Multiphase Microfluidics
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Lecture - 19
Flow Measurement Techniques

Hello, in this lecture we are going to discuss about the Measurement Techniques; in particular which are useful for micro channels and specifically which are relevant for multiphase flow in micro channels.

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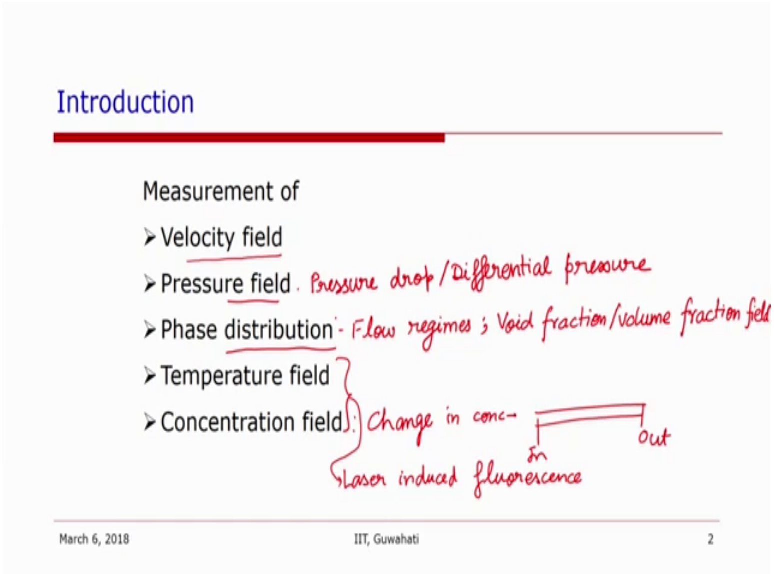

So, because for the flow measurement first we need to think about what are the parameters that we are going to measure. In micro channels it is often difficult to do point based measurement. For example, what I mean by point based measurement say in a flow, one wants to measure the velocity; then the velocity measurement for say for whose measure the speed of aircraft is done by say pitot tube and pitot tube measures the velocity at one particular point only.

Such measurement devices affect the local flow field and in micro channels it is almost impossible to have such a sensor to measure the velocity at all. Even though these sensors will affect the velocity field, but if we neglect the errors introduced in the velocity field, because of such probes even then it that the size of the probe itself will be of the micron size. So, it is not possible to do such velocity measurements in the micro channels.

So, thinking about what are the parameters that one would be interested in measuring in micro channels. And most of these parameters except say a pressure measurement, one would be interested to measure these parameters as a whole field measurement; that means, one would like to have information of the parameters as detailed as possible.

So, for example, when we plot the information that we get from computational fluid dynamics, if we are able to get all that information from the measurements, then we can validate our CMD simulations as we as we can use this data to develop accurate models and design efficient devices.

So, thinking about the equations or the Navier-Stokes equations we have 4 equations the continuity equation as well as the conservation equations, momentum conservation equations. And these 4 equations are solved to obtain the flow field in a isothermal flow for incompressible fluids. So, the unknowns in this are velocity field and pressure field.

So, those unknowns if we can measure while it is not possible to a measure or where, while there are very few techniques available which can measure the pressure locally, but recently there are techniques being developed which can measure the pressure locally, but if you look at the literature there are very few articles available where the local field local pressure field measurements have been performed.

So, what we are interested in to measuring the velocity field or the three components of velocity and pressure field if possible, if not possible pressure field then the one would like to definitely measure pressure draw or differential pressure between the two points. So, at the entire channel cross section, because the flow that we are focused about is a multiphase flow and in a multiphase flow as we have seen throughout the course the heat transfer the pressure distribution, the velocity distribution is strongerly coupled with the phase distribution, where the gas phase is present and where the liquid phase is present.

So, based on this we need an accurate prediction of the phase distribution. So, this phase distribution can be in form of flow regimes, which is the first cut information that we would like to have and then we would also like to know the void fraction or the volume fraction of the phases, when the temperature field.

So, if you look at the now we discussed about the velocity and pressure fields and then for multiphase flow we also need to know the volume fraction field now if that temperature is an important parameter; that means, if the flow is non-isothermal there is heat transfer involved and we also need to know the temperature field.

But as you have seen and as we have also discussed during heat transfer in the Taylor flow regime and during boiling that measurement of temperature in the liquid is rarely done. Generally it is the measurement of the temperature of the wall is performed it may be by using thermocouples or more recently by using IR cameras; the measurement of the wall temperature is performed.

So, the wall temperature is obtained easily, but obtaining temperature of the fluid is challenging there are some experiments have been performed and they are increasingly being performed using LIF laser induced fluorescence. So, where a dye is introduced in the liquid, which emits the fluorescence light or which emits the light whose intensity or the intensity of the light is a function of temperature. So, one can measure the temperature of the liquid in such a case.

So, one also need to know the temperature field and for mass transfer applications one need to know the concentration field. So, again most of the measurements of concentration are based on the point measurement that one major change in concentration, that is concentration at the inlet and outlet the distribution of the solute in the channel or local distribution of the species is not known really in such a case.

So, again increasingly the use of laser induced fluorescence with suitable dyes is being used or it is to measure the local concentration field as well as.

So, the temperature field and concentration field they can also be used by using they can also be measured using laser induced fluorescence. So, as most of this discussion or the velocity field pressure field they are coupled with phase distribution in multiphase flows. So, let us discuss about phase distribution first before we do that.

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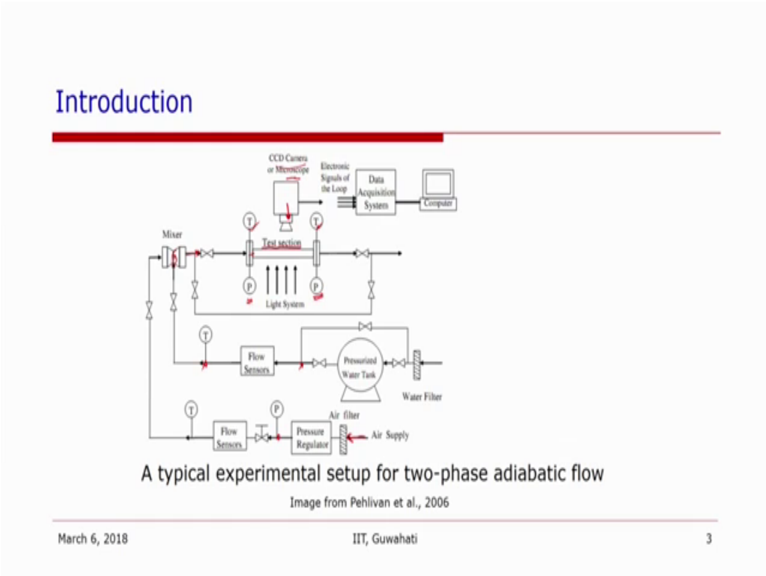

Here is a typical experimental setup of which is used in most of the experiments where there is only adiabatic measurement of the flow. So, this is the test section and in this test section the air if it is gas liquid flow the air is supplied from a source or it might be either from a compressor or from a cylinder and then the pressure is measured at this point the flow is measured and this comes into a mixing device, the water comes through a mass flow meter the temperature of water is measured and the two phases is mix in this mixer.

Now, in some cases the mixer can be in the test section itself which is good because then the channel dimensions are not going to change. So, then these mixers they the flow from here comes in and it is passed through the channel cross section. And then the pressure differential using the two pressure terms as a measure the temperature at the inlet and outlet in measure and the images of the pick test section or the flow in to test section is taken using a CCD camera with either a zoom lens or a microscope, because it is not possible to get good enough resolution using just using the camera. So, one either need a zoom lens or a microscope to do the task

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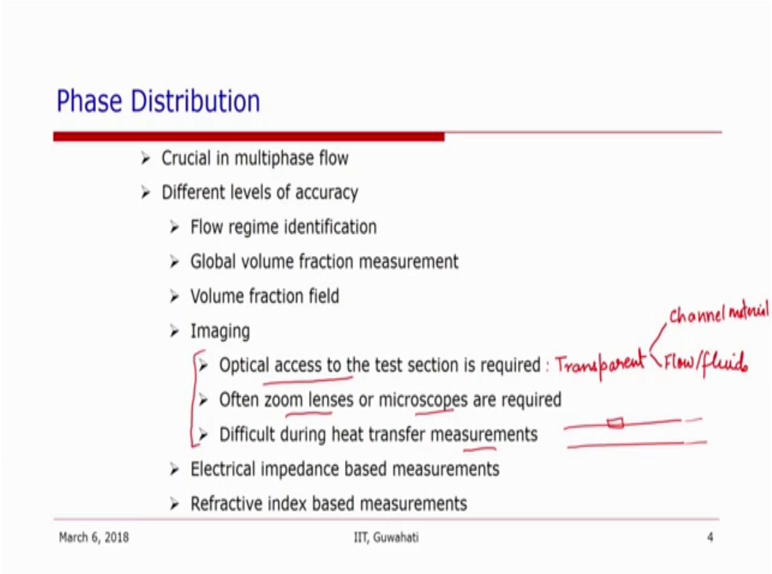

So, for the phase distribution of course if one can image the system then one can get the phase distribution. So, for imaging one needs optical access to the test section, by optical axis I mean the test section should be transparent.

So, the transparency is required that the channel should be of a transparent material, as well as the flow should also be or the fluids they should also be transparent. For example, if there is there are a large number of bubbles present in the channel, then the visibility inside the channel will be affected and it will not be possible to obtain the images at of what we will get is the images at the wall of the channel and not at a particular cross section in the channel.

So, of course, this task in micro channels we require zoom lenses or microscope, then we perform heat transfer experiments often it is required to supply the heat through the channel wall. So, when we supply the heat through the channel wall it has to be covered by a metallic or electrical heater. So, the optical axis to channel in such cases is restricted and often the measurements or the optical axis is obtained either making a small section visible, in such test section or looking at the flow field looking at the imaging the system just downstream the heated section.

So, these systems are based on the imaging or optical imaging then one where optical imaging is not possible one can also measure the phase distribution, based on the properties of the two fluids which have good enough contrast the properties, which are significantly different in the two phases.

For example, one can measure the electric impedance of the 2 phases, that can be the measurement of resistance, the measurement of capacitance, or the measurement of inductance the most common ones are the measurement of electrical resistance and it is easier to cheap and build one just need to put in the wires and then one can get the cross sectional averaged resistance of the phases it is or the other technique is based on the refractive index based measurement.

So, the refractive index of the phases if they are different then with the development in the techniques, which can capture very sensitively the variation in the refractive index then those techniques can be used again to get an estimate of the phase distribution.

So, when we have optical axis to capture the image we generally need to use cameras and these camera need to be very high resolution and high speed camera also. So, there are in presence of specifically two types of cameras, which are used one is called CCD and another is CMOS and these names of the cameras are based on the sensors that we use.

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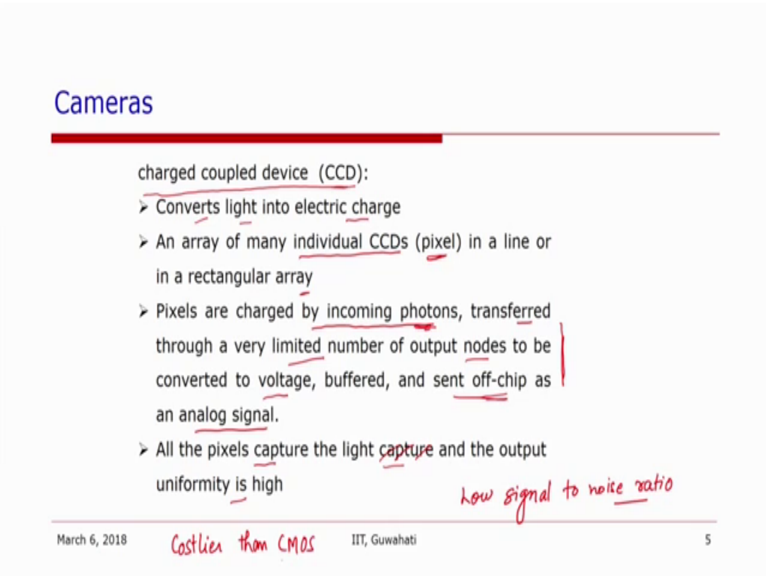

So, CCD camera is based on a charged coupled device which is in short is called CCD. So, the CCD camera converts the light into electric charge, based on the photoelectric effect and the CMOS sensor is also based on the same principle.

So, in the CCD camera an array of many individual CCDS or many individual the sensor elements they are arranged either in a line or in a rectangular array and then and this is element is called a pixel these pixels are charged by the incoming photons.

So, the charge this charge is transferred through a limited number of output nodes which is converted to the voltage and this voltage is sent off as an analog signal to the computer.

So, this the speed of the CCD camera is limited by the number of outputs; and through which the signal can be sent. So, the frame rates that can be achieved in a CCD camera is limited. However, they have because all the pixels capture the light and the uniformity of the output is high. So, they have low signal to noise ratio and the picture quality that one get using CCD camera is better, especially in the low light CCD cameras are known to perform better than coms also or CMOS counterparts.

But for their manufacturing a special technique is need to be used so, they are costly they are costlier, than the CMOS counterparts CMOS cameras which is complementary metal Oxide Semiconductors.

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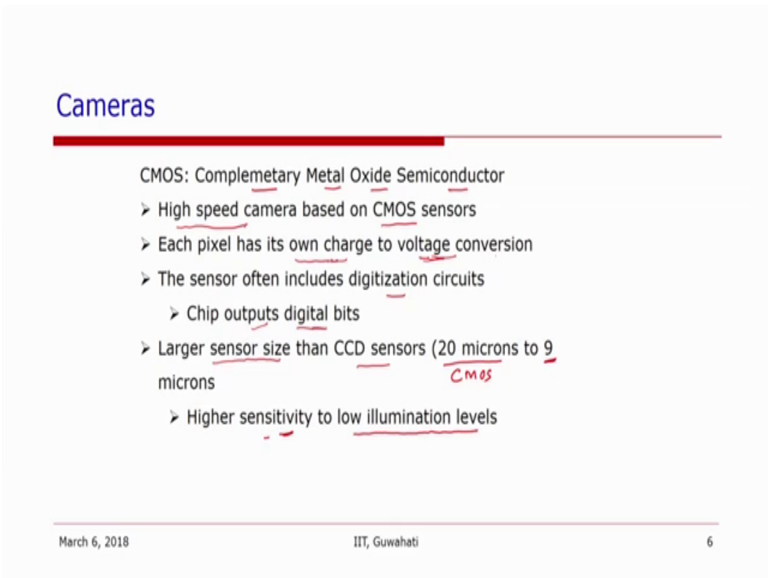

So, they have the semiconductor sensors and again these semiconductor sensors they has they have it is own charge to voltage conversion devices. And so, each pixel or each sensor has charge to voltage conversion device and then this sensor itself has a digitization circuit. So, there itself the voltage is converted to digital bits. So, it is it the rate of transfer can be high. However, the sensor size in CMOS cameras is larger than the CCD ones. So, a typical CMOS camera will have 20 micron whereas, a CCD camera sensor will be 9 micron.

So, the sensitivity of to low illumination levels is high. So, they might perform poorly or they perform poorly when you compare with CCD cameras in lower light. However, they can have very high speed thousands of frames per second or at and at low pixel or at low resolution they can even go to up to half a million frame rates per second.

So, most of the high speed applications are based on CMOS cameras and with the new development in the camera technologies these days, the sensors are being developed which combined the good of both of words, which can use CCD camera technology for the better resolution and the CMOS technology for the better or the high speeds.

So, these cameras they need to be used along with zoom lenses or microscopes. So, the simplest microscope that is used is based on bright field microscopy.

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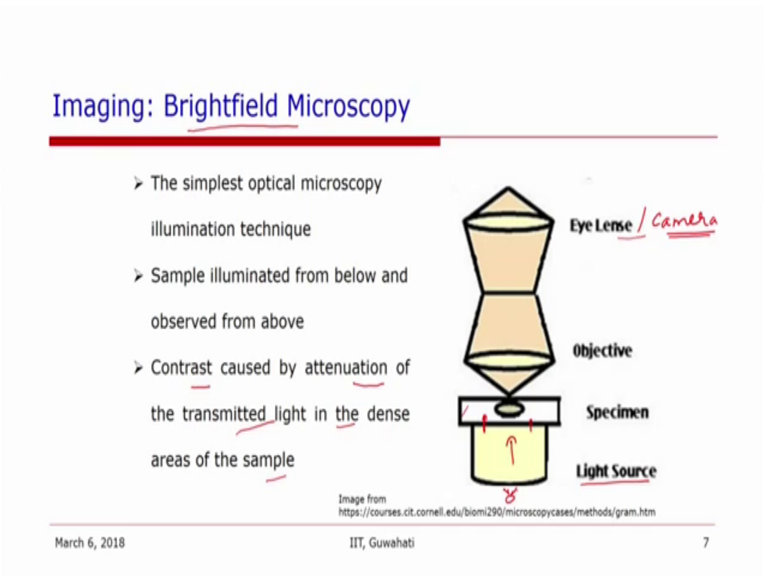

So, the bright field microscopy is that a light source emits the light from the bottom. So, the test section is here and the light is emitted from the bottom and it is visualized either through eyes or a camera. So, of course, when we want to do the measurements and recorded we need a camera.

So, the recordings were made will be done from the other side and the illumination will be done from the below and observed from above. So, this results in the contrast by the attenuation of the transmitted light that is transmitting being transmitted through the test section in the dense areas of the sample. So, you see a good and contrast image of the sample.

Now, this will be dependent on because these are not static images we have flow happening in this. So, we need to look at that the camera should have a sufficiently short camera's at a time.

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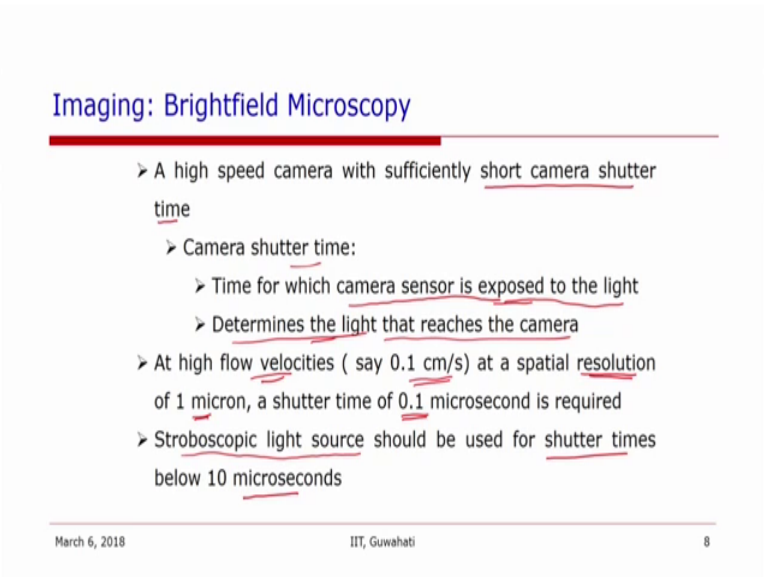

So, for those who do not know what the camera shutter time means, it is the time for which a camera sensor is exposed to the light when the picture is being taken. And this determines the exposure time it will determine the light that will reach the camera.

So, at high flow velocities and this exposure time so, when we look at the exposure time that will be determined by the resolution that we want and the flow velocities that we want to capture. So, say for a flow velocity of 0.1 centimetre per second and the spatial resolution of one micron a shutter time of around 0.1 microsecond is needed.

Now, the illumination that happens is generally using a continuous light sources. However, at low shutter times or smaller shutter times less than 10 microseconds it is preferred if one have a stroboscopic light source so, that the illumination can be matter and enough light is provided to the camera.

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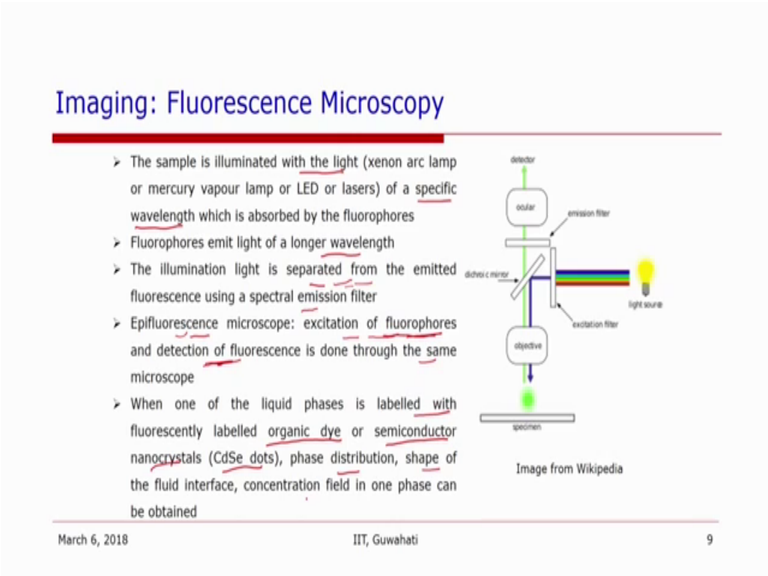

So, the simplest method for the illumination or and the visualization is bright field microscopy. However, that met that is not always good enough to take the pictures or to get the better resolution. So, the fluorescence microscopy is often used and it has a number of applications specifically with respect to diagnostics in micro channels one can measure the void fraction distribution, one can measure the flow velocity, one can measure the temperature field, one can measure the concentration field, using fluorescence microscopy.

So, the fluorescence microscopy in this the sample is illuminated with a light, which is often of a specific wavelength. So, this light is monochromatic light this can be done using a sub say xenon arc lamp or mercury vapour lamp LEDs or lasers and this light, which is incident on the sample and this sample exceeded sample means the flow. One of the phases of the flow often the liquid phase or the continuous phase, exceeded with fluorescent particles or which are called Fluorophores. So, these fluorophores they absorb the incident light and then emit the light.

Now, when they emit the light the emit the wavelength of the emitted light and the energy of the emitted light is different from the energy the light of the light, that is incident of course, the energy of the light that is emitted will be lower than the light that is incident. As a result the wavelength of the emitted light will be higher than the light that was incident.

So, the fluorophores they emit light of a longer wavelength, when the light is incident on it. And this light is collected and goes to the detector, which may be a camera using a dichroic mirror and emission filters the illumination light the light which was being used for illumination is separated from the fluorescent light.

And in epifluorescence microscope this is both the lights which is used for the excitation of fluorophores, and detection of fluorescence both are done in the same microscope epifluorescence microscope is where the excitation of fluorophores and the detection of fluorescence both are done in the same instrument, it is called a Epifluorescence microscope.

So, it is basically that the images are taken of the fluorescent particles. So, based on the intensity of that fluorescent particle one can capture a field. And if this intensity of the emitted wavelength or the emitted light is temperature dependent then one can measure the temperature field. If it is concentration dependent then one can measure the concentration field and if it is not dependent on such parameters then one can measure the distribution of one phase.

So, it is often used and this technique is also used or epifluorescence microscopes are also used for micro PIV applications, because the illumination in micro PIV is the volumetric you know illumination, unlike a general PIV, or 2D PIV, where the illumination is through a light sheet. So, we have discussed the we will be discussing the details in a separate lecture about the PIV.

Now, this liquid phase can be labelled with either a organic dye or semiconductor nano crystals for example, CdSe dots and then one can obtain phase distribution shape of the interface and concentration fields etcetera.

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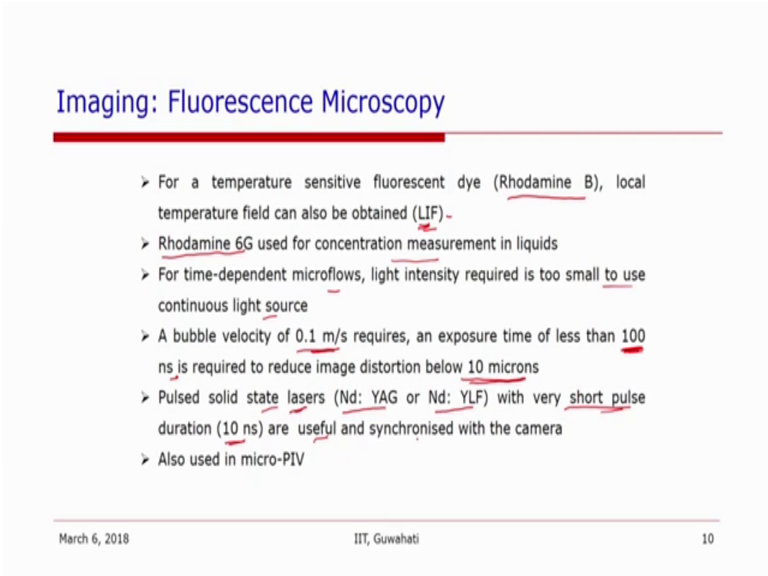

For temperature measurement a dye named as Rhodamine B is used which can be used to measure the temperature field and this technique is known as laser induced fluorescence or LIF to measure the temperature for concentration measurement in the liquids the dye that is used is called Rhodamine 6 G, for now in micro channels the intensity of the light is very small. So, one often does not use a continuous light source, but rather a pulsed light source is required. For example, a bubble velocity of about 0.1 meter per second and exposure time of less than 100 nanosecond is required.

So, that the resolution is below 10 microns. So, when such high x such high temporal resolution is required, then one need to have pulsed light source, which are often also used in micro PIV and PIV application. So, the two common light sources are Nd: YAG and Nd: YLF solid state lasers, which can have very short pulse duration up to 10 nanoseconds and they are useful and the trigger of the pulse is synchronized with the camera.

So, we need a synchronizer to synchronize the pulses that when the camera shutter opens and when the light is triggered from the laser and the same technique is used in micro PIV as we have just discussed.

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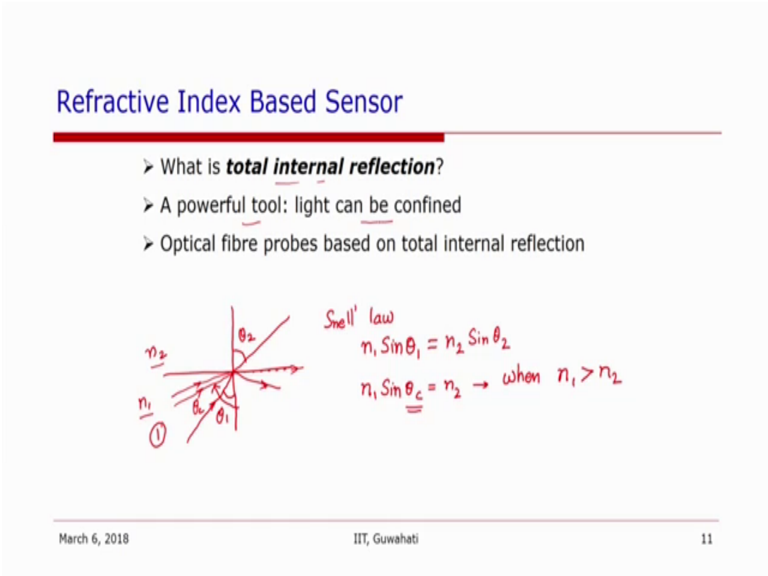

So, now other technique till now we have discussed about 2 microscopes and cameras. So, these systems can use the microscope that can image the flow and from this one can obtain the volume fraction field in the channel, using a temperature sensitive dye one can obtain the temperature field, using a concentration sensitive dye one can obtain concentration field.

Where the optical axis is not there then there are different other techniques one can use so, one is say based on refractive index based sensor. So, as we know that as the light enters from one medium to another the part of the light is reflected and the part of it is reflected. So, what is total internal reflection?

So, we have let us say 2 mediums medium 1, where the refractive index is n 1 medium 2 where the refractive index is n 2 and the light is incident at an angle theta 1. And it goes out at angle theta 2 and we know from Snell's law that n 1 sin theta 1 where theta 1 is the incident angle and 2 sin theta 2 theta 2 is the angle of reflection.

Now, if we keep increasing theta 1 then at one particular angle let us say theta c the reflected light that light will not respect anymore say if we have this n 1 sin theta c is equal to n 2.

So, of course, this is true when this is only pass possible when n 1 is greater than n 2. So, this at this critical angle the light will not reflect anymore and for a higher angle the reflection will be there.

So, that is what is meant by total internal reflection that their light does not reflect any more it reflects. So, this is a powerful tool based on which the light can be confined and the optical fibber's and optical fibre probe probes are also based on this technology or based on this principle total internal reflection.

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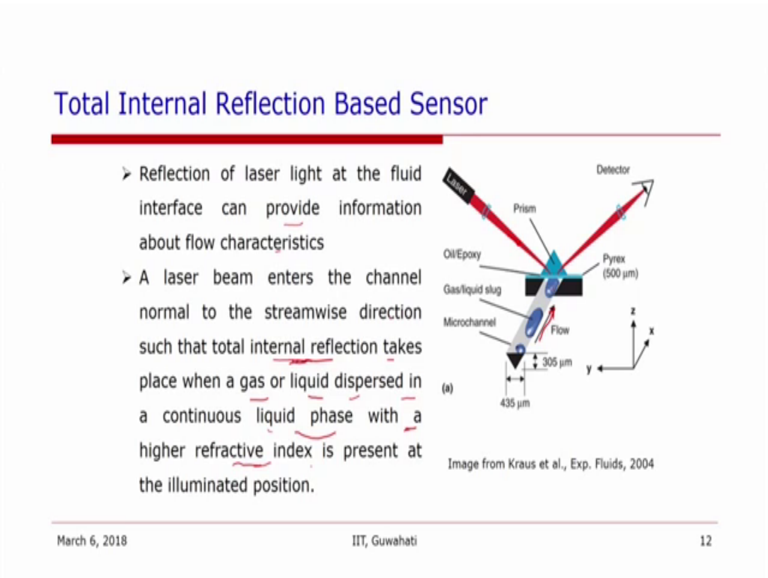

So, one of the techniques that have been developed is that the reflection of laser light, at the fluid interface it can provide the information about the flow characteristics.

So, in this case a laser beam enters the channel normal to the flow direction, at such an angle that the total ref reflection, total internal reflection takes place when a gas or liquid which is dispersed in a continuous liquid. So, it might be either a gas phase or liquid phase which is dispersed, that when a gas or liquid phase dispersed phase it passes through and this is dispersed in the continuous liquid phase; which has a higher refractive index is present at the illuminated positions of the.

It is done in such a manner that when the dispersed phase passes through and the dispersed phase should have a lower refractive index than the continuous phase. And it should come at such a angle light should come at such an angle that the total internal reflection can take place.

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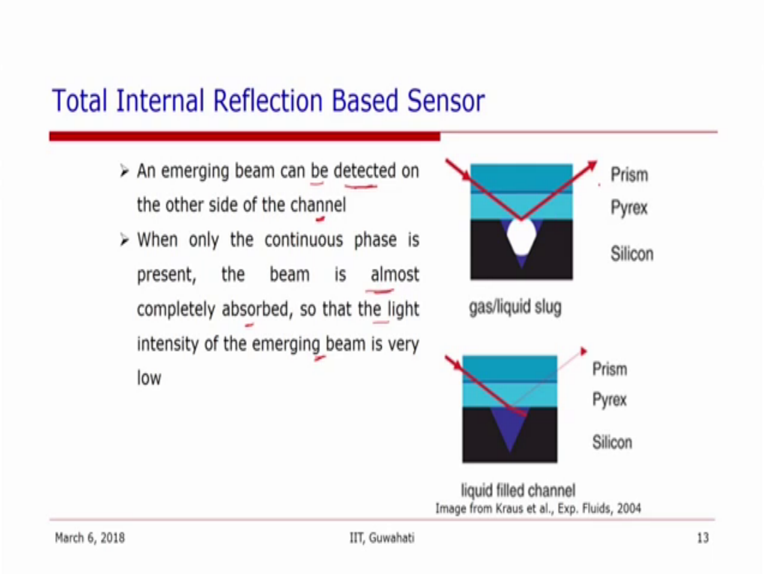

So, by detecting the emergent beam on the other side of the channel; one can obtain the phase distribution. So, when only the continuous phase is present, the beam is almost completely absorbed there is no nothing happens.

So, that the light intensity of merging beam image very low in such a case where as it will it may not be the case in case of when the liquid passes. So, based on ref changes in the refractive index one can obtain the phase distribution.

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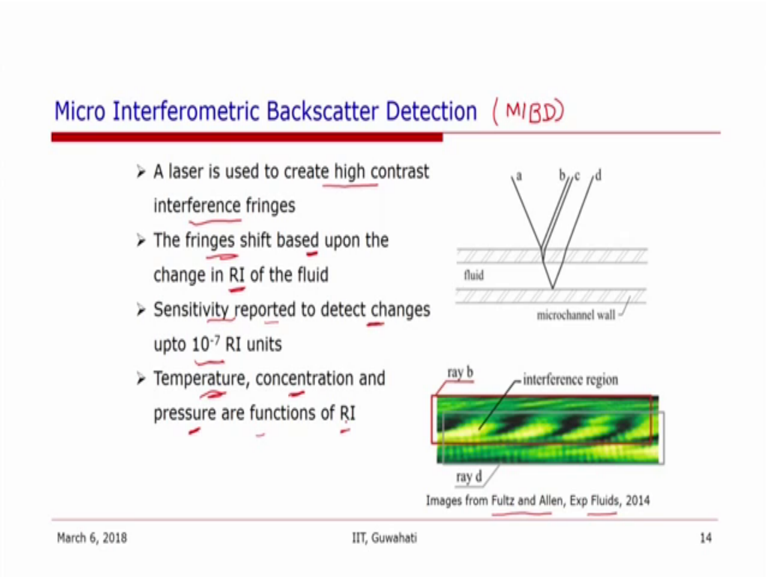

Now, another technique, which is known as MIBD or Micro Interferometric Backscatter Detection so, in this case a laser light is used to create high contrast interference fringes. And the shift in fringes is based upon the change in refractive index of the fluids. So, because the two fluids will have different refractive indices so, based on the fringe shift one can measure the change in the refractive indices and change in the properties of the fluid.

So, the technique it has been reported the sensitivity it can the technique can detect the changes up to 10 to the power minus 7 of refractive index units. And this technique can be used to measure temperature distribution concentration and pressure distribution as a function of refractive index. So, in this work by Fultz and Allen recently, they have developed a technique to measure the local pressure distribution in a channel by this technique by MIBD technique.

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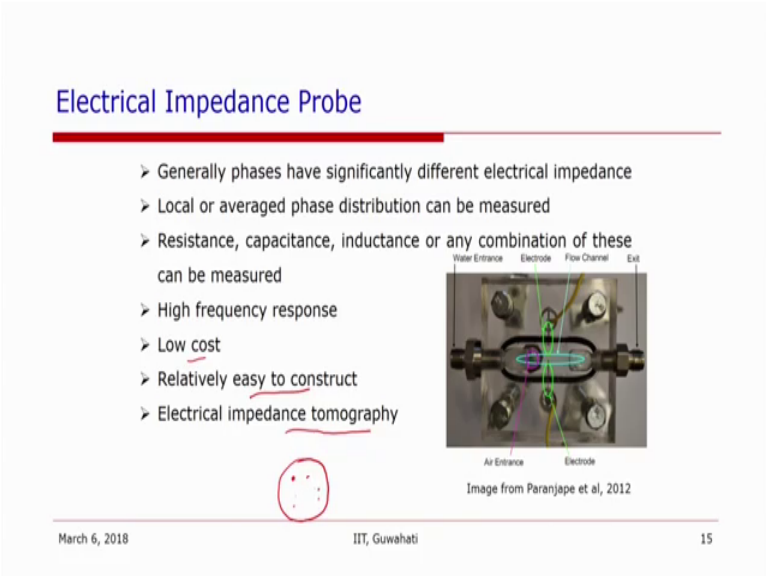

So, the other technique that can be used apart from imaging and refractive index change is based on the change in the electrical properties of the two fluids that when one fluid say gas and liquid they have a very different electrical conductivity or resistivity or electrical capacitance.

So, if one can have a probe which or one can have wires two wires through, which the which connect the 2 ends of the channel. And if this voltage or the resistance is measured and from this measurement of resistance one can know the change in the phase distribution, or one can know the phase change at one particular location with respect to time.

These probes are easy to construct, they are low cost and if a number of electrodes are used then with reconstruction algorithms, one can use these techniques as tomography techniques, where one can determine the entire 2D field at a cross section using tomography. So, one can reconstruct the phase distribution at the entire section using the using a number of probes which is called tomography technique.

So, based on this a number of velocity measurement techniques are also developed for velocity measurements in micro channels. Now most of the techniques which are used in micro channels for velocity measurement or otherwise are non-intrusive, because as we have discussed and the start of this lecture it is not possible to do the point measurements in micro channels.

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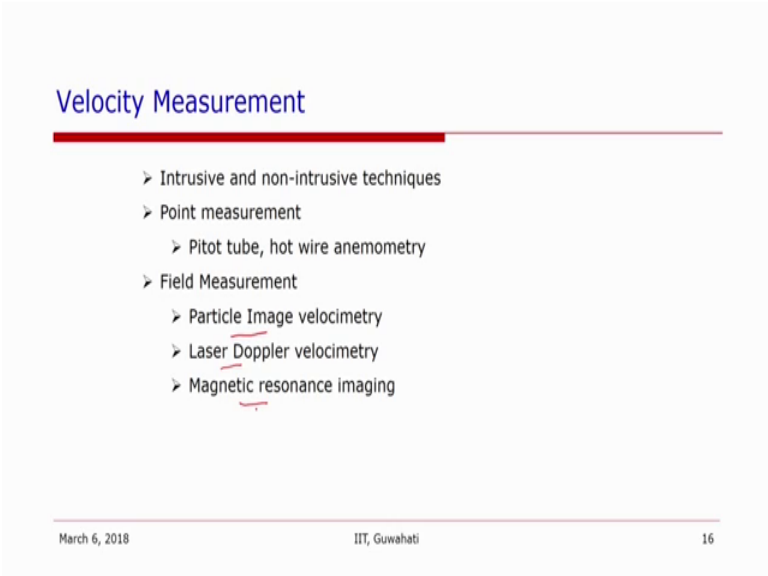

So, some of the popular techniques are particle image velocimetry and the related technique particle tracking velocimetry, then laser Doppler velocimetry, and MRI or Magnetic Resonance Imaging. We will discuss micro PIV or Particle Image Velocimetry in a separate lecture.

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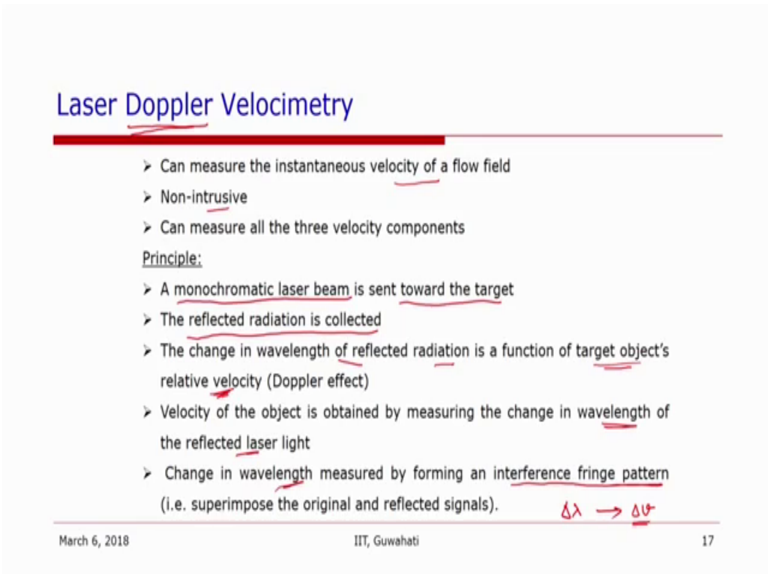

So, it has a brief discussion of laser Doppler velocimetry, in this technique like micro PIV; it is also non-intrusive and it measures the instantaneous velocity of the flow fields.

So, one can measure the velocity in the space as well as in time and in one can measure all three components. So, full 3D velocity with temporal resolution.

So, it is again a powerful technique it is based on the as one can guess from the name it is based on the Doppler principle and the wave that is used for it is a monochromatic laser beam, it is sent towards the target and the light that is reflected is collected and the change in wavelength of this reflected light is of course, a function of the relative velocity between the target object the relative target objects relative velocity with respect to the source.

So, based on the Doppler Effect this relative velocity can be measured and then velocity is obtained by measuring. The change in wavelength of the reflected laser light this change in wavelength is often measured by interference fringe patterns by superimposing the original and reflected light. So, from that one obtain the delta lambda and from delta lambda one obtain the. So, what is delta v or the relative velocity? So, that is the principle may have laser Doppler velocimetry.

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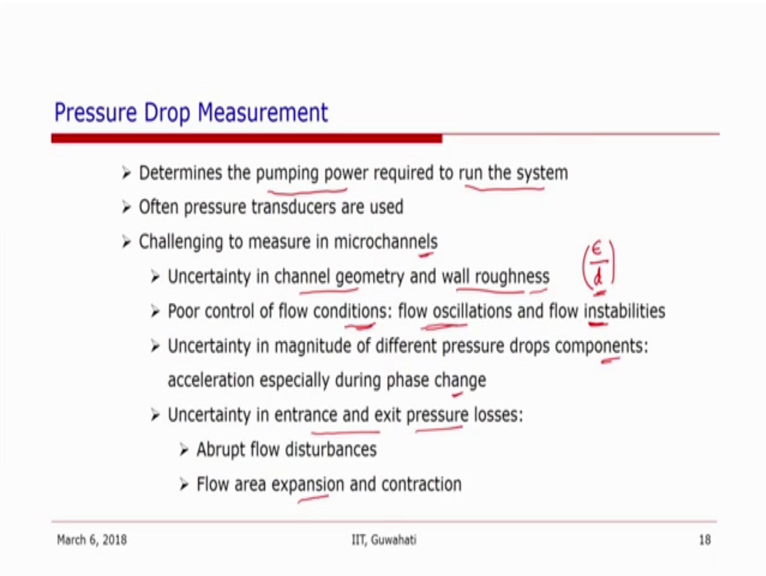

Now, coming to the pressure measurements the pressure measurements is a difficult bit, but it is very important bit because it is required to determine the pumping power to run a system. So, it is always required to design a system efficiently, one need to have an idea about the pressure drop that happens in channel. Often pressure transducers pressure transducers, which can capture the low changes or small changes in pressure are used and depending on a particular system one can estimate the range of pressure changes, that are that should happen in the channel and accordingly one should select a laser transducer for a particular application.

It is particularly difficult in to measure pressure changes in micro channels, because one is the channel geometry and wall roughness. So, specifically as we have discussed earlier also that the roughness of the channels can be an important factor in micro channels, because the roughness which is let us say epsilon over d the channel characteristic might be negligible in a small in large diameter channels, but this is something which can be important in large channels.

So, the pressure drop is of course, being will be a function of roughness so, that is one factor. Then that experimental test tricks that are developed for micro channel applications if not developed carefully they are often susceptible to flow oscillations and flow instabilities and the pressures that are being measured they are small pressures.

So, a even a small change or small oscillations in the flow or small instabilities they can cause errors large errors in the pre measurements and then specifically during the phase changes. The accelerational pressure drop which is a large component of the pressure drop when the phase change happened, because the because the areas occupied by different phases keeps changing along the length the accelerational pressure drop is a important component of the pressure drop.

So, that the different magnitudes of pressure drop component is difficult to obtain in specifically in micro channels, because no particular correlations are available which can relate the void fraction will the change in the pressure drops. Apart from that there are entrance and exit pressure losses, which happen in micro channels also, in a large diameter or micro channels also, they can be because of expansion or contraction or the flow distribution where the two phases mix.

So, pressure drop measurements are generally done using pressure transducers, but one need to take into account all these factors so, that the accurate pressure drop measurement can be obtained ok. So, with that we can summarize that one of the or the techniques in micro channels are based on where one wants to have the good view of the flow field and the phase distribution and that is possible using either bright field microscopy or fluorescence microscopy.

For void fraction measurements the techniques are being developed based on the electrical impedance changes, total internal reflects will reflection or based on the changes refractive, indices and these techniques have potential to measure the local temperature and pressure distribution also.

So, with that we have an overview of flow measurement techniques in micro channels, in another lecture we will discuss briefly the micro particle image velocimetry technique and it is basic principle.

Thank you.