Multiphase Microfluidics

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Lecture – 22
Microfluidics: Applications

Hello. So, we are now about the last stage of this course and in this lecture and the following lecture, we will be discussing about the different applications of Microfluidics and these applications may include the applications which are at the research stage, which have been already realized in the industrial applications or some of the potential application that they have potential application, but have not been explored fully yet.

These applications may be of the particular focus that I have tried to keep is on multiphase microfluidics, but some of these applications can be op of microfluidics in general as well.

So, the microfluidics has the potential to impact in a number of a spheres of our day to day life and I have listed some of these applications in this slide. This list is by no means and of adjustable list.

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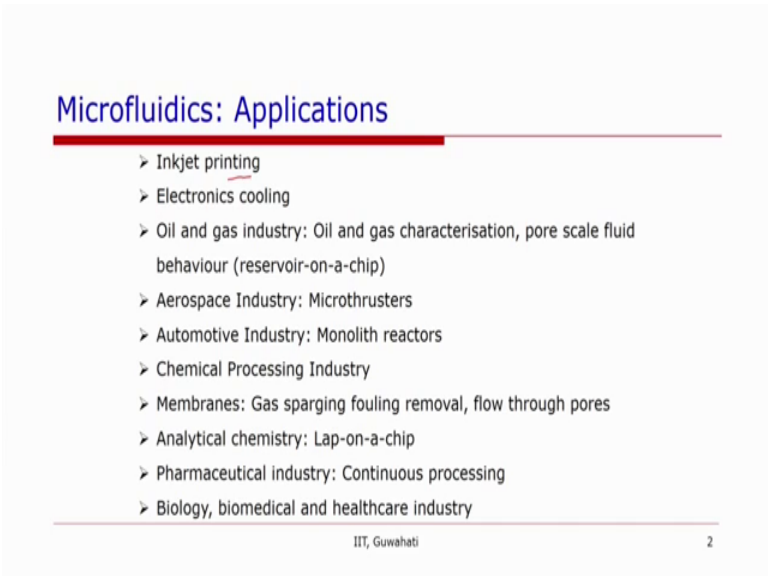

So, the first application I have listed is Inkjet printing and we will be talking about it in a bit detail later on. So, inkjet printing is the printing technology that we all of us have heard of and it is widely used for office and desktop printing apart from the newer application that the technology is finding every day.

Another application Electronics cooling; so a lot of research on boiling and heat transfer in microfluidics or 2 phase fluids in a flow of 2 phases in micro channels and boiling in micro channels is driven by its application in the electronics cooling industry. In the electronics cooling, we need to remove very high heat fluxes and the space constraint. Due to the space constraint, we need to have the compact heat transfer mechanisms.

So, the Electronics cooling has lot of applications of microfluidics or micro channel based exchanges. Then in the Oil and gas industry though the potential of it is not fully explored, but as the oil reserve oils which contains the oil the systems that are used in the oil an industry for the drilling and exploration, they are of course, gigantic if not and they are of considerable size and then, they cannot be by any means micro channels.

But the reserve oils in which the flow takes place the pores they are of the micron size and lot of research in the oil and gas industry. A lot of research in the flow of about flow in micro channels has been driven before the advent of microfluidics or before the considerable effort in microfluidics took place. Lot of research say for example, on Taylor flow in micro channels or Annular flow in micro channels or Capillarity in micro channels barrage driven by its application or to develop models for reservoirs.

In the Aerospace Industry; so, the goal in the aerospace industry is to achieve high performance having while having the system to be very compact system because one need to reduce the payload or one need to reduce the load that it want to carry for any system. So, the aerospace industry always looks for the solutions which can provide compact system designs and one of that is say Micro systems and apart from that say combat heat exchangers micro thrusters etcetera is also in the aerospace industry.

Automotive Industries; in the automotive industry one of the most common applications is monolith reactors which are used for capturing the exhaust gases from the engine. Then, in the Chemical Process Industry, as we have discussed during the course that there are a number of applications in the chemical processing industry and when it comes to multiphase flows in general, there is the drive towards micro processing where one want to achieve high interfacial area density.

So, example microwave operators, micro contactors, micro distillation column or gas liquid reactions where the reaction is limited by mass transfer or the diffusion limited reaction. So, the diffusion paths are small and the interfacial area density is high, so chemical processing industry. Actually, in the chemical process industry the drive is towards developing the entire plant based on the micro reactor systems or a micro channel system.

So, one need to develop while there has been lot of work on developing micro reactors, now the drive is towards a scaling up or better to say numbering up of these reactors and developing additional and sillier is to integrate the plant and the system into a chemical plant then, in Membranes. So, we have a number of different membranes where fouling is an issue and the gas sparging has the sparging of gas by having bubbles which create the fluctuations in the flow and as a result the wall shear stress on the membranes. So, that also have an application in membranes. Apart from that the flow in the membrane pores, the pores are of micron sites if we want to understand what is happening at the pore level. Then, one need to understand this using microfluidics or microfluidic systems.

Then, the 2 most common applications from which the microfluidics has grown in the past few decades are in the Analytical chemistry and in biology and biomedical and health care industries.

So, in analytical chemistry, where were want to deal with a small amount of the agents which may be carcinogenic or which may be which not we are not be so safe or risk is high or the cost is high.

So, in such cases one can deal with we call it a Nano liter volume of the droplets and do the reactions one can also have flow chemistry solutions has come up for from microfluidics to do flow chemistry in micro reactors.

So, that is another application in biology one can have because of the predictive power and the control that one can have in microfluidics, a number of applications are there and people are looking to use it for separation techniques, cell separation or a number of a DNA separation or a number of other applications.

In Biomedical a number of diagnostic devices are being developed for especially the remote area applications where one do not need to use the laboratory high end machines in the in the laboratories. But one can use the diagnostic devices, microfluidics base or lab on a chip based devices for the different diagnosis.

Then, when we come to the our Physiological systems, the Cardiovascular system or Lungs, they all have micro channels, the arteries apart from the larger arteries; for example, Aorta, the Capillaries and Venules, Arterioles.

They are all of micron size flexible channels and to understand the flow and understanding the rheology of blood in such systems, understanding the air flow and the mucus air interaction and so on.

One need to develop micro fluidic systems which can mimic such physiological system and one can understand the flow behavior and different flow and biological reactions interactions etcetera in those systems.

Apart from that in the tissue engineering when one wants to develop the issues or the then, one need to have an understanding and that also is part of microfluidics. In the pharmaceutical industry, the continuous processing most of the things that in happen in the pharmaceutical industry most of the reactors R batch reactors because of the small amount of volumes that are generally handled and the use of the reactor for a different for a number of different reactions.

So, the industry prefers batch reactors, but the there are certain distance disadvantages in the batch reactors. For example, one may not have very uniform uniformity in different batches that are there and continuous or the cleaning time etcetera.

So, there has been in recent years or drive from some of the pharmaceutical industries also to look for the continuous processing method for pharmaceutical applications. For example, Novartis collaborated with MIT to develop continuous processing solutions for some of their applications.

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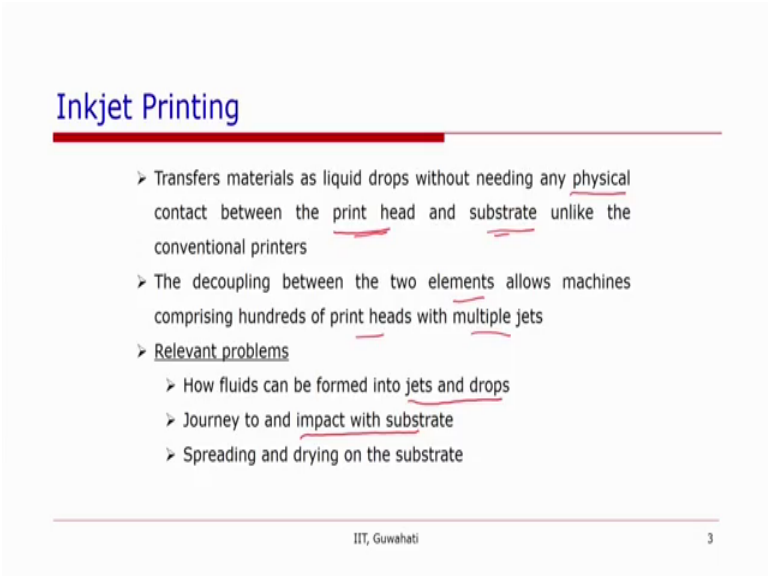

So, let us look at a bit in an Inkjet printing which is an interesting problem and interesting application of some of the things that we have learned. And it also gives us a number of problems that we can further study on based on the physics that we have learned in this course. So, Inkjet printing is different from the conventional printing in that; when we have conventional printing generally for printing a newspaper or printing a books, a master pattern is prepared and then, from that master pattern it is transferred a number of times to the paper or the book or the or the cloth on which it is to be printed.

The inkjet printing is different in this manner that in this the jet of ink from the jet of ink or the droplets of ink are deposited on the surface and this deposition takes place without a need of the physical contact between the print head from where the ink is being ejected and the substrate or the surface on which the printing is to be done.

So, there is no master pattern here and one can do the same thing or one can print the same thing again and again or one can change the printing pattern every now and then. So, that is one of the biggest advantage that inkjet printing has. It decouples the print head and the substrate elements and allow machines comprising hundreds of print head with multiple jets. So, one can scale up these print heads and do and using multiple jets do the required printing.

Now,. So, as one can think of that in the inkjet printing, the jet of ink is generated or the droplets of ink are generated and then these droplets are deposited on the paper on the cloth or on the tile on the surface on which the printing is to be done. So, we need to understand because the printing requires very fine length and time scales to be dissolved.

The accuracy or the or the refinement of the printing would come when the exact amount of droplet volume, a very small amount of droplet volume can be deposited on a surface accurately and then, this droplet can be evaporated in the minimum possible or the in the required time in any time which can be estimated beforehand.

So, the entire process depends on the accurate knowledge of the physics that is involved there and there is lot of microfluidic knowledge a lot of multiphase flows bubbles not bubbles; but, droplets and the flow of droplets and the interaction of the droplets which involve. So, we can divide these problems into three categories. First, the generation of jets and droplets. So, in the continuous inkjet printing for example, one will have jet and from these jets the droplets.

So, the formation of jets and droplets from the fluids and then, this droplet will travel to the surface. So, the travel time, the travel path and if the droplet is to be discarded or is to be collected or is to be deposited on the surface and the time between the 2 droplets all those will come in the journey. So, from the jet to the or from the print head to the substrate the journey of the droplets and then, spreading of the droplet on the surface and its interaction with the droplets adjacent to it and finally, the drawing of the substrate.

Now, the technology has been developed in 3 phases or what we can say that the development of inkjet till date can be divided into 3 periods.

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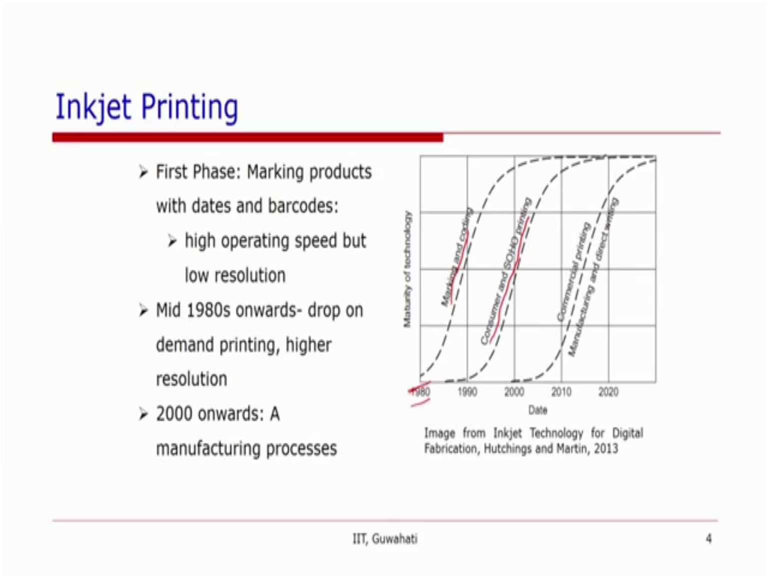

The early developments for the inkjet were about 70s and 80s where, it was developed to mark and code to develop or to have barcodes for the food products or to do the print the dates and prices on the packagings.

So, these were the applications where one needed high speed the same job has to be done again and again and it has to be done at high speed. But, high resolution is not mandatory and the technology matured slowly then, mid 90s onwards about 1985 or so. The drop on demand printing came into picture.

So, from the continuous inkjet printing the drop on demand printing came into picture and one could achieve higher resolution and consumer printing and the small office and home printing took into picture which is the most common way, we know inkjet printing.

Then, in the 21st century, there has been a drive to use inkjet printing for as a manufacturing process. So, it is a bottom up approach for manufacturing and by depositing the droplet of different substances, the potential of the technology is being explored to develop different materials. It may be the chips, PCB circuits or it may be printing on the deserts or it may be printing on the tiles or it may be printing on the carpets, it may be printing on the notes or it may be printing off say 3D printing, what we have the digital manufacturing; so the printing of tissues, printing of cells or printing of different materials twice that we see in the market ok.

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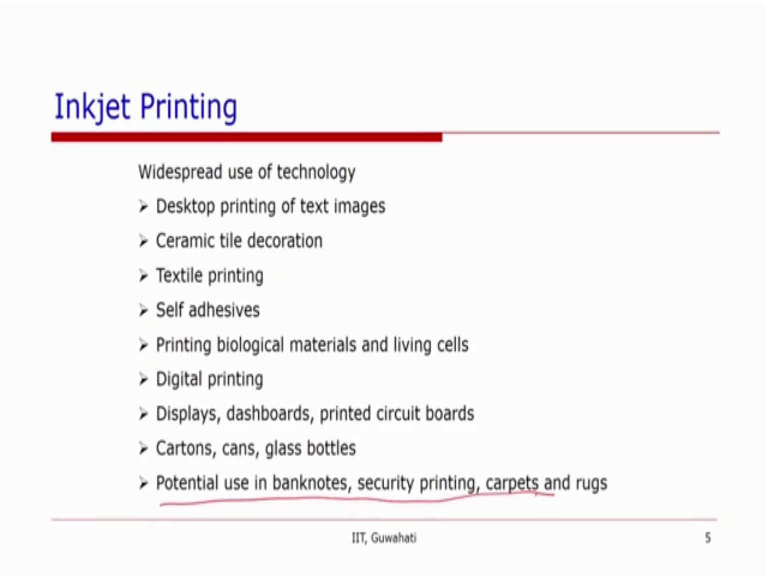

So, here are listed some of those different applications that we just talked about of inkjet printing and some of these application has already been developed and some of them are in the developing stage and others have potential to be develop and they are at the researches stage only for example, the last ones.

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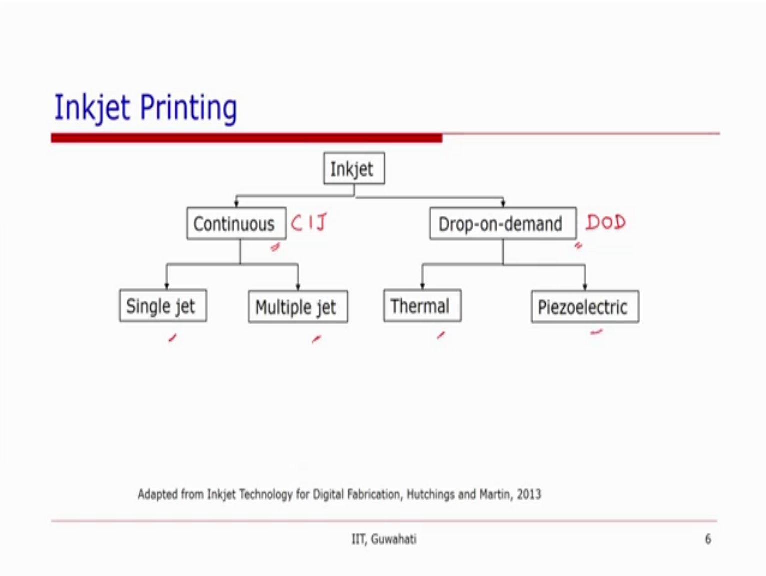

So, if you look at inkjet printing technology, we can divide the technology into 2 or the inkjet printers into 2 different categories. One is Continuous inkjet printer or which is called CIJ in short or Drop-on-Demand inkjet printers or DOD. So, as the name suggests the Continuous inkjet printer, a continuous jet comes out from the reservoir of the ink and then, jet disintegrates into the droplets and then droplets are deposited on the substrate.

Whereas, in the droplet on demand systems, the droplet which are required only those droplets are collected or only those droplets come out of the reservoir; whereas, in the continuous ink jet printer a continuous stream of droplets are coming out. So, the droplets which are to be printed on the substrate, they are printed on the substrate other droplets are deflected and collected for the use.

So, that is a challenge in continuous inkjet printer, but in the drop on demand, only those droplets which are required for the printing only those droplets, then and there are generated. So, Continuous jets have again 2 types of technologies the first one is as we see Single jet; so, in this one jet is generated.

And then, Multiple jets drop on demand, their classification is based on the technology that is used for the generation of the droplet. So, the 2 most common methods are Thermal and Piezoelectric. There are other methods, but I have not listed those here.

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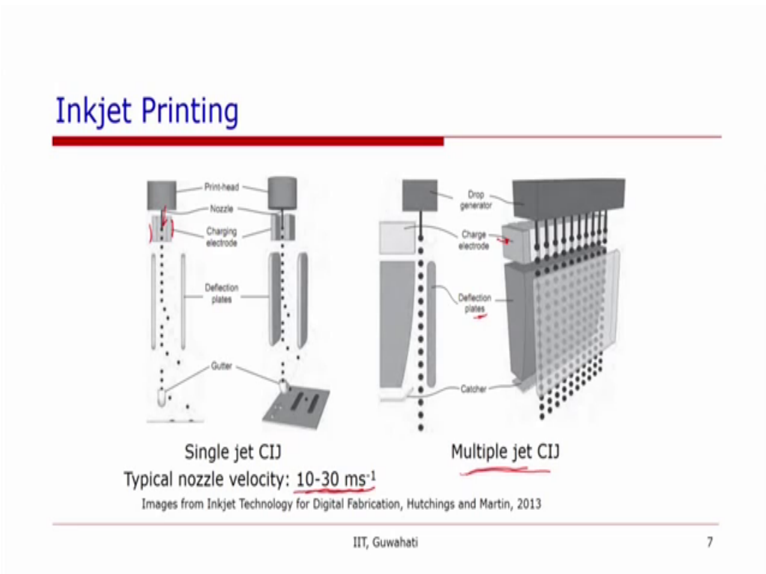

So, in the continuous inkjet printer for the single continuous inkjet printer the jet of the ink and this ink is generally it has a some solvents into it. So, it might behave (Refer

Time: 22:07) like as a viscoelastic fluid a bit and so, the jet of ink it comes out from the nozzle.

And then, it is perturbed a bit this jet is perturbed a bit. So, that the droplets of a certain size are generated from this jet, as we know from the relay plateau instability that a continuous jet will disintegrate into a into the droplets. But the droplet size will be different. So, by perturbing this continuous jet, one can manage the droplet size that is required. And then, when it is passed to the charged electrode, these droplets are charged this might be positively or negatively charged.

Now, when these droplets are passed through the electrode, once they have become charged and they are passed through the deflection plates. So, the droplet which needs to be used, they go through and the droplets which are not required or which are not to be printed, they are deflected and collected in the gutter or other way round.

So, in this case what we see here, the droplets which are not required they go directly and they are collected in the gutter and then, they can be reused. Whereas, the droplets which are to be printed they are charged. So, this charging electrode can be done based on a program there that the its electric charge the charging of the electrode can be in one direction or it might be the electric field is such that that might be positively charged or negatively charged.

So, the droplet material needs to be sufficiently conductive. So, that puts a constraint on that ink material that can be used in this printer and then, these charged droplets are deflected and printed up on the substrate. The typical nozzle velocities in these cases can be as high as 10 to 30 meters per second ok.

Multiple jet is same technology, but in this case what we need is or what we have is multiple jets and all of these are charged through an electrode and then, the deflection plate plates can deflect the droplets or the droplets which are not to be used, they can be collected in the catcher.

So, using multiple jet of course, will speed up the process the resolution of single jet to inkjet printers is relatively poor and one can do the jobs which require high speed to be done repeatedly, but the resolution or very good resolution is not mandatory.

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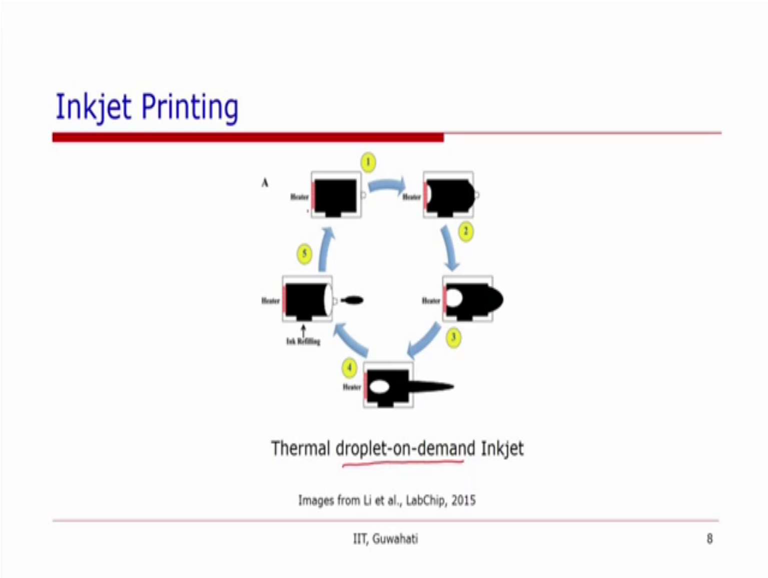

Now, in the droplet on demand the Thermal inkjet printer as the name suggests the technology for the droplet generation is based on thermal magnet. So, the in the jet or in the nozzle, there is a heater and this heater might be placed on a at different positions.

So, the heater is placed and when a droplet is required the heater is heated from this, the heat is given quickly. The ink becomes superheated and it evaporates and the bubble forms. This bubble grows in size and sufficiently does grow that a droplet ejected once the droplet has been ejected the heater switches off and then, the to fill that space the ink comes to the heater.

So, by playing with the heat flux on this heater one can generate the droplets of different size. So, this is the principle of thermal DOD inkjet printer. Then, another technology is based on the Piezoelectric effect. So, Piezoelectric effect is based on the fact that for certain materials as a result of electric field certain mechanical deflection can be achieved or based on the mechanical deflection, the electric field can be generated for the from the piezoelectric materials.

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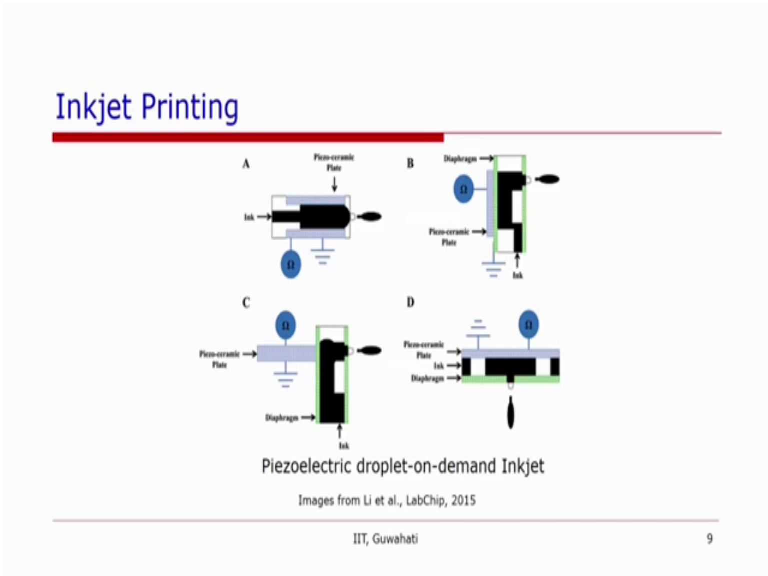

So, this Piezoelectric material is connected with the ink via diaphragm and this podia position can be different as we can see in different images and once, the electric field once we need a droplet, the electric field is applied.

And the diaphragm, the piezoelectric plate deforms or displaces the ink and once, the droplet is generated and ejected the piezoelectric material comes back to its position or the piezoelectric plate comes back to its position and the ink is filled in this system.

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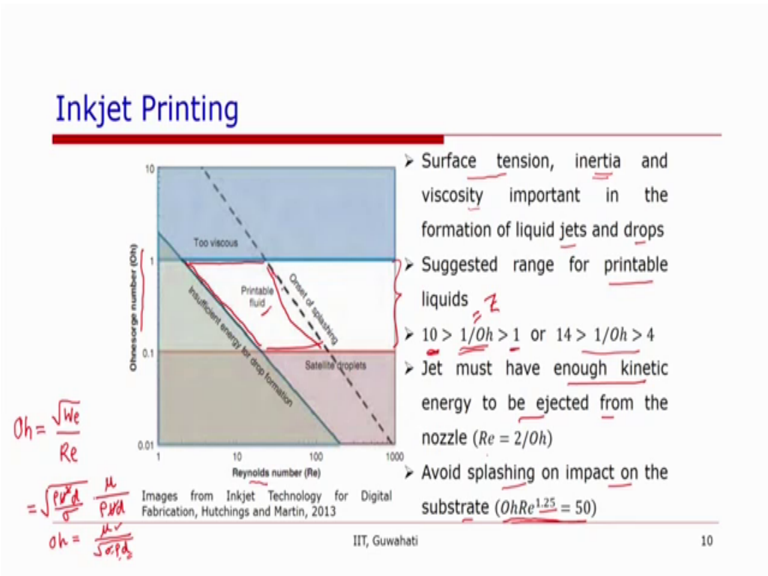

So, now the gas sorge the properties of the material that should be used as printable fluids or that can be used as inkjet. So, this graph is between Ohnesorge number and Reynolds number. We can remember that Ohnesorge number is defined as the root of the wavier number divided by Reynolds number. So, this is equal to the wavier number is rho u square d over sigma Reynolds number rho u d over mu. So, we can cancel out u here and that will be equal to mu over square root of sigma rho d.

So, as you can see here that this Ohnesorge number is a function of the properties of the fluids viscosity, surface tension density and the diameter of the jet or the droplet. And Reynolds number of course, contains the velocity of the jet. So, all these effects surface tension, inertia and viscosity.

So, inertia comes in the Reynolds number, they are important for the formation of liquid jets and drops. Based on the experiments in the theoretical analysis it has been suggested that the range for this printable liquids the inverse of Ohnesorge number which has been defined as z in the literature, it has to be according to one suggestion and it has to be between 1 and 10. And according to another suggestion, it has to be between 4 and 14. So, this according to that this is the range that we have in which the material can be printable.

Now, further on we also need that the jet that are being used that those jets must have sufficient kinetic energy to be ejected from the nozzle. So, that is the line Re is equal to 2 by oh below which the energy is not sufficient for the formation of droplets.

On the other side, as is shown by this dotted line, the material should also avoid or the liquid should also avoid the splashing on impact on the substrate and for that the criteria has been suggested as Ohnesorge number into Reynolds number raised to the power 1.25 is equal to 50. So, this is the region in which the fluid should be printable.

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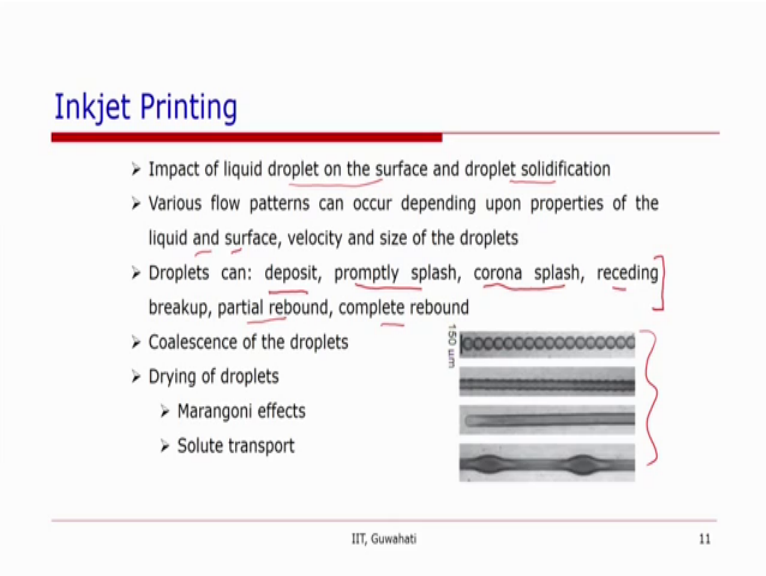

So, once what we have discussed in the technology that drop in the it is continuous inkjet printer, one need to look at the generation of the droplets which is happening by giving perturbation to the jets. And then the travel of this droplet from the print head to the substrate, once it comes to the substrate; then, it is impact on the surface and the droplet solidification are 2 important factors.

Depending on the properties of the liquid and the surface and the velocity and the size of the droplets different flow patterns can be mechanical. And the droplet can have different fields for example, it can deposit or it can promptly splash or the splash can be corona splash or the receding breakup or it can rebound partially or it can completely rebound. Apart from that so, we have seen in the previous slide that how we can or at least one criteria that is therefore, to avoid splashing of the droplets.

And then, when these droplets they are splashing continuously and they are depositing side by side. So, the droplets will interact with each other or may coalesce with each other. So, the interaction of the droplets as has been suggested that they can have different forms say at the form of beads or if they are close enough; then, they can have a pattern like this or different patterns depending on the distance between the droplets.

Then, the next issue is the drying of droplets because the ink has a continuous fluid plus some solute particle suspended into it. The ink also have a temperature effect for example, in the Thermal DOD, the ink is being heated. So, when it deposits on the droplet, it will have a temperature gradient the different.

So, the different regions of the droplet will have different temperatures and so, there will be a temperature gradient set up which will cause a surface tension gradient. And result as a result we will have (Refer Time: 33:57) flow there. The particles, the solute that may also cause the change in surface tension and that may also have Marangoni effects and the solute transport.

So, the drying also have what we call as coffee ring effect that the particles of the solute they tend to take shape or they tend to reach out towards the ring, those effects. All those effects need to take into account. So, the message here is that in the inkjet printing, it is an interesting problem. We all know that it is being used very effectively for different printing applications and it is finding newer and newer applications every day.

So, we need to understand the physics very clearly; while, some of this has already been understood and lot yet need to be understood especially to develop applications. For example, printing of issues or printing or 3 D printing using polymers etcetera.

So, there is lot that need to be understood from the fluid mechanics or multiphase flow perspective.

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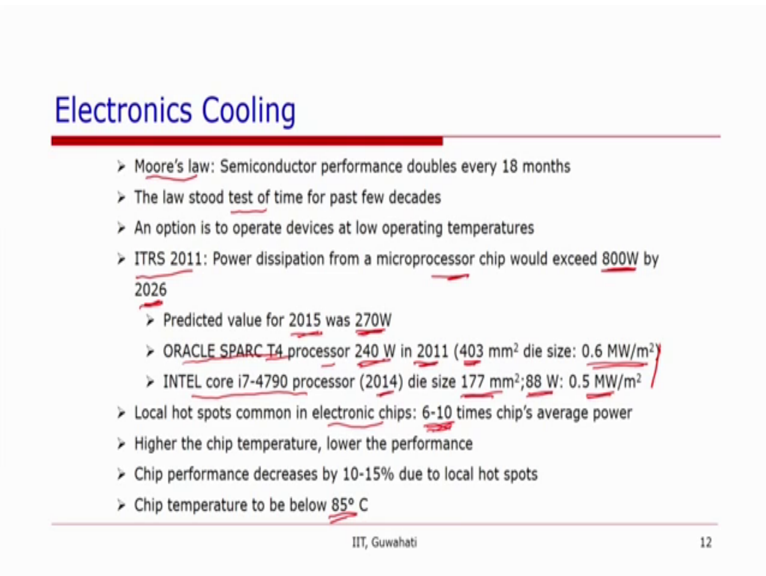

So, now we come to the other application, Electronics cooling. As the Moore's law suggests which was given in 1965 and then again modified in 1975 that the number of semiconductors or the performance of semiconductor doubles every month, every 18 months and this law has a stood test of time in past few decades. So, last 30- 40 years.

This has been happening that the performance of the semiconductor has been increasing and as a result we see we have seen the tremendous growth of computing power in last 20 years. That is one of the reason that today, this video is being without any problems, it is being transferred to you.

So, now soon it seems that if there are no further developments into the semiconductor technology; then, this the this may saturate the Moore's law may not no longer be valid the same the semiconductor performance or may not grow at the same rate that we have seen in past few years.

And one of the problems or one of the bottlenecks in this is the cooling requirement. So, as we can understand that as the number of semiconductor chips that increase on a board, the cooling requirement is also increased better because when all the chips work at high performance rate.

They release lot of heat and that heat need to be removed for them to maintain a at a particular temperature and this the temperature of the chips has to be below 85 degree centigrade. So, an option is to increase the performance to be able to operate these at lower temperature. So, once one can operate at lower temperature, one can afford to have higher performance.

Now, according to an ITRS estimate by 2016, so in about 8 years, the power dissipation from a microprocessor chip will exceed 800 watt and put this in perspective 15 to 20 years back, it was predicted that by 2015, this value will be 270 watt and in 2011, ORACLE SPARC T4 processor a high end processor. It has power dissipation of the order of 240 watts and the size of the die or the area was about 403 millimeter square.

So, this amounts to about 0.6, the heat flux of 0.6 megawatt per meter square; the INTEL core i7 processor that we use in our desktops which was released in 2014. It has the power dissipation of 88 watt and the die size in this is 177 millimeter square. So, it is about 0.5 megawatt per meter square heat flux. So, the heat flux that we are dealing with is about 1 megawatt per meter square already and once we achieve a higher performance, this what we need to be looking at atleast 10 megawatt per meter square or higher those kind of heat fluxes he should be able to remove.

Apart from that these chips will also have local hotspots, the heating is not uniform and at these hot spots the heat flux that is need to be remove which may be 6 to 10 times or we can say one order of magnitude higher than the average power and due to this it has been estimated that due to this local hotspots, the performance of the chip decreases about 10 to 15 percent.

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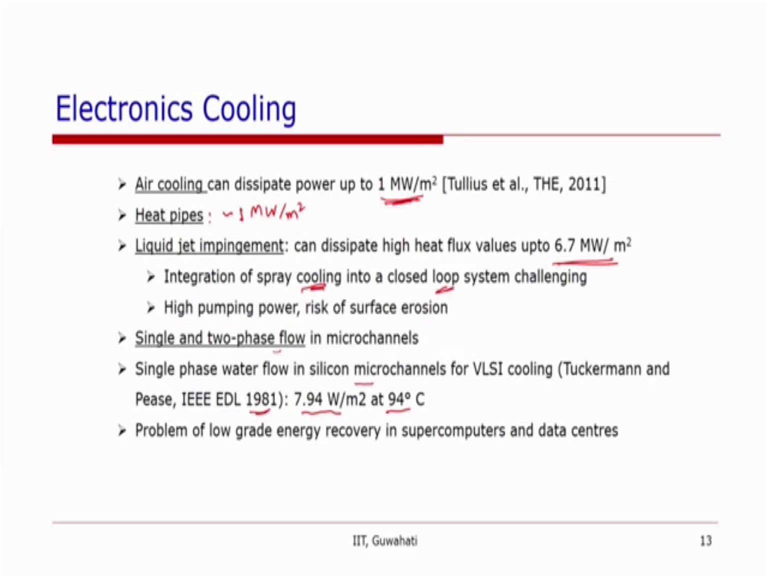

So, what are the methods that are used? Air cooling, when you see your laptop or your desktop computers you can hear a fan running at the back and sometimes, when you will laptop is old for example, then one fine day, you realize that the fan is not running anymore and the laptop reaches to higher temperature. And if the laptop reaches to very high temperatures or the set temperature and sometimes you may just see that the laptop just turns off because of the heating.

So, this cooling is the air cooling is the common method that we find in most of the computers and laptops. And it can dissipate power up to 1 megawatt per meter square. So, we are approaching the limit of heat fluxes that can be removed by air cooling alone. Another method that is used by using heat pipes and they are also their performance also can, they can heat remove heat about same range 1 megawatt per meter square or lower.

Now, another technique that has been suggested in literature that Liquid jet impingement. So, the jets of liquid that can be impinged on the on the surfaces and this can achieve high heat fluxes up to 6.7 megawatt per meter square and, but it requires that the spray cooling needs to be integrated into a closed loop system. So, designing such a system is a challenge. And then, it also the creates an object require high pumping power and it also has the risk of erosion of the surface at which it will be hitting.

So, a Single-phase and Two-phase flow in micro channel; so Single-phase means the flow of water in micro channel because water have high thermal capacity than air. So, of course, by changing the fluid to water or changing to fluid to coolants, one can have high heat capacity removal. And this heat can be removed efficiently when we have Two-phase flow then, the boiling.

So, due to the boiling the temperature of the surface can also be uniform. So, this uniform the local hotspot problem can also be minimized. So, recently some of this has been the recent research in flow in micro channels especially from the heat transfer perspective with and without phase change has been driven by applications in electronics cooling.

And the single phase water flow in micro channels has been shown to achieve high heat flux of 7.94 watt per meter square at 94 degree centigrade; quite few decades ago.

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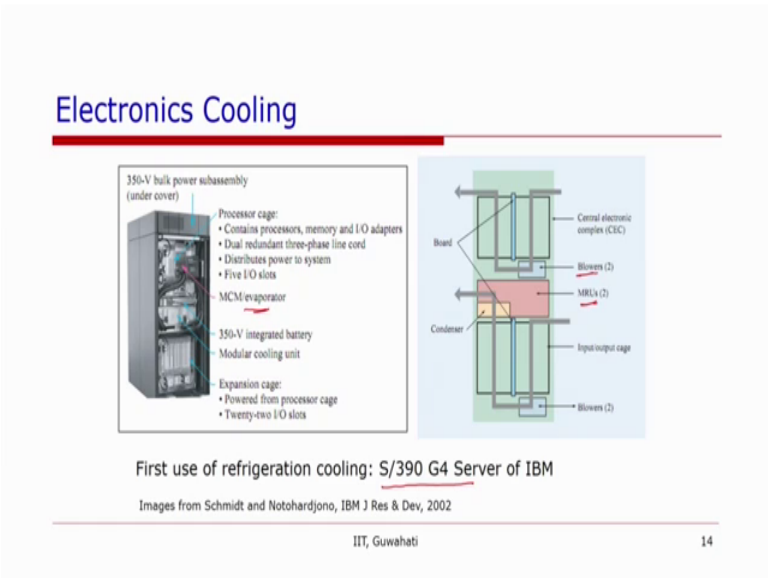

So, here is a image where IBM. They introduced in one of their high end servers or high performance computers and evaporator for the cooling purposes. So, this evaporator this had blowers, but the evaporators were introduced for cooling of some certain components of the system and this was in about 2 decades ago.

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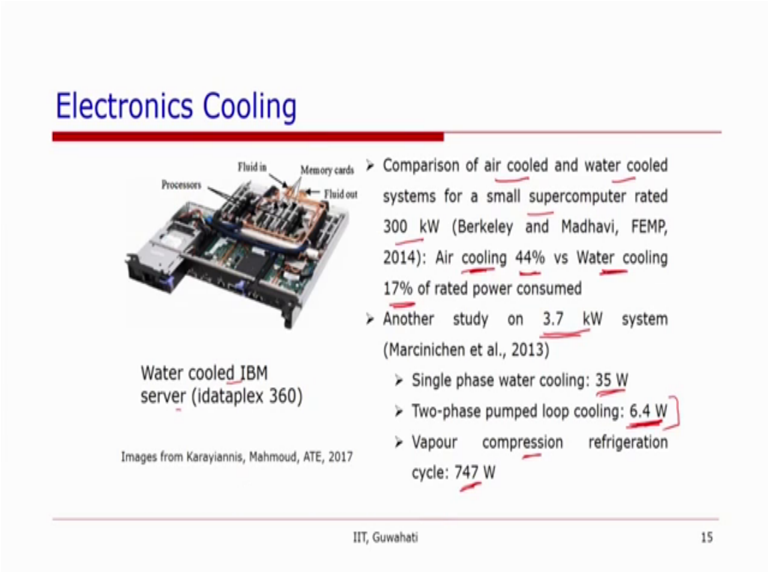

There is another system again by IBM in which the water cooled IBM server has been developed. So, this is based on micro channel and. So, the technology being utilized by INTEL and IBM for the cooling of the electronic systems especially, the computers servers data servers and so on.

In a comparison of air cooled and water cooled systems for a small supercomputer which was rated at 300 kilo Watt. It was found that when the air cooling was being used, it used 44 percent of the power; whereas, in case of water cooling only 17 percent of the power was being consumed for the cooling purposes.

In an another study for 3.7 kiloWatt system, small high performance system; it was observed that single phase water cooling required 35 Watt; whereas, Two-phase pump loop cooling 6.4 Watts and when the refrigeration cycle Vapour compression refrigeration cycle acquired 747 Watt of.

So, the Two-phase where, the fluid is being pumped it required the minimum energy. So, that is also an advantage of as we have seen here in the previous that the energy recovery is also high in case of micro channels and the use of micro channels with pumped cooling.

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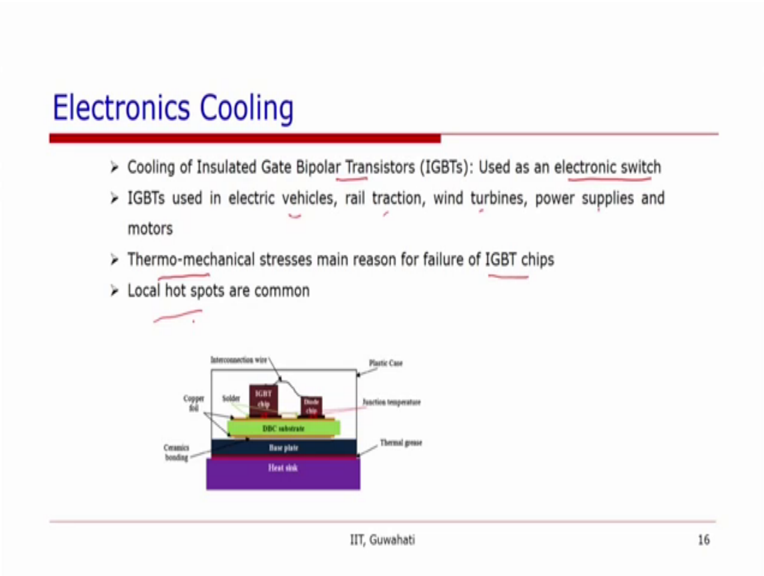

These electronics cooling is also required for example, IGBTs the Insulated Gate Bipolar Transistors which are used as a electronic switches in electric vehicles, rail tractions, wind turbines, power supplies and motors. And it is often observed that the failure of this IGBT chips occurs due to the thermo mechanical stresses which are which might be generated because of local hot spots.

So, it where the high heat fluxes are being generated, the micro channel cooling is also have applications in such IGBT; the cooling of IGBTs and other lot of different electronic systems and servers and so on.

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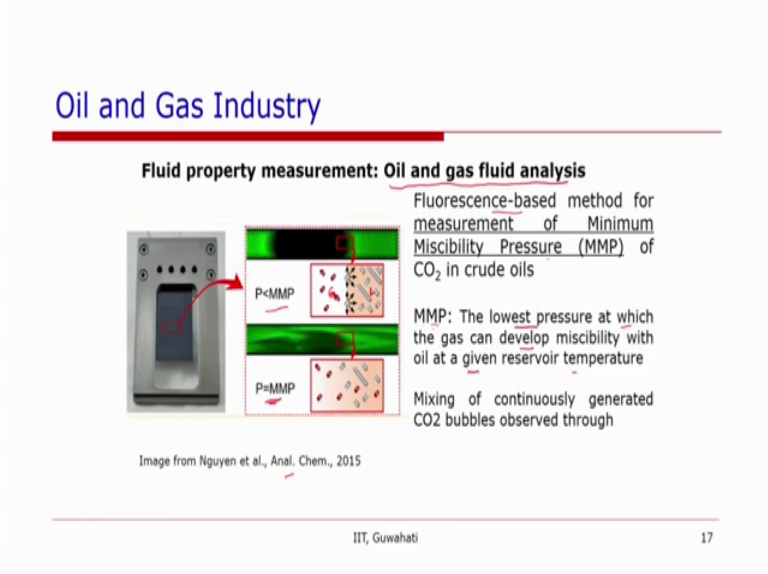

The other application of microfluidics that we are going to talk about in this lecture in the is in the Oil and Gas Industry. So, in the Oil and Gas Industry, one application of microfluidics is as we have seen in the chemistry is in the Analytical chemistry or Analyzing the Oil and Gas.

So, for example, here is an image in which a fluorescence based method has been developed by Professor Symptoms lab in Canada for the measurement of Minimum Miscibility Pressure of CO 2 included our [vocalized-noise. So, what is Minimum Miscibility Pressure? It is the lowest pressure at which the gas can develop miscibility with oil at a given reservoir temperature.

Now, when the gas is not miscible, there is a surface tension or there is an interfacial tension between the gas and liquid phases. So, there will be a sharp interface between the 2 phases. As we can see here that when pressure is less than MMP; then, the interfaces sharp, as can be shown here this is gas and this is for the liquid phase.

When it becomes equal to MMP, then, there is no the surface tension is 0. So, in this case what one will have there is no sharp interface and using fluorescent based method where, the authors have taken the advantage of the inherent fluorescence of the crude oil.

So, based on this fluorescence microscopy, they could identify the MMP which is comparable or even better than the conventional methods that are used for identification of Minimum Miscibility Pressure. For example, the bubble observing the bubbles.

Another application is so, the first application that we talked about that in the oil and gas industry. The different applications of microfluidics which have already been developed, they can be used or they can be tailored for analysis different analysis of fluid and gases, say viscosity of the oil mixture of the density of the oil mixture or the surface tension or the dew point or the bubble point and so on.

The other application is that the oil and gas process in which we have reservoirs and the transport of fluids, oil and gases across through the pores. And often specially for secondary or tertiary recovery of the oil we need to put in the fluids in the reservoir for enhanced oil recovery and that may be the polymers or may be a forum or it may be specialty chemicals or it may be nano fluids or this is microbial based enhanced oil recovery.

So, for all these enhanced oil recovery applications, we need to understand what is actually happening at the pore scale. So, even before that when talk microfluidics there have been development in people were developing the micro models.

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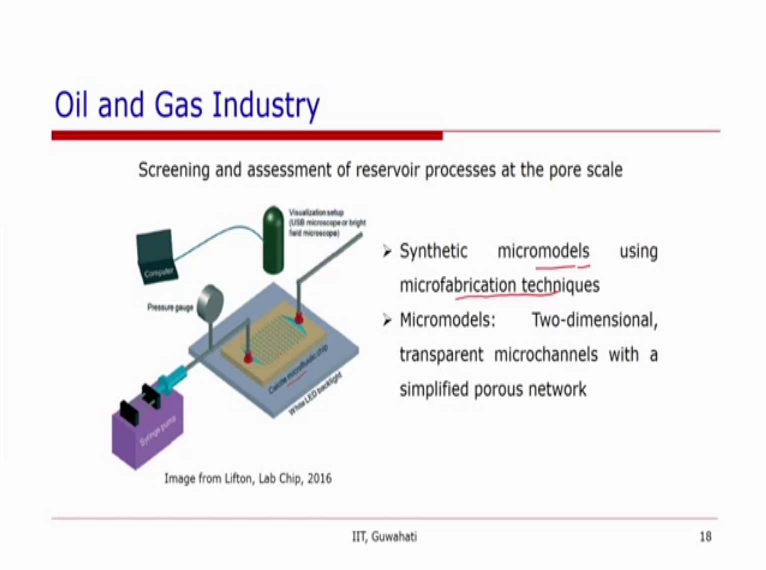

Using and now, the developed and in micro fabrication techniques have a speeded or speeded up or accelerated the process of investigation using these Micro models and one can have the capability to develop novel micro models to understand the transport processes the wetting phenomena, you know multiphase flow behavior in the channels.

For example, here is a it calcite microfluidic chips. So, the researchers in this case they have on a calcite material itself they have developed the micro pattern and studied the fluid flow behavior to mimic and understand the flow behavior these micro channels.

Now, one of the challenges in this is because the pressure in the reservoir is very high and it is often not possible for the microfluidics chips or microfluidics systems that are being developed as of now to withstand such high pressures. So, that is one of the limitations, but as we go ahead the solution to this problem will also be.

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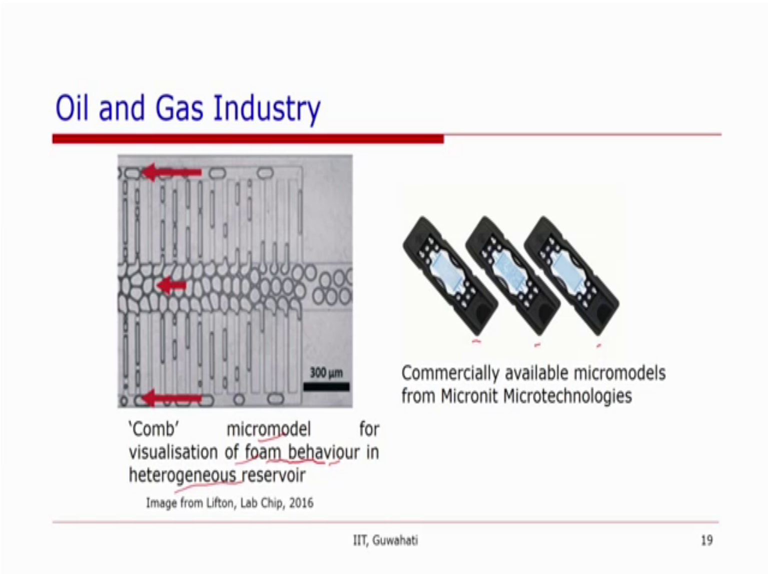

In another Micro model, there is this is say 'Comb' micro model for visualization of foam behavior and heterogeneous reservoirs.

So, in heterogeneous, the flow of foam this is for the foam assisted enhanced oil recovery application that how does the foam flow in a in heterogeneous micro structure which can which can be a this can be a simplified or where is very simplified the structure of heterogeneous structure in a reservoir.

So, these micro models gives one the power to understand the flow behavior with different fluids. There have been also a lot of tricking around the wetting behavior of the of the chips. So, that one can understand the flow of the fluid. The contact of the 2 fluids say oil and water with the different areas in the chips.

With the applications of microfluidics in oil and gas industry, these are some of the chips that have commercially available and they can be called as a reservoir chip where the post of the reservoir has been mimicked on the transparent microfluidic chips and these are from Micronit Microtechnologies.

So, in summary, the Microfluidic technologies or Micro fluidics has lot of potential to understand the actual flow behavior than that happens in reservoirs at the pore scale ok.

So, in this lecture, we have looked at the applications of Micro fluidics for Inkjet printing. The relevant problem that we can apply the knowledge learned in this course to understand and solve further the relevant problems inkjet printing, what are the applications or what are the systems that can be cooled using electronics cooling we have talked about 2 or 3 systems in this.

And then, oil and gas industry the 2 applications, the characterization of the oil and gas and the understanding the flow behavior at the pole scale, the 2 main applications of microfluidics in Oil and Gas Industry.

In the next lecture, we will further continue some of these applications in other spheres.

Thank you.