Experimental Methods in Fluid Mechanics
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Lecture 37
Measurement of microscale flow features – II

Good afternoon, we will continue a discussion on the micro PIV measurement and today we will see that using micro PIV analysis we can measure the micro scale flow features both qualitatively as well as quantitatively.

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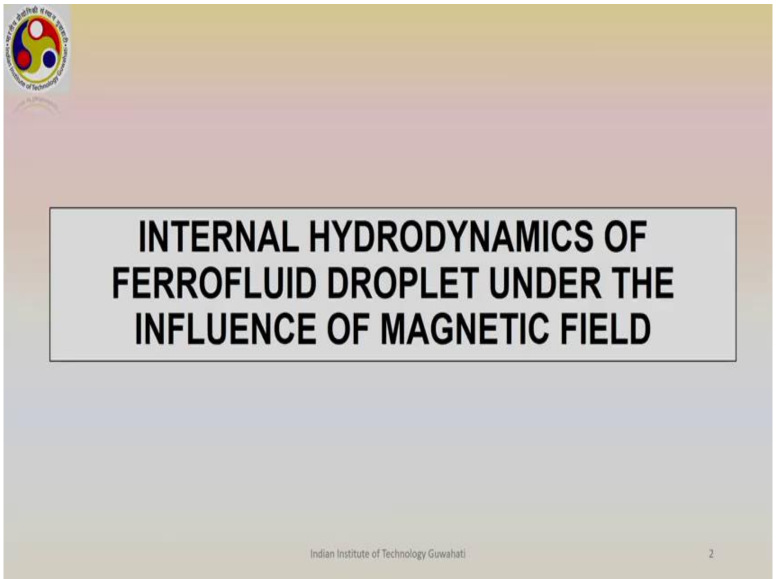

So to discuss that aspect, I will be focusing today on the internal flow dynamics of a ferrofluid droplet under the influence of a magnetic field.

And while I will be talking on the internal flow dynamics of ferrofluid droplet under the influence of magnetic field, essentially we will be focusing on the micro PIV analysis to capture the internal hydrodynamics. Flow feature, micro scale flow feature which is important to understand, important to know essentially for the design of the lab-on-a-chip based microfluidic platform.

So in the context of micro scale flow feature, use of PIV is an important aspect rather to know the procedure, operational principle of the micro PIV in analyzing the micro scale flow feature is very important.

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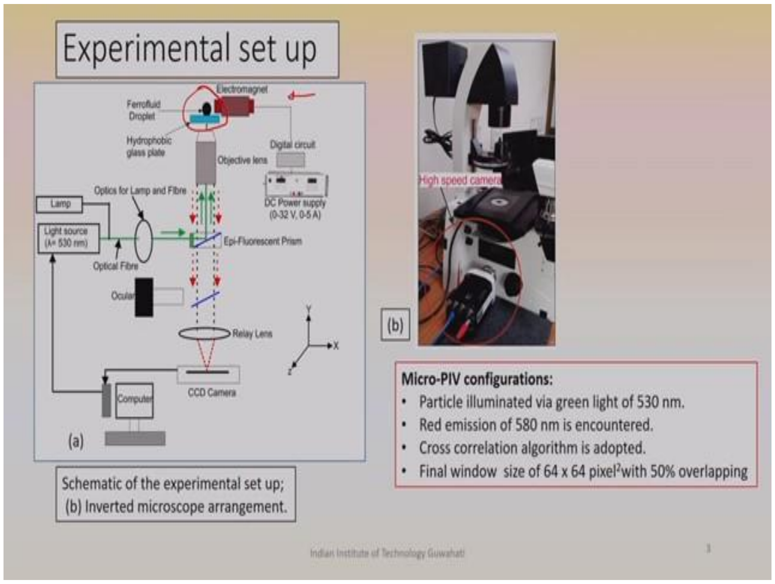

This is the schematic setup, however we can see the micro PIV arrangement. In fact, we have discussed in detail in the last class about the micro PIV setup and of course different parts, components which are associated with the micro PIV setup. Just today since we will be discussing the use of micro PIV in measuring the internal hydrodynamical flow feature, I have inserted the schematic and what we can see in fact we have discussed all the things in the last class, extra thing that is there today that is the object.

So if we try to recall our last lecture, then we will see that we need to illuminate a particular zone or a particular portion of the flow field using a light source. And today we will see that of course we will be using a light that is seen from the schematic, lamp is used to provide light which the light source which is used for this analysis has, that is wavelength now which is given, now object that is shown at the top, so this is the object.

Now what we can see that object is a drop, a ferrofluid droplet, so we are illuminating the droplet flow field that are internal flow field of the droplet. Why we are calling flow field? If we now try to look at the schematic we can find that droplet is now part of using electromagnet circuit and that electromagnet circuit is shown at the right. So this is the electromagnet circuit and this electromagnet circuit that is a magnetic field is produced using electric field and that magnetic field part of the ferrofluid droplet.

Ferrofluid droplet, again I am just telling, since our discussion today will be on the measurement technique, in fact, we have outlined the procedure, we have discussed the post processing part of the captured images and today we will see if we are really interested in measuring the flow field, of course micro scale flow field then using, of course using those procedure which we have outlined in the, which we have discussed in the last class, we will see that what are the precautions we need to take in to account and that is why today I am going to present this.

Now, the droplet is ferrofluid droplet and the droplet is having a few nanoparticles, iron particles. Now when the droplet is placed in front of a magnet, the particles will be definitely attracted towards the magnet. And because of this attraction depending upon the strength of the electromagnet, the gap that is maintained so that the particle should not, I mean the liquid droplet should not rush towards the electromagnet.

So we need to maintain a safe distance, our objective is to study the internal flow dynamics. And by switching on the digital circuit, we can produce the magnetic field and the moment when we produce the magnetic field, internal there will be the, there will be a development of a flow internally.

So, within the droplet volume, we can see that the flow is produced, a flow field is developed and that is because of the moment of the nanoparticle. So our object is not to capture the ferro dynamics in details, but because of the moment of the iron particle, nanoparticle towards the magnet, a flow field will be developed inside the droplet domain and our object would be to capture the flow which is being produced both qualitatively as well as quantitatively.

Now, the light which is taken from a lamp is now allowed to go through a lens and then if I try to, if we try to recall that in the last class we have discussed about the dichroic lens. So this is epi-fluorescent prism that allow only the green light to pass and the green light is now allowed to illuminate the droplet domain through object lens, objective lens. And since the analysis is micro PIV, so as an important prerequisite of this analysis the droplet is now seeded with a few fluorescent particle. So on the top of that iron nanoparticle, the droplet domain, the droplet is now seeded with a few in a fluorescent particles. Those particles are very much important, very much needed in visualizing, in capturing the flow field using this technique.

And since the droplet is having a few seeded particle, fluorescent particles now the light which is used to illuminate so the moment when light falls on the droplet domain, the particle will reflect light and the reflected light which is red light which is again coming through the dichroic lens that is epi-fluorescent prism and the lens will allow only to light, red light to pass and it will be taken through the relay lens and finally to the CCD camera.

And we can see that CCD camera and is now connected to the computer which is used for the post processing through the FFT analysis. So this is what is the experimental setup which is used in real life applications essentially to measure the micro scale flow feature and that is what I would like to discuss today in the context of measuring the droplet flow dynamics.

Now here at the right panel I have written something that particle, particles are illuminated via green light of 530 nanometer wavelength and red emission of 580 nanometer is encountered and this red emission is taken through this epi-fluorescent prism into the relay lens and finally to the CCD camera.

We will be using cross correlation algorithm essentially to post process the captured images to find out or to predict the flow velocity, velocity in that flow field. And final window of 64 into 64 pixel square with 50% overlapping is considered and we will be discussing this aspect little more today in one of the next slides.

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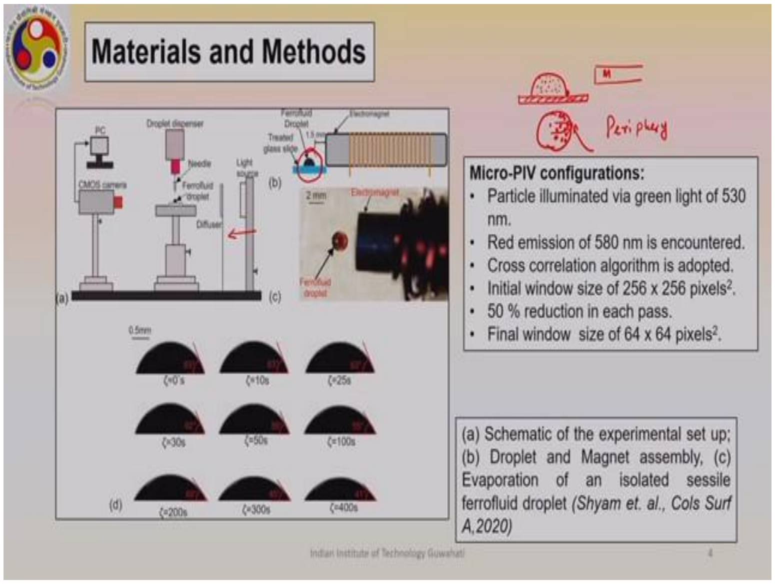

Now, if we go to the next one, here I will be discussing the materials and methods. So I am not going to discuss again the methods and materials, so we have used ferrofluid droplet. The droplet is having iron nanoparticles, these nanoparticles are intentionally mixed with the DI water, I mean ferrofluid, to produce a ferrofluid droplet, what is the objective?

Objective is to create an internal flow structure using magnetic field. So if we do not mix iron particles, then what will happen there will be internal flow structure because of the surface tension effect. So there will be Marangoni convection and all other things but to get sufficient insights in the flow field and only to know the presence of nanoparticle, there are the alteration of the flow field due to the nanoparticle which is, which will be energized, the nanoparticles will be energized by an electromagnet.

Now, the nano, ferrofluid droplet that is placed over here that is on a glass slide that is placed over here and the distance between the outer surface of the electromagnet which is produced which is fabricated, I mean there is a iron core and copper wire is worn around the iron core and depending upon the number of turns we can vary the strength of the electromagnet, of course we can vary the current through the wire.

Now, the gap is maintained which is 1.5 millimeter and at the bottom that is in C what we can see the ferrofluid droplet, we have taken the top view and we can see the electromagnet which is iron core over which we have a few turns of copper wire. And we pass current through the copper wire and we can produce the magnetic field rather using, by that is electromagnetic, because of the electromagnet interaction, electromagnetic interaction.

Now, our objective is, again I am telling, to find out the internal flow structure. So since iron particles are there, thus if we switch on the circuit the moment when magnetic field is induced the particles where we attracted will be migrated towards the magnet. We are maintaining sufficient distance and which would not allow droplet to be, the droplet to be in contact with the iron core rather we can see that the switching on the electromagnet circuit we will now create a disturbance, we will initiate a flow inside the droplet domain and that is what we are interested in measuring.

Now we also have the circuit, so we will be measuring the flow velocity using micro PIV analysis. In this context I would like to mention that micro PIV analysis is used to quantify the velocity flow structure. Now, we can predict, we can even we can consider that the droplet will be, droplet will have a few nanoparticles and now our intuition is that when the electromagnet circuit will be on, that means the magnetic field will be produced and the moment when magnetic field is produced, particles will be migrated towards the end, towards the contact line.

So what is contact line? So if I now draw so this is, say this is the surface and this is drop, so we will have a few particles. Initially, particles will be in the disbursed phase and that is what we need to ensure that the particles should not be agglomerated (())(14:22) so when we start doing experiments, when we put a liquid droplet on a surface and we need to ensure this is the surface, we need to ensure that the particles will be in the disbursed phase. So the particle should not be agglomerated, rather we should not allow particles to be agglomerated.

Now, if we switch on the magnetic field and if we, this is magnet and by switching on the electromagnet circuit if we develop the magnetic field. What will happen? All the particles will try to migrate toward the contact line. So this is the contact line, so if we take the shape, if we look at it from the top view we will find shape is like this. So this will be the droplet shape. Now, all the particle will be, move towards the migrate. We will migrate towards the contact line.

So particles will migrate towards the contact line, so this is the periphery of the droplet. So all particles will be moving towards this end. So the contact line outer periphery of the droplet which is very close to the magnet, particles will be moving towards that periphery. This is our intuition.

To ensure that, I mean ultimately you will be measuring the flow velocity so while particles are moving towards the magnet, we will have a few fluorescent particles that is what I was telling. So the droplet will be having a few seeded particles and when the iron particles are moving towards the magnet, by virtue of viscosity the particles will try to drag liquid towards the periphery.

So when particles are moving towards the periphery which is towards the end of that periphery which is close to the magnet, their movement will try to drags liquid towards that periphery. So we will have a bulk flow towards that periphery because of the movement of the nanoparticles.

Now, since the droplet is now seeded with a few fluorescent particles and the fluorescent particles in, I can say that following the important characteristics of the seeding particles, we have selected particles in such way that the particles will try to follow the bulk flow that means they are neutrally buoyant. Now as the liquid is moving with the iron particle towards the periphery, we also can see that the fluorescent particle also will try to move and that is what we will capture using this micro PIV technique.

So using micro PIV technique we will be capturing this movement of the seeding particles and by capturing the movement of the seeding particle we will predict the flow velocity internally which is developed because of this magnetic field. To capture qualitatively that the particles are moving, so iron particles are moving towards the periphery which is close to the magnet core, we have also used another flow visualization technique and that is known as bright field visualization and that is what is shown in the schematic A, what we can see that we have, so we are having droplet dispenser and we can dispense small droplet of known volume and we know what will be their diameter. The moment when droplet is dispensed and droplet is injected on the sub-state, we can see we have a light source from the right, so this is the light source, light is coming and light is taken through a diffuser and this light is used to illuminate the droplet domain.

And we just record image using CMOS camera and just our objective in this schematic through using this schematic our objective is to capture the qualitative picture of the flow field which is being developed inside the droplet domain because of this magnetic perturbation.

So, the magnetic field will be produced, because of the magnetic field we know a priori that the iron particle will try to move towards the droplet periphery which is close to the magnetic core. And we will try to quantify the velocity which is being produced because of this moment of the iron particle using the micro PIV analysis. And for that we have seeded with the, we have seeded fluorescent particle.

Before we go to discuss that, before we go to capture the quantitative estimate of the flow field velocity, we do here another experiments, another measurement analysis that is the bright field visualization, essentially to capture qualitatively whether the bulk fluid, that means when bulk fluids are moving towards the periphery, then we can see whether the bulk fluids are moving towards the periphery in which direction their orientation and if the particles are moving towards the periphery then they will try to be, the particles will be deposited over there for a moment depending upon the strength over a period of magnetic actuation.

So if we can capture that particle movement using only the bright field visualization, that is only by visualizing without going into the quantitative measurement, just qualitatively we can capture. The particles are moving towards the periphery and that is what the schematic is.

So in these experiments we will do, in this measurement experimental method rather experiments we will be using two different methods, first is the bright field visualization to (())(20:39) the qualitative picture, qualitative estimate of the droplet flow field internal hydrodynamics. And after knowing the internal hydrodynamical features qualitatively, we next will move to see rather we will next move to quantify, predict the quantitative picture through the micro PIV analysis.

Before we go to do so, here we need to ensure one important point that we have taken very small droplet volume. Now, if our objective is to calculate, to predict the internal flow velocities which will be developed because of the movement of the magnetic nanoparticles.

Now, we need to ensure that this measurement technique will take some finite amount of time and within this time, droplet liquid, I mean it is droplet so particles are mixed with the carrier fluid. So, within this time that is a time required for the qualitative estimate of the flow velocities or internal flow structure, the droplet should not be perpurated. So that means the droplet volume should not be reduced drastically otherwise our measurement will be affected. We can measure but we will come up with the results which are not, which would not be the correct.

So that is what we have shown that what you can see from the images up to tau is equal to 400 second, the droplet shape is remaining more or less same, so up to this 400 second we can predict that there is no substantial drop of evaporation. There is no substantial reduction of the droplet size and our analysis which we will be doing now, within this if we can complete our analysis within this time sake within this time period then our results will be correct rather we can come up with the correct results.

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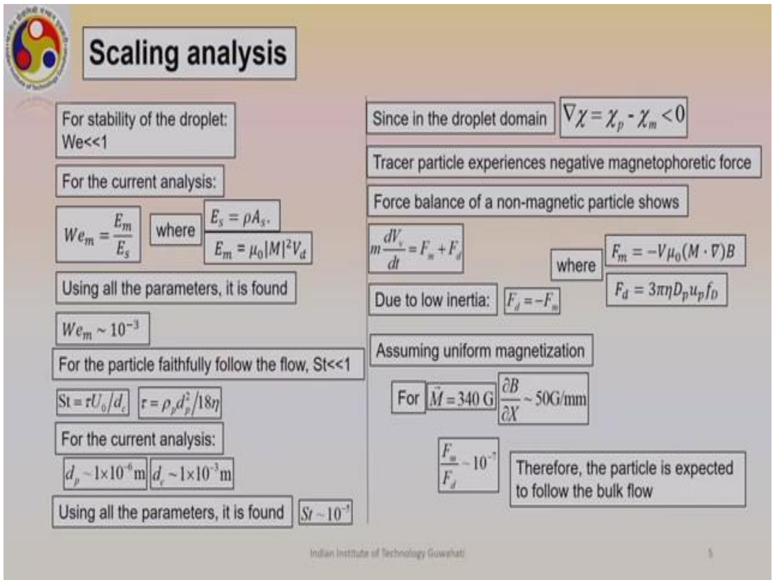

So if we go to the next slide, here you have done some scaling analysis. This scaling analysis is very important at least from the, as I said to you that we have taken very small amount of very small droplet volume, that is tiny droplet. Now, that droplet as I said to you that droplet will remain in its position, so we are energizing the droplet domain using magnetic field. Droplet volume is having a few magnetic nanoparticles, so but as the as you are using magnetic field to energize the droplet domain, droplet should not have movement.

So that is we need to ensure and that is done using mathematical scaling analysis that (())(23:35) number is very, very less than much, much less than one. That means (())(23:38) number is nothing but the inertia force by the self extension force and what we can see that the inertia force is predominantly less. So the droplet volume is not having, I can say, a movement, so no movement of the droplet volume. So droplet volume will remain there so that our analysis should not be affected because of the movement of the droplet volume.

And as I said in the last class that particles to faithfully follow the flow, Stokes number should be much, much less than one and that is what is calculated and we have ensured that for this particular analysis, stokes number is 10 power minus 5 and it ensures that the particles are neutrally buoyant, the fluorescent particle which we have used. And another important point is that our objective is to measure the flow velocities, the complexity in this analysis is that we have used magnetic nanoparticles and the magnetic nanoparticles will be part of influence of magnetic field. The moment we switch on the magnetic circuit, magnetic nanoparticles will try to move towards the periphery which is close to the magnet and because of the moment we will get the flow velocity.

We need to ensure that when the particles are moving, magnetic nanoparticles are moving towards the periphery, their movement will try to drag, rather their movement will drag small volume liquid volume and I will get the flow velocity. While the particles are dragging fluid, molecules fluid and we can see the development of the flow velocity and the seeding particles also will try to follow the similar path.

Now we need to ensure that the reverse would not happen, that means magnetic nanoparticles are moving towards the periphery because of their movement we will get the flow velocity and that is what, for that only we have used fluorescent particle. So we need to ensure that while the magnetic nanoparticles are moving towards the periphery, seeding particle would not move in the reverse direction. Otherwise, we would not be able to calculate the flow velocity correctly.

So again I am telling, the movement of the nanoparticles, magnetic nanoparticles will try to create a movement of the liquid, a movement of the fluid towards the periphery that is in a same direction. Now that will be captured using the fluorescent particle, now if the fluorescent particles are moving in the opposite direction then our objective will not be fulfilled. To ensure that, we will have done that tracer particle will experiences negative magnetophoretic force. So, that is what we need to ensure and that is done using the delta chi that is not less than zero, that is negative magnetophoretic force will be there.

And finally, again, here we need to ensure that the magnetic particle will try to follow the bulk flow, so the first case, this is another important thing, the first case when we switch on the magnetic field, magnetic circuit, magnetic field will be induced, developed and because of this magnetic field, particles will try to move. Now droplet domain although tiny, so the particles are moving towards the magnet and particles which are on the other periphery also needs to move in the magnet. So the particle will try to follow the bulk flow and particles should not have sufficient inertia, otherwise it will be difficult to maintain the flow field.

So what I mean to say, if we switch on the magnetic circuit, magnetic field will be developed, the particles which are very close to the periphery, droplet periphery and in the distance very close to the magnetic core, we will try to follow towards that periphery. The particles which are distance away from the, from that particular periphery that means the particles which are from the other periphery, the particles will also move towards the periphery which is close to the magnetic core.

If the particles are having sufficient inertia then they would not be able to flow the liquid. So we need to ensure that particles are also expected to follow the bulk flow. Which particles? Magnetic nanoparticles, and for that we have calculated the magnetic force by the drag force and it is seen that magnetic force is very less. That means, so particles will try to follow the bulk flow. And doing this analysis, we will next see how we can predict the velocity rather internal flow structure qualitatively as well as the quantitatively.

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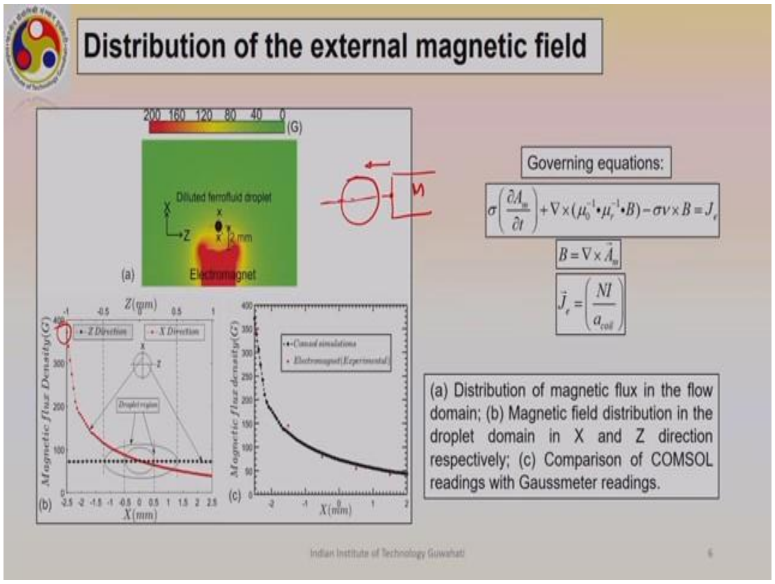

So this is the just numerical simulation we have used because sometimes even for the experimental investigation we need to ensure that we can measure the magnetic field intensity. Magnetic flux density we measure experimentally because we are creating magnetic field using electromagnetic circuit, so if using gaussmeter we just can calculate what are the magnetic field density change.

So this is the starting point, that means this is at the, just at the outer surface of the magnetic core and if we traverse from that towards the, say this is the magnet we have one magnet over, this is the droplet domain and this is the magnet. So this is magnet. So if we, here the magnetic field which is magnetic flux density which is produced that is near about 400 gauss, if we now traverse from this particular point towards the droplet domain rather allowing the diameter of the droplet and we have measured the change in magnetic flux density.

And we have, if we now look at the right figure which is on the right panel, so we can see that our experimentally observe values are similar to the values which are obtained in the numerical simulation. So that means we can say that magnetic field, magnetic flux density variation which we have measured using gaussmeter that is more or less correct, that is correct rather.

Now here, I will just show, so as we said that if we now go back to the previous slide, if we go back to the previous slide, so just I will be referring to the slide a few I mean while I will be discussing the results we need to refer this slide. So that is why I have again selected this slide. What we can see from this slide is that the droplet is placed over here and the droplet is energized using a magnetic, using a magnet electromagnet and if we now switch on the magnet, the particles will be attracted towards the periphery which is close to the electromagnetic core. That means particles will move towards the right.

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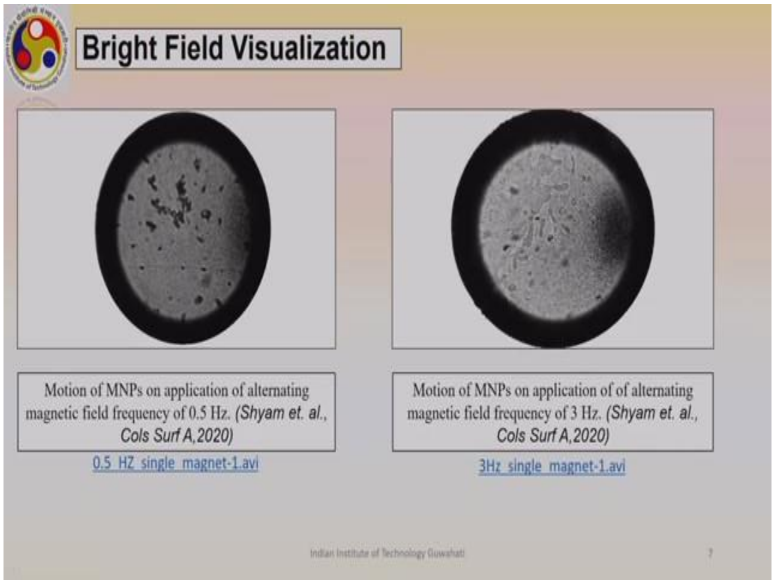

Now if I go to this slide, what we can see, from this moving we can see that particles are getting attracted towards the magnet. And since it is electromagnet, we can control the magnetic field strength by switching on by suitably designing the electromagnetic circuit. Here, this is kind of time period in magnetic field.

So the time duration over which magnet is in on mode, the particles will be attracted towards the magnet, towards the magnets and they will be deposited at the periphery, droplet periphery and during the off mode of the magnetic field actuation, the particles which are deposited which are being deposited during on cycle, will now try to dispersed.

We will be discussing and this is, these two different movies are shown, this is obtained for 0.5 hertz that is as I said this is time period in magnetic field actuation and this is for the 3 hertz. So what we can see that from this movie that this is constant movement, so since time frequency is 3 hertz higher frequency so the time period over which the magnetic field, magnetic circuit is remaining on and off is very less and as a result of which what we can see, we can see almost continuous. So particles are getting attracted and getting refilled.

So now this attraction and repulsion using of the particles by the magnetic field is very instantaneous, the time gap between these two attraction and repulsion is very less and as a result of which we can see the particles are getting attracted but again they are getting refilled and again they are getting attracted.

So the time between these, time between two consecutive attraction and repulsion is very less as a result of which we can say particles are almost remaining there in the cluster form at the periphery. But if we now compare this one, what we can see that frequency is 0.5 hertz, so the time gap between two consecutive repulsion and attraction very less relatively higher. And as a result of which we can see, we can clearly see the difference between particles are getting attracted and then again they are getting refilled.

So this is the, we have observed using bright field visualization, so as I said that this is very important to have qualitative picture. Out intuition was that particles will be attracted and after they are getting attracted towards that, during off cycle they will be dispersed. But this dispersing is not very prominent for the 3 hertz case because the time scale, perturbation time scale is very small while for the 0.5 hertz case the perturbation time scale is ratably large as a result of which we can clearly distinguish the attraction and the repulsion.

That means they will be attracted, they will try to form cluster-like formation and after, during off cycle the cluster-like formation will break and they will try to be dispersed.

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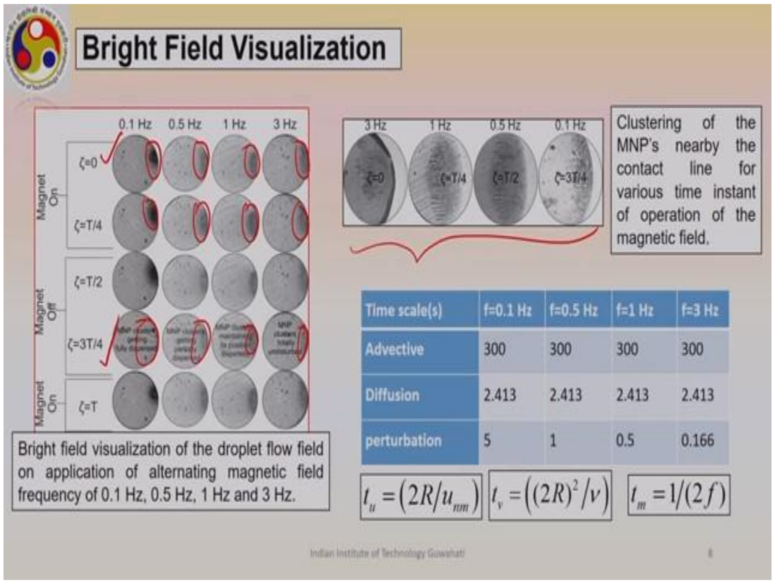

And if we go to the next slide, this is even I can say the bright field visualization but which we have obtained for four defined frequencies. So what we can see? Just we have considered four different frequencies and we have shown magnetic on and off, so tau 0 plus that is magnetic is on, so 0 that means the particles are from the previous cycle and 0 plus that means magnetic will be, 0 plus that magnetic is on and particles are getting attracted towards the magnet at the right side and particles what we can see, particles are getting attracted and particles will be getting attracted.

That is what we can see. And particles will be deposited at the periphery of the droplet which is close to the magnet. Now, T by 4 is the on period of the magnetic on cycle, but T by 2 tau is equal to T by 2 that is the, this is time periodic magnetic field. So 0 to pi by 2 that is remaining on and pi by 2 to the next pi that is, that will be remained off. So what we can see from T by 2 that is at T by 2 still it is, T by 2 that means the magnet, this will be T by 2 plus.

So T by 2 that magnet is still on stage, T by 2 plus magnet is now off. What will happen? The particles which are being deposited at that periphery, periphery of that droplet which is closer to the magnetic core when the magnet is off, the deposited particles will be now dispersed and that is clearly seen from the figure which have obtained from 3 T by 4. So 3 T by 4 if we now look at 0.1 and 0.5 hertz, the droplets are almost dispersed.

As I said that for 0.1 hertz and 0.5 hertz, the perturbation time scale duration is relatively high, so that means the time duration over which particles are getting dispersed from the deposited zone is relatively higher and we can see almost complete dispersion. While for the 1 hertz case and for 3 hertz case, we can see that particles are not getting enough time to be dispersed as a result of which we still, we can see the cluster-like formation at the periphery which is close to the magnetic core.

So this cycle will be defeated and because of this repetition and here we have shown the particles just the movement of the particles towards the magnetic core because of this magnetic actuation. So we have seen that particles are moving and that is what our intuition was and we have verified using the bright field visualization technique.

So particles will be moving, they will be deposited at the periphery during the on cycle and when the magnet will be taken on the, taken into the off cycle, then the deposited particles will be dispersed and the zone will be free so we can see. So if we compare this one and this one, we can see that the particles are deposited, we can see the cluster, formation of cluster, particles are dispersed we can see the clear space. So this is the bright field visualization, this is the qualitative estimate.

So we can say that when particles are moving, flow velocity is supposed, the flow, their new velocity of the fluid from the left to the right so that is our intuition is.

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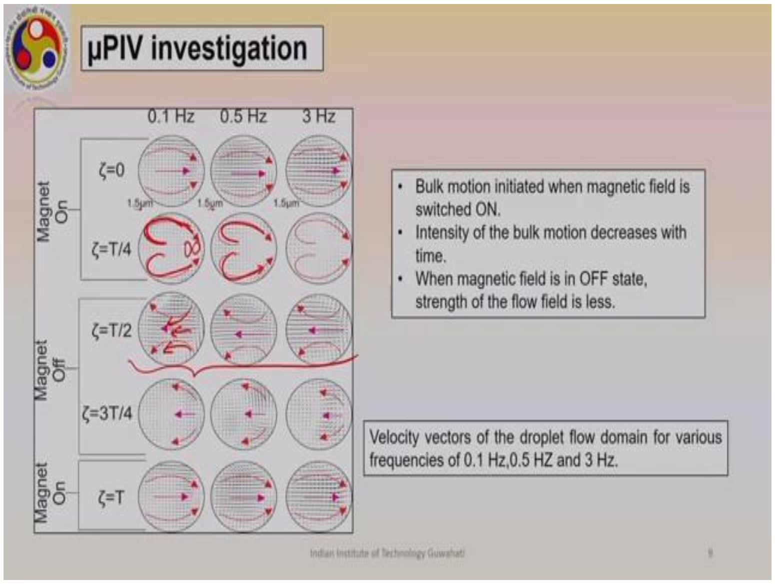

Now, to obtain the quantitative picture of the flow velocity that is developed inside the flow domain and for that we have used micro PIV analysis and for that we had to consider seeding particles. What we can see? Here we have considered three different frequencies and these three different frequencies are good enough to obtain the physics, to obtain the insights about this method.

So when magnet is on, that is tau is equal to 0 plus, that means particles are trying to move towards the periphery, periphery which is very close to the magnet. So we can see that the red color arrow which is used to show the velocity vector. So what we can see, the particles are moving towards the magnet.

So that we have seen from the bright field visualization, the particles are moving towards the magnet but now we have seen that because of this movement of the nanoparticle movement, magnetic nanoparticle movement we will have fluid velocity and that we have captured during the seeding particle (())(39:56) particles.

Now, what we can see that when tau is equal to 0, I mean then the particles are start moving towards the magnet. When tau is equal to T by 4 still we have a bulk movement towards the magnet that means magnet is still in the on mode, but what we can see? We can see the fluid velocity are having movement initially will have the movement in a vector is like this, so like this. Why? So with time, the particles which are being deposited at the periphery which is close to the magnetic core, the deposited particle will now try to create resistance the other particles to come, that means there will be continuous movement of the particles towards the magnet because magnet is remaining in the on stage.

Now because of the deposition with time, the particles which are being deposited, the deposition of the particle will be now the hindrance to other particles which are going to come, that means with time the farthest particle will come to the magnetic zone to the periphery which is close to the magnet.

Now since that particular zone is already covered by the particles, so the deposited particles will now create resistance for other particles which are going, which are coming from the farthest end and because of that, the liquid will try to move in a path following the path which is shown over here.

That means, still particles are moving because of the magnetic on stage but the particles movement is not straightforward, but particles are moving but particle movement is shown and the movement will be following the path which is shown by the arrow. Similarly, that means the particles which are there that will be create resistance, as a results particle will now try to follow the this path. But when magnet is off that means the deposited particles will now try to disperse from the deposited area.

Here an important physics that I would like to discuss that is very important and that is physics we can obtain from the experimental observation. What we can see from at tau is equal to T by 2 that means magnet is now off stage? What we can see? We can see that the particles are now getting dispersed but the, when particles are deposited it is not the case that particle will be deposited haphazardly.

So particles will form, particles will form cluster and they will have certain directional preference and that depends upon the magnetic movement. Now, when the particles are remaining deposited, they will be allowing towards the magnet and they will have certain direction of their alignment.

Now when the magnet is off, that means if I switch, if you switch off the magnet then what will happen? Their magnetic movement will now break as if and the energy which is being stored within the magnetic particle, so when the magnet is on particles are getting attracted towards the periphery of the droplet which is close to the magnetic core.

When the particles are being deposited within the particle we will have internal energy and because of this internal energy particles will try to form agglomeration version and they will have directional preference and they will be aligned following certain direction of their arrangement.

Now when the magnet is off, the magnetic movement will break, when the magnetic movement is getting break particles also not, particle are also not moving randomly rather they are trying to follow the magnetic force lines. And as a result of which what we can see, particles will follow this and which is largely captured by the flow field which is being developed because of the dispersion.

So when particles are now moving, getting dispersed because of this magnetic off stage, the dispersion also will try to create flow field where the particles are moving they will try to drag liquid. And what I would like to emphasis over here is that the particles when they are getting dispersed they are not following random path, they are following certain path and the path which are because of the path which are in tune with the magnetic force lines and we can see initially we will have flow direction like this.

So since the magnetic particles are following certain path, flow field will have certain structure and that is what we can see from these three images. And with time since the magnetic particles are now, so with time the internal energy the stored energy will be used to create flow field.

So now the flow field which is being developed because of this internal energy, so when we magnet, if we off the magnet then because of this internal energy the particles are now moving from this periphery towards into the domain. And because of their movement we can see the flow velocity but at the initial temporal instance of their magnetic off cycle, they are following certain path lines. And as a result of which we have seen the initial stage flow field, flow structure looks like this but with time again the flow field will change and we can see the undefined structure. And that is equal to tau is equal to T plus, the cycle benefited and we will get the similar structure which we have seen at tau is equal to 0 plus.

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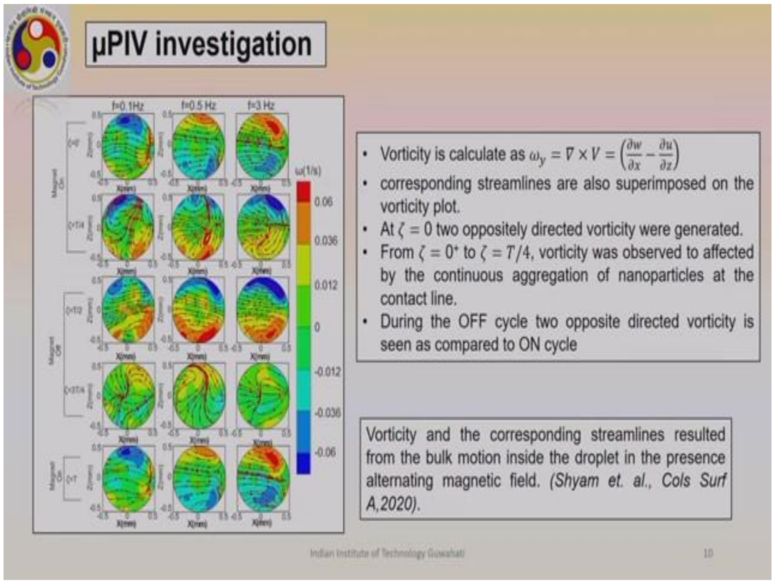

So this is very important to note that using this micro PIV technique, we can actually capture the internal flow structure which is very important to know. That means our intuition was that at tau is equal to T by 2, the particles will move haphazardly but this is not the case that we can really capture.

That means the micro scale flow feature which are very important to know, micro scale flow feature which we are capturing which is micro PIV technique is very important and we can capture accurate physics that is there because of this phenomenon that is magnetic field driven moment of the nanoparticle.

Here the, we have shown the vortices structure, the structure is very important to know as we are disturbing or perturbing the magnetic field so it will definitely have, it will enhance the evaporation rate, so droplet will be evaporated. And this formation of vortex structure has big role to play on the overall evaporation kinetics.

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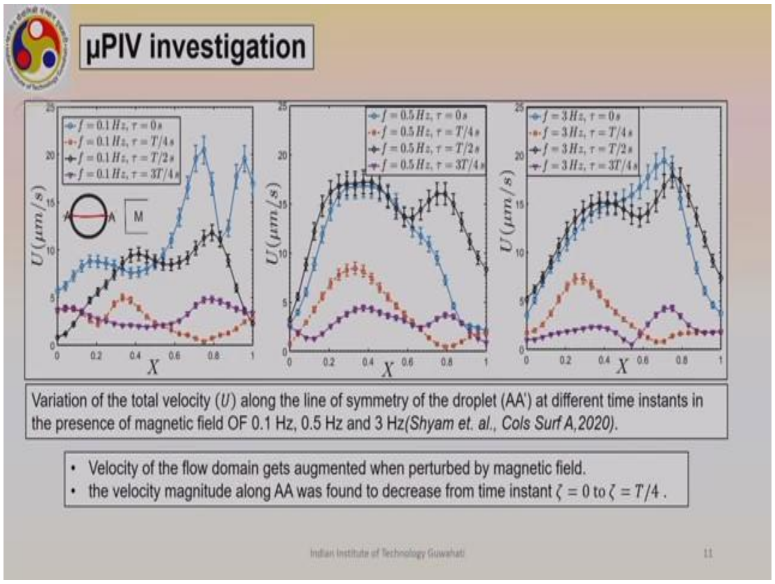

So this is what is final important thing is that we can also capture the flow velocity which is being developed inside the, so here all the flow velocity field which we have captured along the line A, so we have captured the absolute value and we have captured the flow velocity so velocity of the fluid particle along line A using this micro PIV technique, what I would like to say that using this technique, using the images, capturing the images which we have taken using this micro PIV analysis if we do the cross correlation algorithm and we can capture the velocity and we can see that what is the strength of the flow velocity that is being developed because of the magnetic field actuation.

We have obtained this flow velocity along line A for three different cases that is the 0.5 hertz, 0.1 hertz and 0.3 hertz cases.

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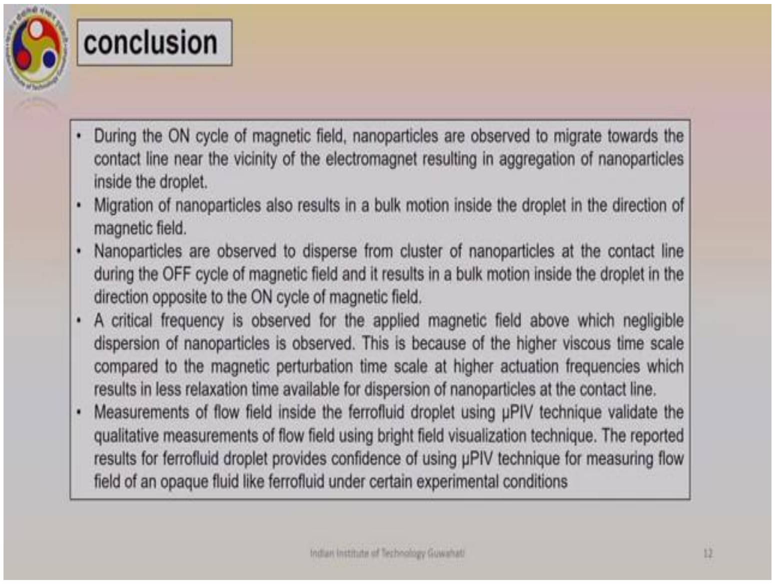

So that means to summarize today's discussion that micro PIV analysis is I can say is a sophisticated measurement tool to obtain the internal flow features, internal complicated rather rich, internal flow feature which is rich in physics. So if we do the bright field visualization we can only capture the qualitative estimate but we cannot capture the quantitative picture.

So we have seen today that from the bright field visualization we can only capture the gauss, velocity gauss movement of the nanoparticle but we have captured the rich physics which is involved with the underlying transport processes, underlying transport processes of magnetic nanoparticles in presence of magnetic field because the movement of the nanoparticle is important to predict the internal flow structure, so we can, if we would like to capture that rich flow structure using which is there in the micro droplet domain then micro PIV analysis is an important tool.

And we also can quantify the magnitude of flow velocity that is very important in the context of micro flow features, micro flow experiments. So with this, I stop my discussion today and we will continue my discussion in the next class. Thank you.