very rough approximation, correct?

Therefore, what will be a better way to do this? Therefore, what we do with this method called tube cutting method.

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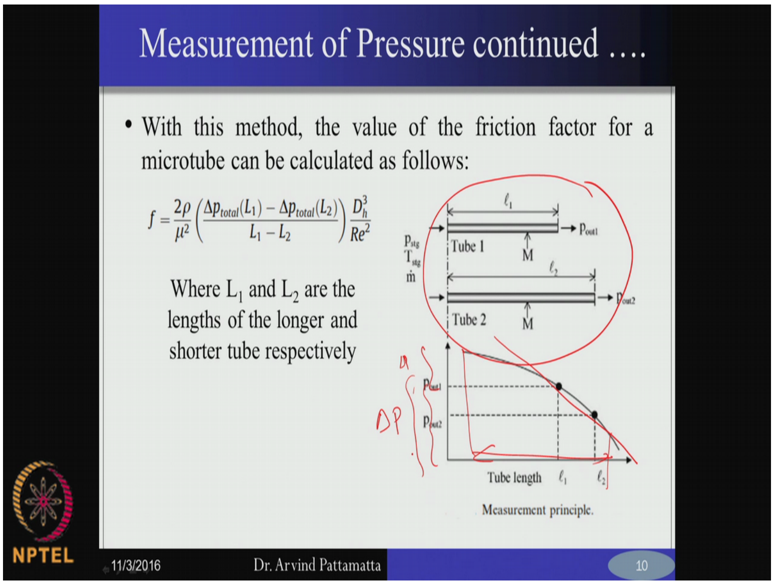

That means now, you take a big tube a large tube and you measure the delta P like this and now you cut this tube to a smaller length and again measure delta P and take the difference the delta Ps. When you take now the difference between the delta P is of the longer tube and the shorter tube, what happens? The common factors are the inlet and exit loses. These are going to be the same whether it is a long tube or short tube as long as the tube diameter is the same. Therefore, that will get automatically eliminated. From which you can calculate your friction factor which will give you the pressure drop only within the tube and not the including the entrance and exit loses. This is 1 of the very simple ways you know there is no technology really used all you need to first do is take your actual tube, measure the delta p and then either cut this tube or make another tube with the same diameter.

And again measure delta P for that, take the difference between the 2. This will now eliminate all your uncertainty with respect to the in entrance and exit loses, is it that clear? This method is called the tube cutting method. As it says this technique consists of repeating the same mass flow rate conditions of a long tube in the short 1 with the same (Refer Time: 30:35); that means, if you want to measure the delta P, again you have to make sure the mass flow rate is the same, because your delta P is the function of flow rate. Since the effect of the minor loss is the approximately identical for both tubes. We have to just only do a subtraction of delta P between the longer and the shorter tube.

And how do we select it? The short the short and the long tube can be selected from the set of identical tubes. Suppose you have just tubes. You can simply select from the same lot or you can cut it cut the longer 1 and then get the shorter 1 out. Now, therefore, if you see the pressure distribution, strictly speaking you know if you are looking at incompressible flows and if the if you assume the flow is fully developed, how in the pressure distribution look at it should be straight line correct; that means, your D P by D X should be a constant, that is why the Poiseuilles law valid, but this curve actually shows in a realistic case where for example, if you have compressible effects. You may not have constant pressure drop pressure gradient. Therefore, there it will be deviating from a linear curve. Usually this method will give you very accurate results as long as you have a linear variation of pressure, linear drop.

This is valid if you if your mostly focusing on incompressible flows and fully develop flows, but if you have compressible effects then this method will fail because now your pressure difference is going to be different in different regions. Therefore, if you have a longer tube you have therefore, parking about a pressure difference which is may be here this much and if you take the shorter tube. Your pressure gradient is going to be somewhere here delta P. Therefore, this difference will give you a different value which is not corresponding to the same pressure gradient your D P by D X is going to be different in different regions. Therefore, you cannot use this tube cutting method, if you are working with for example, compressible flows.

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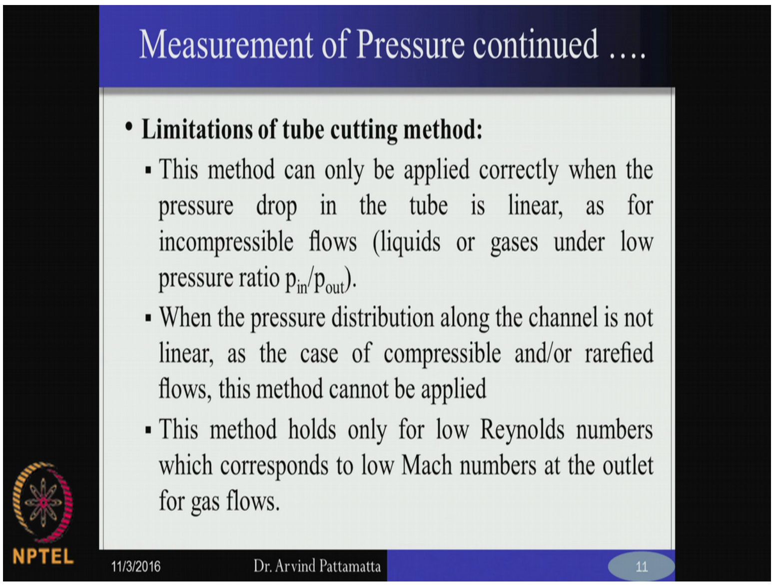

Therefore, what are the limitations of this particular method? This method can be applied correctly when the pressure drop in the tube is linear as for incompressible flows. Generally if you are talking about ratios of P in by P out, the reasonably small then this could be if the pressure distribution is not linear as in the case of compressible flows the method cannot be applied. Therefore, there is a short follow up this method you cannot extend it to all kinds of flows especially slightly higher math number flows or very large pressure ratios or compressible flows.

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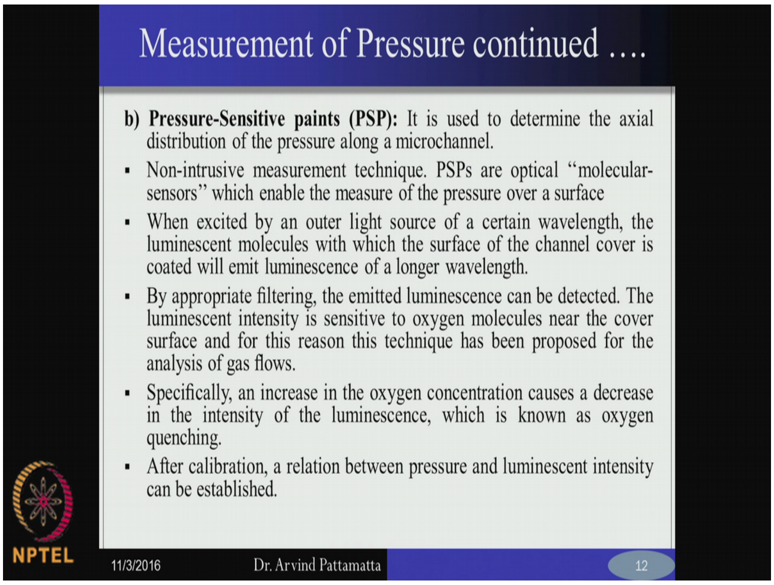

In such a case, you have to use other techniques. The other technique 1 such technique is call the pressure sensitive paint. This is not so commonly used you know in our institute for example, but and this also requires highly sophisticated equipment compared to simple differential pressure transmitter in the earlier case.

In the case of pressure sensitive paint, we rely on applying a coating, which are like molecular senses. This, what you do is you shine a light, it could be a normal white light or it could be a laser light and these sensors that you coat on the paint that you coat on the wall. This will respond to the light. The beam that is emitting from this particular coating, responsive to the intensity of light that you shine from outside and also on the pressure excited by the molecules on the surface, for example, if the pressure is on the higher side, this intensity of emission coming from the paint will be higher. What you do is you calibrated with a normal surface, you apply the paint. For example, you can have a square micro channel, you apply the paint on the wall of the micro channel you pass the flow at a certain pressure you record, they are corresponding intensity coming out and then you increase the pressure.

With variation with respect to pressure you record, what the intensity of the emission is. Therefore, you can build a calibration and with that you go to the actual case. Now you can record the actual variation in the intensity across the tube or the micro channel length, along the micro channel length. From that calibration, you convert this back into pressure. This is the method of course; you know this not very straight forward method. These are non-intrusive; however, because you do not put any pressure tapping and pressure probe into the channel, but you adjust imaging this from outside and you are also probing this by using white light or a laser light which is kept outside. All you are doing is only applying this, the sensor which is the paint on to the wall. The non-intrusive measurements P S P are optical molecular sensors which enable the measurement of pressure over surface. When you exit this molecular sensor by an external light, light source and defined wave length.

If you are using optical white light, then you should know what wave length you are operating or if you are operating a monochromatic light source like laser you know exactly the precise wave length at it is coming. The luminescent molecules from which the surface of the channel cover will be coated will emit luminescence of a longer wavelength. It is just simply luminescence which is meaning there is an emission coming from this molecules which is having a different wave length, then the wave length that is falling there is a correlation to that. If you generally use particular Lambda, the emitted wavelength will be greater than this Lambda. You basically filter out, you use some processing tools where you filter out all the noise and then you look at only the intensity of emission of coming from the molecules and this intensity is now sensitive to how much pressure the molecules apply to that particular surface.

Primarily the existing pressure sensitive paints respond more to oxygen molecules than other molecules. Therefore, it depends. If you are using only oxygen gas as the working fluid then this kind of method will work, but if you change it to nitrogen or organ or air in general then this will not work. The existing pressure sensitive paints are mostly sensitive to oxygen molecules and therefore, for this reason only gas flows can be used to this method. Specifically an increase in the oxygen concentration causes a decrease in the intensity of luminescence and so on and so forth. Therefore, we calibrate it first to derive a calibration curve between the pressure and the intensity of the emission.

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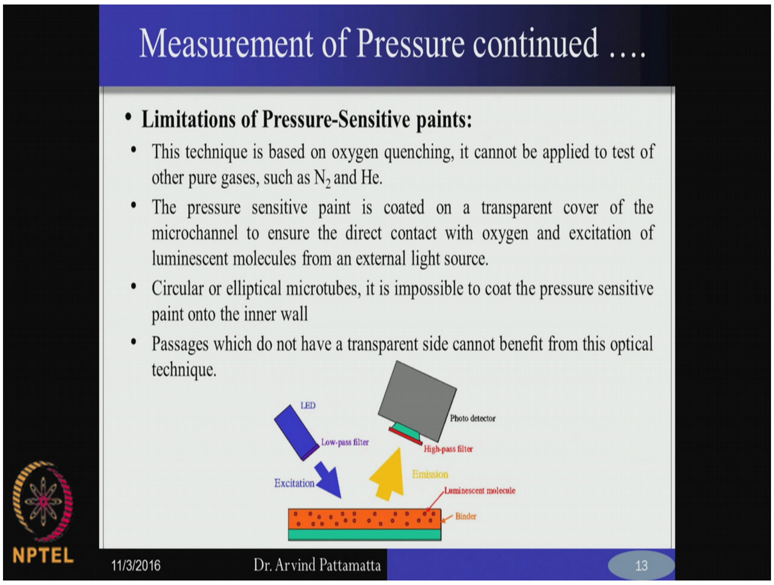

Once you calibrate then you will be able to get back, what is the pressure.

What are the limitations? This technique is based on oxygen quenching. Therefore, it cannot be applied to test other pure gases like nitrogen and helium, the pressure sensitive paint also needs transparent access. It needs an optical access because what you are doing is, you have a L E D which is emitting light and you have a photo detector or camera which is going to detect the intensity coming from the surface, but it has to passed through the optical access you know and then it should reach the surface and from which again the emitted light should travel through the optical access and reach the camera. For this, your surface should be optically accessible.

If you have an opaque surface close from all ends then again it is very difficult to do this use this technique. Passages which do not have a transparent side cannot benefit from this optical technique.

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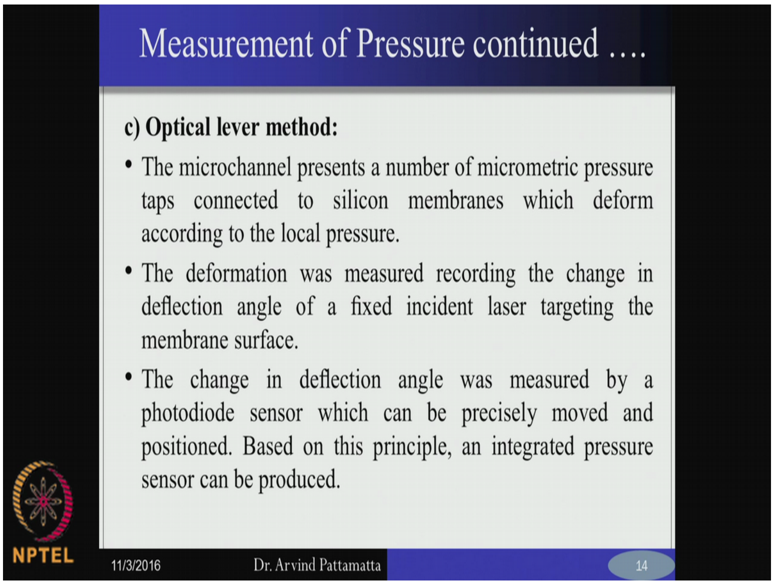

We will look at therefore, 1 more last method for measuring pressure for we stop the pressure measurement. The third method is called the optical lever method, now this is a slightly bit more sophisticated I would say methods than the other 2 methods you need a lot of investment to do this part with this method you can actually do for a large range of working fluids without any restrictions. Now, what we do is in a micro channel. You have all these pressure tapping. We take all these pressure tapping to a silicon membrane like here. This is a flexible membrane. This membrane will deflect. This deflection is proportional to whatever pressure that is falling on this membrane.

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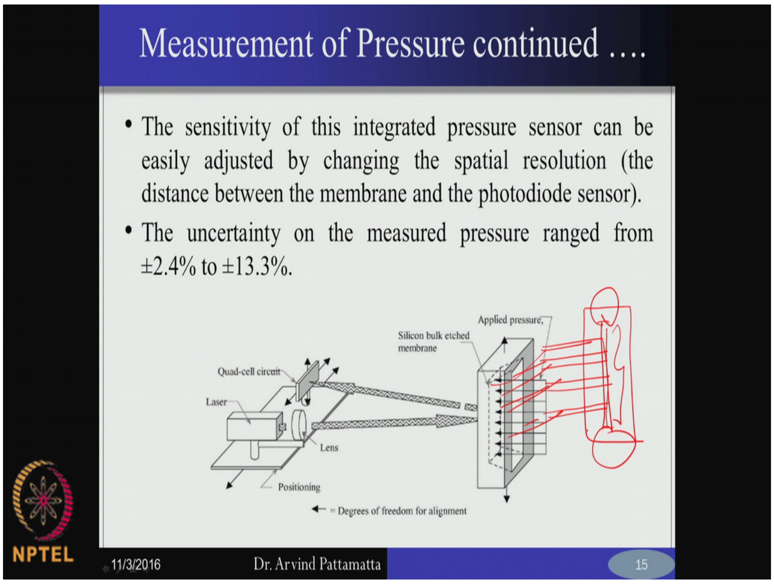

For example, if you connect few pressures taping, on to this surface, the entire surface will deflect at a differential amount depending on what is the local pressure, correct? Now, what we do is we now have to have the laser source and we have to have a sensor which can detect what is the intensity of the laser light that is reflected or deflected from the silicon membrane. A laser source will be eliminating light, laser light on to the membrane now depending on the deflection. The angle of the deflected light that is the deflected light coming from the membrane will be different.

If there was no deflection it will reflect in a particular angle. Now due to deflection this angle will change either in this way, or this way. There is a sensor which is placed there which can actually also move, which can be movable in different direction. It can actually move, travel this way, this way or this way, this way and it will detect the intensity which is deflected from the membrane and therefore, from that it can detect what is the angle at which it is actually coming from.

Depending on this angle, this angle can be calibrated to the actual pressure. Initially you do a calibration.

You know what is the exact pressure with a pressure probe? And then you know what the angle which is picking up is. You build a calibration as a function of this deflected angle and later on once you know what a deflected angle is; you can get back the pressure. This is the basic technique. The deformation is measured recording the change in the deflection angle of a fixed incident laser targeting the membrane surface. The change in the deflection angle is measured by a sensor; it is a photodiode sensor which can be precisely moved and positioned based on this principle the integrated pressure sensor can be produced. The sensitivity of this pressure sensor can be easily adjusted by changing the special resolution.

If you wanted to be very sensitive place it, very close, if the deflection is fairly large you can keep it further away and you can get reasonable accuracy and the uncertainty can be ranging from anywhere between plus or minus 2.4 percent to 13 percent. But you know this does not have any constriction over what kind of working fluid you use. Compare to the pressure sensitive paint and the tube cutting liquid, it can be a compressible fluid or can be any kind of you know fluid, but you can use this method to measure the pressure.

Student: It may be possible that at some position that deflection of the membrane as more and at the other base the deflection is possible in this case cross section yeah.

Actually what we can do is that 1 1 simple simpler way you know you do not have to really have ports. You are talking about a micro channel like this. You have the flow, now this can be attach directly to this membrane. Then the fluid locally will be sensing you know will be exhorting the pressure on to the membrane directly. You do not have to actually you can also make ports; you can also make ports and connect it like to the different points in the membrane. It is depending on how you want to do it.

If you do this then it will sense the differential deflection. Each point on the membrane will have a different deflection, depending on that it can get the pressure. But what it does is it is only directly measuring the pressure in the channel and we are not measuring the delta P. It is actually measuring the local pressure that is the advantage of this technique says any differential pressure measurement will now involve the entry and exit loses.

We will stop here and next class we will look at temperature and velocity measurements.