Microscale Transport Processes

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Lecture No. # 39

Electrohydrodynamic Atomization (Contd.)

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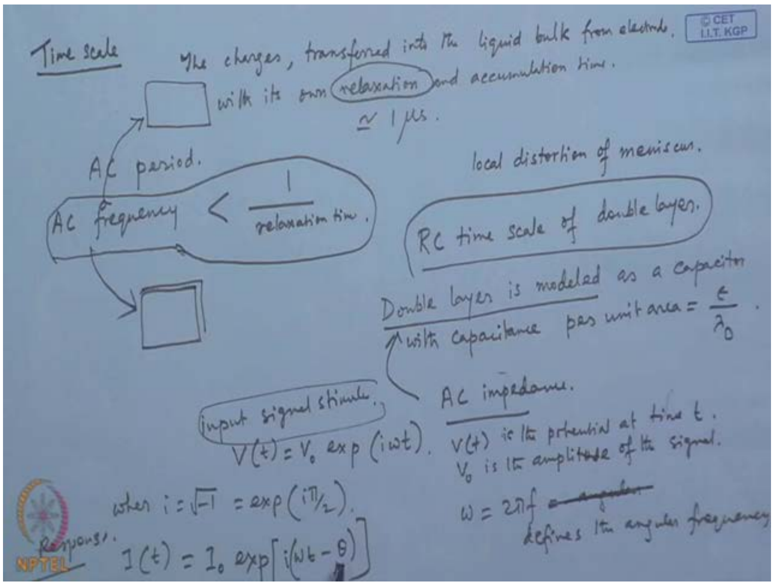

Welcome to this lecture of microscale transport process. What we have been discussing was this electrospray and in that, at the end of last class, what we were talking about is, trying to find out this time scale for a DC electrospray, we discussed about this time scale. When it comes to the AC electrospray, we have another time scale that is featuring, that is arising, because of this AC time period or AC frequency. So, one has to ensure that this AC frequency is sufficient that it is not merely causing just local change in the meniscus. But this is, but not finally culminating to the formation of droplet or it is just it is not letting the, this double layer to equilibrate fully.

So, these are some of the things that need to be understood. In this connection, what we were discussing was the RC time scale and where we were in the end of last class, was basically we were trying to show that there is double layer has a particular model as far as these RC time scale is concerned. If one looks in to the input signal stimulus, if one defines input signal stimulus this way, which is a very conventional one, not that one wants to, I mean that is the way it is very traditionally done. So, there would be a response signal which is given by (No Audio From: 01:55 to 02:01) this quantity. So, this is the, what you call current response signal and this is shifted with the phase difference theta; this current, this signal is shifted by the phase difference this theta. So, this is, this is how this would be the response current.

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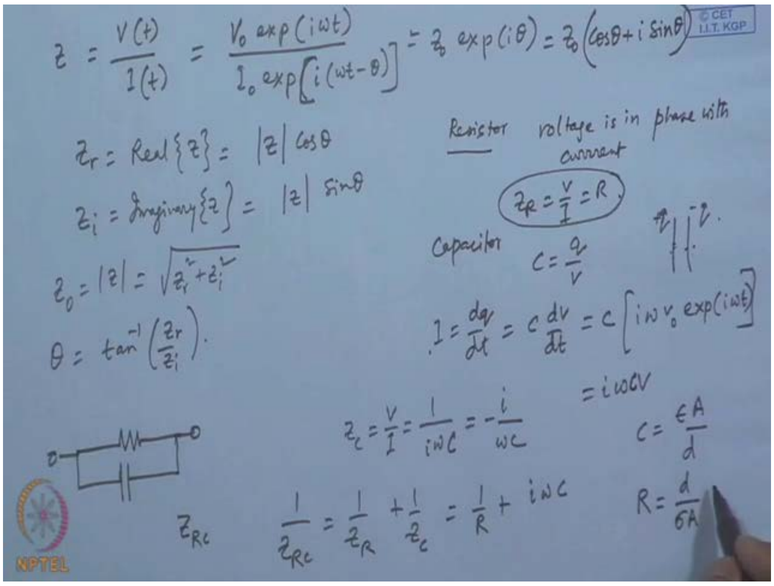

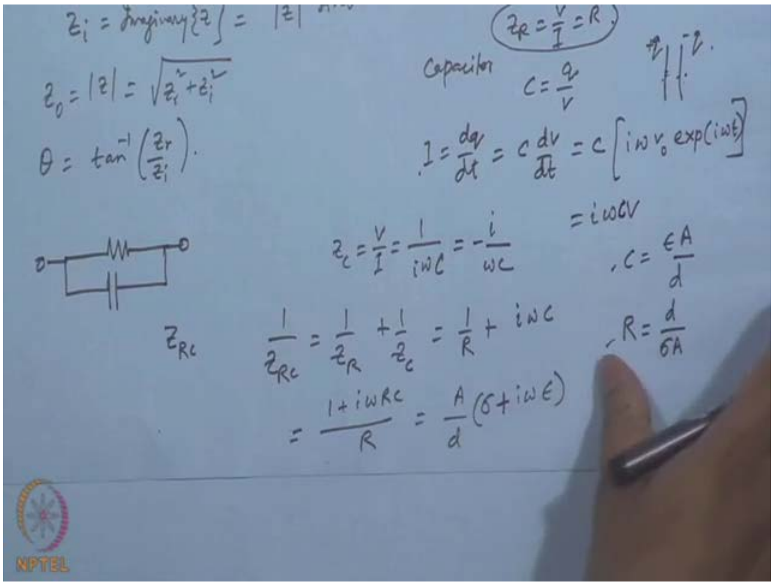

And in that case the impedance is traditionally, this is v divided by I and that is (No audio from 02:38 to 02:52) this quantity which is in turn written as, (No audio from 02:56 to 03:07) so, this has real and imaginary parts as always. So, this is.

(No audio from 03:14 to 03:31)

So, in that case the magnitude of this complex impedance, (No Audio From: 03:38 to 03:51) Now, if we look at a classical resistor, it is for a resistor voltage is in phase with current. So, this is how it is defined and for a capacitor c is equal to q by v, where basically you have two capacitor plates and one is holding plus q charge another is holding minus q charge in the two plates. So, then the current here is basically d q d t that is how it is defined by the concerned researcher. So, it is this now d q c is q y v, so it would be c of d v d t, q would be equal to c v, so d q d t would be c d v d t. So, this would be equal to, now if you bring in this d v d t now, we have some expression for v, what is that, v naught exponential i omega t.

So, if you bring that then it would be d v d t would be here. So, this is in turn you can write v naught exponential i omega t as v, as from this expression. So, you have here now, if somebody wants to, I already defined z R if somebody by the same token define z c which is again v by I that would be equal to, we have the v and so v by I would be nothing but I is equal to I omega v. So, v by I would be one by I omega, one by I there is one c I forgot, there was AC here, so one by I omega c. So, that is equal to multiply both sides by numerator and denominator by i, i by omega c. So, this is for z c and this is for z R. Now, if somebody works, so you have choice if somebody works with a resistor and the capacitor and try to find out what is the Z R c.

So, then Z R c then this would be 1, it will be defined by 1 by Z R c is equal to 1 by Z R plus 1 by Z c. So, this gives to 1 by Z R, here I see it is 1 by Z R would be 1 by R and this would be 1 by Z c would be I omega c, because omega c 1 by Z c omega c would go to the numerator. Now, if one also make note that c is equal to epsa A by D, where D is the distance of separation between this two capacitor plates and A is the area of the plate and epsa is a permittivity. And, one also notes the fact that the R is equal to D divided by sigma A conductivity and the area. And, so these are the classically the c and R are defined for an electric circuit. So, in that case this 1 by Z R c would be, would look like 1 by Z R c that would be then 1 plus i omega R c divided by R which would be equal to A by D into sigma plus I omega epsa.

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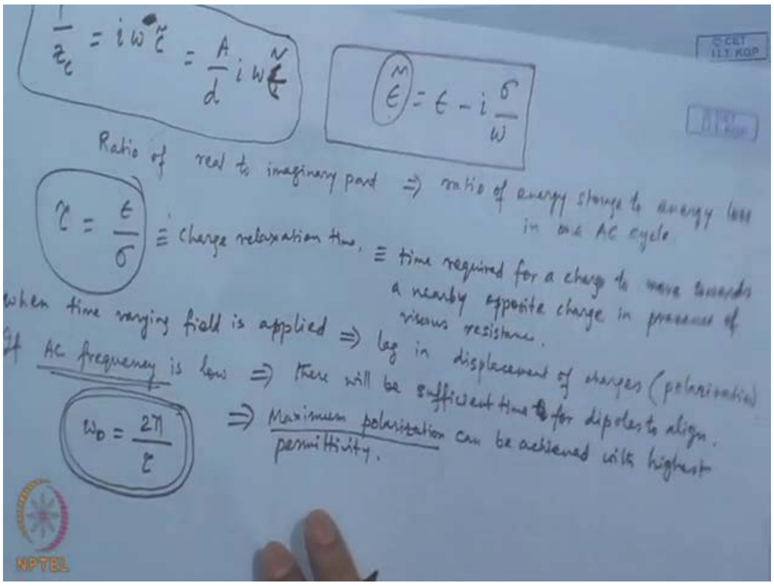

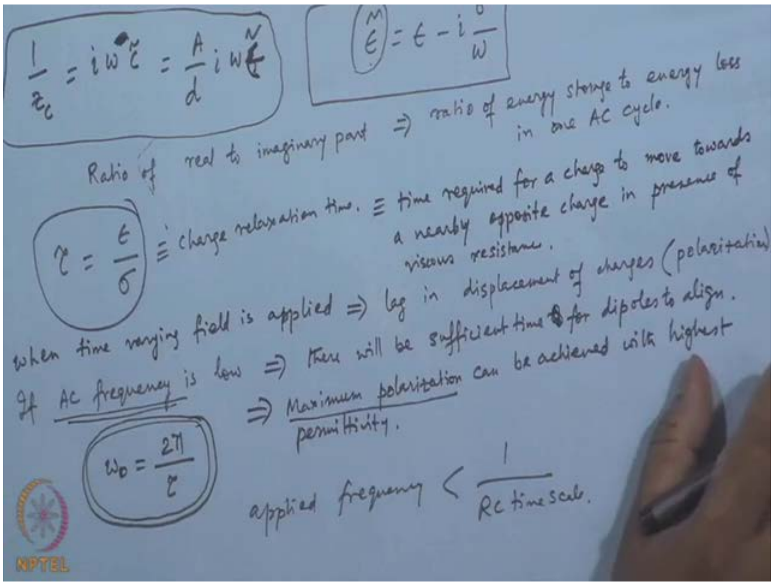

Now, if one wants to define a real capacitor then he has to write it as 1 by Z c is equal to i omega square c and that is equal to A by d I, sorry i omega c and that is equal to A by d i omega. I put tilde here to define this as a complex capacitance or complex permittivity. So, if one wants to define capacitance that way so that is also possible. In that case it would this 1 by Z R c, this would be leading to the I mean if one equates these two, what they will lead to is the one, this will lead to epsa minus i sigma by omega. So, this is something what they will lead to. So, they have so, what this is all about is the complex permittivity that is defined this way. Now, if one wants to write the ratio of real to imaginary part of this complex permittivity that gives the idea of the ratio of energy storage to energy loss in one AC cycle.

So, that is how it goes, in that case the tau would be defined as epsa divided by sigma, this would be called charge relaxation time. So, this is equivalent to time required for a charge to move towards a nearby opposite charge in presence of viscous resistance. So, this is the relaxation time. Now, when it comes to the frequency, see the, it is like this, that the I mean if we try to summarize this here what we are doing, when time varying field is applied, so then this implies because of this R c mechanism present, there would be a lag in displacement of charges of, what you this placement of charges, you refer this as polarization. Now, if AC frequency is low, in that case this implies there will be sufficient time for dipoles to align. So, this implies maximum polarization can be achieved with highest permittivity.

On the other hand, (No Audio From: 14:27 to 14:41) so and we what do we look at, there is a maximum polarization that can be achieved. Now, if this corresponding AC frequency is referred as omega naught say, then this omega naught would be related to this time scale as omega naught is equal to 2 pi by tau, where tau is epsa by sigma. So, this is how, I mean this is how you have, this is how you treat the A C, this AC time scale. This, the I mean if somebody wants to know then what would be the right frequency at which this, what would be the droplet to form, then one would go for this equation where the tau is the charge relaxation time and that is equal to this epsa by sigma. So, this is primarily gives the idea, how you can handle, how you can extend your understanding of this relaxation time? I mean this tau is equal to epsa sigma; we have used it for DC electrospray.

Now, for AC electrospray there would be a similar R C time scale coming in and you can define a complex permittivity this way and still you can come up with the right frequency, such that this issue is addressed. Now, what (No Audio From: 16:43 to 16:57) so, what we have to basically ensure that the applied frequency has to be less than this R c 1 by R c time scale. And, this applied frequency here we are holding it as; applied frequency is equal to the time scale I mean that is the threshold one that we have to address. Now, this there is one another aspect of it which I think is could be looked into here. That is the superposition of AC potential on DC potential.

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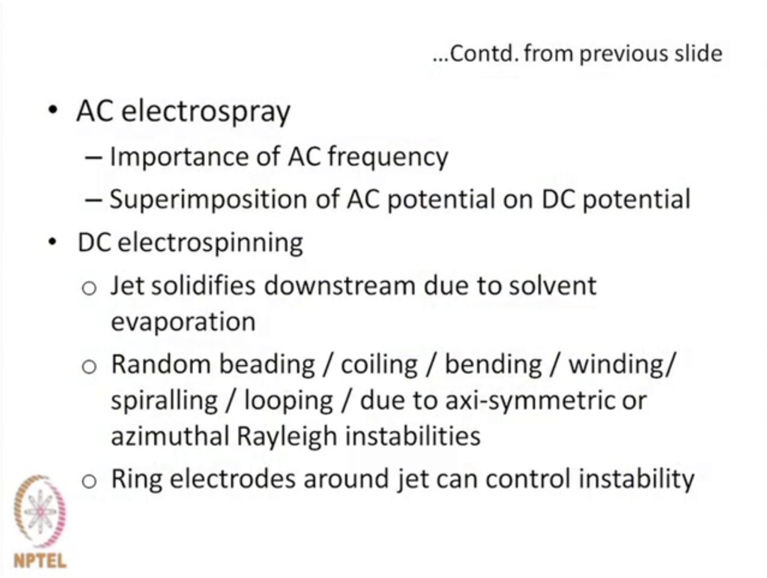

It is not that one has to operate with DC alone or AC alone. What this is talking about is that you can have disturbance, I mean one can have a disturb, so called disturbance wave, so-called disturbance wave using AC frequency.

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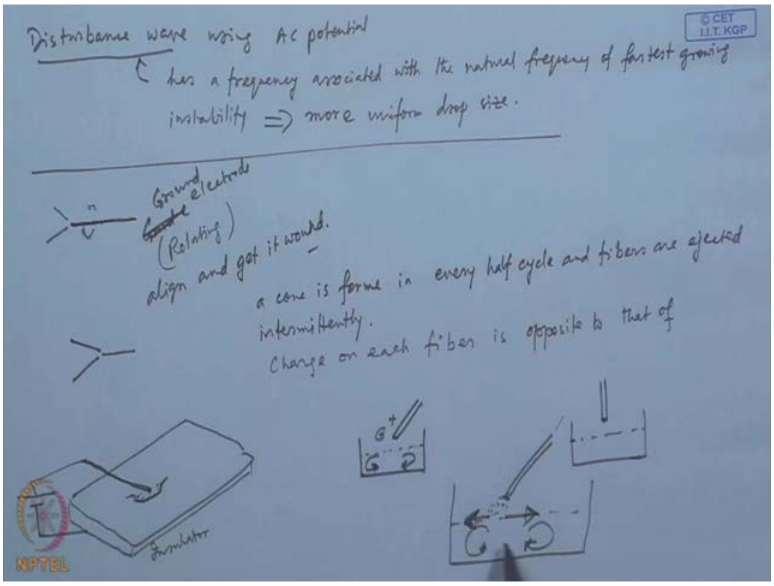

Using AC potential, this disturbance wave using AC potential where this disturbance wave has a frequency associated with the natural frequency of fastest growing instability. I mean why would you, why so all somebody do that? I mean what you are doing is you are superimposing AC potential on DC potential. So, why you are doing this is basically you are creating. So, there is a DC potential existing, on top of that you are creating a disturbance wave using AC potential at a frequency which is as usual to the natural frequency of fastest growing instability. These to where to benefit here is more uniform drop size. So, that is what the purpose here is.

Then, the next topic that we have here in this slide is something called a DC electrospinning. Basically, the electrospray that emanates from the tip of the conical meniscus that can solidify, because of solvent evaporation, so if that solidifies if the spray that is coming out, suppose this is the spray that is coming out. And, that solidifies because of evaporation and this leaves behind a polymer strength which is basically a fiber. And, the ground electrode that you use, you are suppose to have a ground electrode here. So, the ground electrode that you use, if you have this rotating using a rotating ground electrode, then one can align and get it wound. So, this one can take the strength align it in the way they want and do the appropriate winding. So, you can create a fiber out of it.

So, as it comes out these gets because of evaporation this be solidifies and so one can get these winding. Now, jet solidifies downstream due to solvent evaporation that is understood random beading, coiling, bending, winding, spiraling, looping. So, all these are possible due to axisymmetric or azimuthal Rayleigh instabilities. This I mean we had this, we talked about this Rayleigh instability; that means, if there is perturbation that perturbation will grow and it will break this stream at certain points. That is what this instability is all about, but in case of this I mean here, the jet is evaporating. So, one expect I mean it will not be there, would be an axisymmetric as well as the azimuthal instability. So, if such instability exists, there would be if there is an azimuthal instability, of course, you can expect that this jet will have in azimuthal direction some perturbations.

Similarly, in the axial direction there would be perturbation. So, they will be reflected in random beading, coiling, bending, I mean that is what we mentioned here in this slide. And, one can control these by the use of ring electrodes around jet. So, you one can control these by use of ring electrode around this jet, so that instability is less. So, there are ways to do it and this is a method known as DC electrospinning. That means, you are producing a fiber of very small diameter and you are controlling the ground electrode, you are rotating the ground electrode in such a way so that you are having this, if the winding also over a, I mean in the way you want it, you can align it. So, that is allowed; however, DC electrospinning has these instability problems and that can to some extent be avoided by using ring electrodes.

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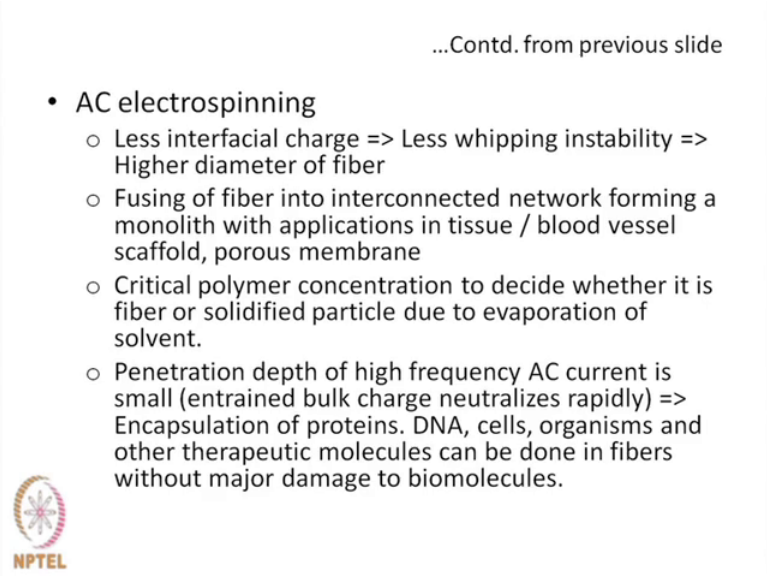

However, the next slide that I have here is AC electrospinning and in case of AC electrospinning, you have some major advantage in this regard. Number one, there would be less interfacial charge, this AC electrospinning will have less interfacial charge. And, so this whipping instability and I mean whatever is arising because of the charge there was some amount of some instability those are less, that those problems are less. So, you have, I mean one can have higher diameter of fiber that is one possibility. Now, the other thing is I mean you got to understand of fact that these, there is AC field operational here. So, a cone is formed and then fiber is ejected and at the next moment the charge on the fiber is changed. So, I mean if I try to write this down, a cone is formed in every half cycle, I mean AC cycle we mean and then fibers are ejected intermittently.

And, more over the charge on each fiber is opposite to that of its, the earlier fiber that has come out of it. Because there is this AC field, so every time every half cycle, so one fiber coming out and it has some charge and then next fiber coming out, it is a opposite charge and next fiber coming out it is a opposite charge again an opposite charge; that means, same charge as the earlier one. So, there would be always the fiber that is coming out next would be of opposite charge. So, that is because of this. So, then there would be more of a fusing of fiber. I mean earlier, when in case of DC electrospinning we are talking about winding the fiber on something and holding it the way we, align it the way we want.

But here it is what will happen is a fusing of fiber into interconnected network forming a monolith with applications in tissue, blood vessel, scaffold and porous membrane. So, there would be so it is basically, these fibers are of opposite charge. So, they are more prone to forming an interconnected network. So, it will form a monolith, that kind of monolith has very good application in tissue as an artificial tissue or a blood vessel, scaffold or forming a porous membrane even. I mean because this would form a very good interconnected network rather than a single fiber strength. So, that is what is typically, what you can expect out of this AC electrospinning.

Now, there is also another point here, which is a critical polymer concentration that decides whether it is fiber or solidified particle due to evaporation solvent. So, when in case of AC electrospinning, first of all we said that there will not be a single fiber strength that comes out. So, it would be small strengths, small pieces of opposite charges that are coming out. Now, on top of this, if there is evaporation going on simultaneously there is a possibility that it gets evaporated on the way. And, so, then in that case there would be a solidified particles rather than a fiber. And, that is decided whether it would be a particle or a fiber that would be decided by the critical polymer concentration. That means, if the polymer concentration is high, then it would be more likely to form particles, because it will be evaporating fast.

On the other hand, if there is a lot solvent in it, the evaporation takes time; so it would be other ways. So, in fact, this method is also considered, one method this is an important method for producing rapidly, these polymer microparticles if one wants to do this, this is one such method. If somebody walks with this critical, close to this critical polymer concentration, then there it would be possible that some are particles and some are fibers also, because the accurate control of this process is not that much possible. So, what if somebody is working close to the critical polymer concentration, I mean there is not a very sharp critical polymer concentration for this application. I mean if somebody works within that range even what will happen is some would be strands, some would be particles and one what they will end up with is a mixture.

So, that is a possibility and then you have these, the other issue here is this penetration depth in case of AC electrospinning that we are talking about here, unlike this electrospinning, in case of AC electrospinning the penetration depth of high frequency AC current is small. Penetration depth of high frequency AC current is small, so, as a result the encapsulation of proteins, DNAs, cells, organisms and other therapeutic molecules can be done in fibers without major damage to biomolecules. Because it is this entrained bulk charge neutralizes rapidly, I mean you are changing the polarity. So, that is why it will not, charge will not go deep into the, it will not penetrate into the core and so as a result if somebody is planning to encapsulate proteins, DNAs this would be a good way of doing it.

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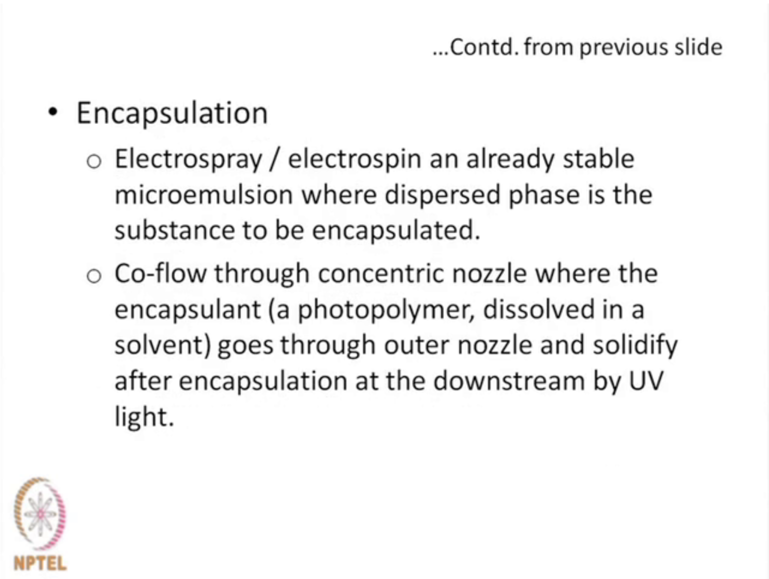

And, this encapsulation is done by two methods. One is electrospray or electrospin an already stable microemulsion where dispersed phase is the substance to be encapsulated. Or the otherwise it could be the co-flow through concentric nozzle where the encapsulant which is a photopolymer dissolved in a solvent goes through outer nozzle and solidify after encapsulation at the downstream by U V light. (No Audio From: 31:07 to 31:16)

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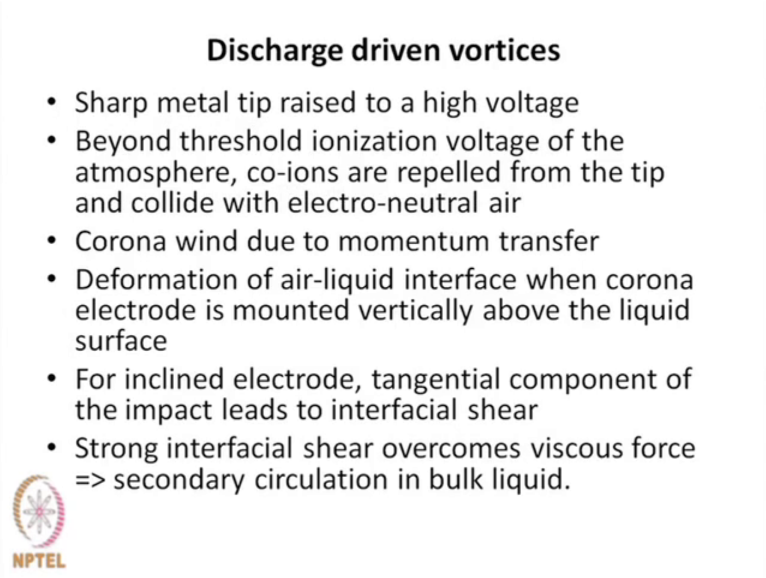

There is another very interesting, I mean if we may look into this encapsulation further, but before that I think there is a very interesting phenomena connected with this electrodes and with the charges here, which is referred as discharge driven vortices. Discharge driven vortices, this takes this is something like this. If you have an insulator and inside insulator plate may be and inside it has a liquid pool, I mean there is a cavity within which some liquid is sitting, which is common application for microfluidic another application. So, if there is a liquid in a cavity on this plate and then if you bring an electrode next to this and then (No Audio From: 32:47 to 32:55) bring the tip of the electrode, but do not touch it touch the liquid, but keep it above the liquid.

In that case (No Audio From: 33:04 to 33:10) if this is the electrode and if this is the liquid level, one will find that there would be vortices generating like this, the reason is something like this. A sharp metal tip raised to a high voltage beyond a threshold ionization voltage of the atmosphere, co-ions. I mean this tip is in the atmosphere; tip is not touching the liquid beyond threshold ionization voltage of the atmosphere, co-ions are repelled from the tip and collide with electroneutral air. So, in the atmosphere there are, if we go beyond the threshold ionization voltage; that means, this atmosphere is getting ionized, in that case the co-ions are repelled from the tip.

So, if this is positively charged, then the positively charged ions they would be repelled from the tip and they will collide with electroneutral air, air is other ways electroneutral and these ions are repelled. So, there will be a corona wind developed due to the momentum transfer. So, because the ionization voltage is reached, so there would be ionization and the co-ions that are formed at the tip, the tip has to be extremely sharp and there is to be very high voltage, these are the primary condition. So, then the co-ions are formed and they are repelled from the tip and because of this collision of this co-ions with this other ways electroneutral air, there would be a corona wind forming, because the momentum transfer.

So, if somebody holds this, I mean this has been shown that if somebody holds this electrode sharp tip of the electrode at high voltage and this is the liquid level, there will be deformation of air liquid interface when corona electrode is mounted vertically above the liquid surface. So, that is something which happens all the time. However, when you have an incline if I look at the slide, if we look at the slide when you have an inclined electrode the tangential component of the impact leads to interfacial shear. So, this inclined electrode, if you have an inclined electrode here on this node if here, I can see if there is an inclined electrode, what this will cause is, this will cause tangential component of the impact leads to interfacial shear. If I look at it bigger this is the liquid level and this is the electrode and then there would be these co-ions repelled.

And, then that would be colliding with the electroneutral molecules and there is a corona wind forming and this is, there is a tangential component of this to the surface. Tangential component of the impact leads to interfacial shear. Now, if this interfacial shear is strong enough, then it can overcome the viscous force and there would be a secondary circulation forming within the liquid, there would be a secondary circulation forming because of this. So, this electrode is referred as corona electrode and there would be such circulation forming. So, (No Audio From: 36:55 to 37:04) typically this is observed that when one use AC field, the critical voltage for corona discharge is lower compared to the DC fields. Because there is a reason to it, there is permanently, yeah minimum voltage is required with AC because of permanently entrained plasma cloud.

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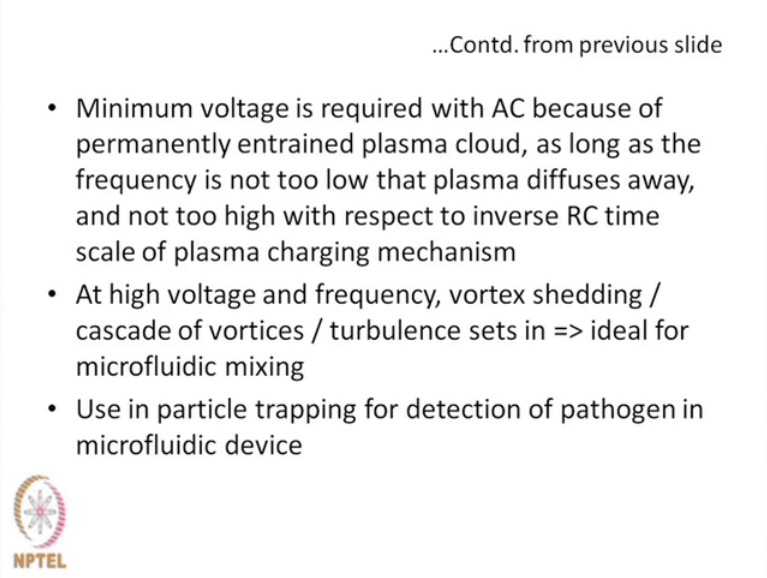

As long as the frequency is not too low that plasma diffuses away and not too high with respect to inverse R C times scale of plasma charging mechanism. So, we are back to then again this R C time scale. So, you can always, this plasma charging mechanism that can also be looked into as a resistance capacitance model and then that will also have its own time scale. It takes some time for the plasma charging, so, the time scale for this AC time period that has to be within this framework, see the minimum voltage is required with AC because of permanently entrained plasma cloud. That means, in AC you have a permanently entrained plasma cloud already, I mean you seen ionized state sitting there. So, when you are coming back next, you have those available.

Now, as long as the frequency is not too low that plasma diffuses away. See, if it is taking too long to come back then the plasma diffuses away, so that is one issue. On the other hand, if it is too fast, if the AC frequency; that means, this imposed AC frequency is too high. That means, it is changing too fast then if that will not match the R C time scale of plasma charging mechanism, in that case there it will be difficult to charge the, it will be difficult to create that plasma of the first plate. So, this there is a again a time scale issue here.

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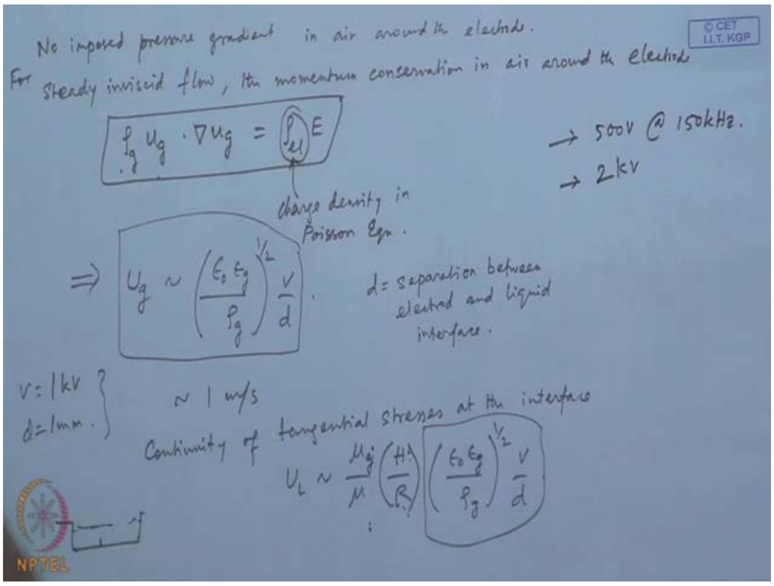

At high voltage and frequency, there would be vortex shedding or cascade of vortices or turbulence. So, this is typically at high voltage and frequency of course, frequency is within this framework, but high frequency. There these issues, these are the few things few that will feature and these are ideally suited for microfluidic mixing. So, this can be a process by which a microfluidic mixing can be performed. Now, if we try to look into some, if we try to understand applying what voltage we would be getting, what kind of circulation that would be important. I mean if I try to sell this, if somebody tries to sell this idea then that is something which has to be clearly pointed out.

Now, here one may start with, I mean one we have one has to understand that there is no imposed pressure gradient here in air, around the electrode. And, if one uses a steady inviscid flow, the momentum conservation, first the momentum conservation has to be done with the air. The momentum conservation in air around the electrode would be rho g u g. So, this would be the momentum conservation equation in this case, where rho g is the density u g is a velocity vector and you have taken the grad of it and this rho e l is the charge density in Poisson equation, density in equation. Now, this has been shown that the u g the order of this u g comes to, (No Audio From: 41:55 to 42:55) this is something what the order of this gas phase velocity.

And, if one uses I mean if one uses one kilovolt as we have done for this electrospray and one uses say one millimeter of here, mind it d is separation between electrode and liquid interface. So, if one takes d as one millimeter and v as one kilovolt. So, in that case what they will get is to the tune of one meter per second, that is something, that is the velocity one can get that is as per as the gas phase is concerned. And, then if they do the continuity, if they use the continuity of tangential spray, if they extend this continuity of tangential stress, stresses at the interface. If this is used then one can come up with u l, what would be the liquid velocity at the interface? That would be (No Audio From: 43:49 to 43:59) so, this was already there.

And, then you multiply this, mu g is the viscosity of the gas and mu is the viscosity of the liquid. So, that is the ratio basically, viscosity of gas divided by viscosity liquid and H by R H is the depth of the liquid chamber, we are talking about the liquid chamber. So, H is the depth of the liquid chamber and R is the radius of the chamber. So, that is what is so, H by R is basically the feature size ratio. So, that is H by R is a geometric parameter, mu g by mu is the viscosity ratio. So, we can work with this u l and one can see that this u l would be coming to about one centimeter; I mean it depends on what kind of geometric ratio you have here. So, the, I mean, it would be it can be related to the gas side velocity and one has shown that this has substantial liquid side velocity, which can give to circulation that is meaningful.

So, the minimum voltage required typically I mean for this entire analysis, we did not consider AC field etcetera. But typically if somebody works with the AC field, the minimum voltage required would be about 500 volt at 150 kilohertz, this is for A C. And, for a DC this would be about, this is 500 volt and this is 2 kilovolt for the D C. So, this is the DC voltage requirement and AC typically, this if somebody uses 150 kilohertz this would be the 500 volt. And, optimum frequency is associated with the inverse, this we have already discussed that minimum voltage is required with AC because of permanently entrained plasma cloud, as long as the frequency is not too low the plasma diffuses away and not too high with respect to inverse R C time scale of plasma charging mechanism.

If one wants to work with this probably 150 kilohertz is good frequency and for that you need one needs 500 volt of voltage. So, that is something we have, one aspect of it which we would like to emphasize here, the use in particle trapping. One big application of this mechanism is the, is of course, the microfluidic mixing at high voltage and frequency. We have talked about this formation of formation of a vortex and then at frequency, at high voltage and frequency, there will be vortex shedding cascade of vortices. And, the turbulence sets in which is ideal for microfluidic mixing, that we have already discussed.

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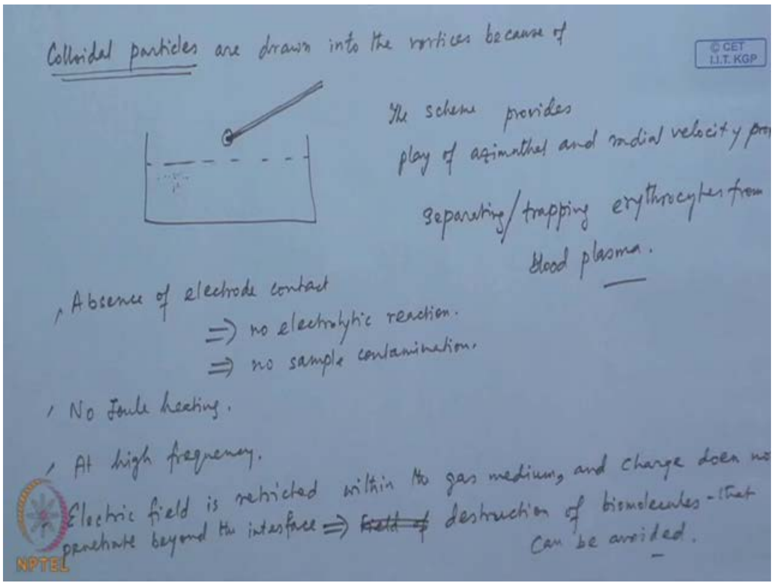

Now, there is another application which has some meaning here is, particle trapping for detection of pathogen in microfluidic devices. The system works something like this, that typically the colloidal particles they are drawn, these colloidal particles are drawn into the vortices because of DEP forces. So, what, so these colloidal particles will be, see this is another mechanism, what we are talking about here is, that this is the liquid pool inside the cavity. And, the electrode is brought in here, electrode that this is called corona electrode, very sharp tip at a very high voltage. So, that is brought in here and this distance is small. So, here these colloidal particles will be drawn into the, so basically this near the interface, the colloidal particles will be pooled by DEP force. So, closes to the corona electrode tip, so they will be coming there.

So, if somebody can manipulate this force at the same time, because the other, the vortex that we are, that vortex that I have been talking about is generated because of the plasma and that plasma is forcing the interface and the interface is creating a viscous that shear effect and so, this is moving. This has nothing to do with the D E P attractive force which is bringing the colloidal particles close to the electrode. So, if somebody can manipulate both these mechanisms, so, what they can do is they can pull the colloidal particles. You can, they can pull it, pull them to basically they pull them to the vortex interior. So, you will you can focus them in the way you want, basically this electrode that can focus the particles say at the inside the vortex, so that, they can be put in, they can be focused in one place.

And, some even some scientists they have gone beyond this, there is a possibility to use gravity as well. So, they have all this three mechanisms at their disposal, one is this corona wind creating vortex another is this DEP force pulling this particles in the interior of the vortex and thirdly there is gravity acting. So, the all these three forces, they are applied simultaneously. So, that one can separate the particles from a bulk liquid I mean the idea here the, this is ideally suited for use in microfluidic devices. Because one is that this scheme allows, the scheme basically provides play of azimuthal and radial velocity profiles. So, they have control over these helical flows swirl, I mean that can be controlled by using these three mechanisms. So, they can be very effective in use in separating or you can call it separating or there is a term commonly referred as trapping erythrocytes, for example, from blood plasma.

There are certain advantages to it which the scientists were working on this scheme, they have highlighted. One is the absence of electrode contact, so the advantage is no electrolytic reaction and so, accordingly no sample contamination. Then the other point is no joule heating, then this operates at high frequency. So, the advantage is that is put forward is that less chance of electrocution. And, another important point which by now you have already seen this, use of this is that electric field is restricted within the gas medium and charge does not penetrate beyond the interface. So, the bulk remains primarily unaffected as far as these movements of charges are concerned. So, I mean the other words that is, this is called field of penetration or the charge does not penetrate beyond the interface.

So, you it is, if there is any possibility of, so, I should write destruction of biomolecules, destruction of biomolecules that is, that can be avoided. So, if I try to quickly sum up what this, we have looked into recently the electrospray. Then, we have found out that there is an issue of time scale etcetera, there is an issue of particularly when you bring in this AC field, then there is this AC frequency which is another time scale brought in here. And, so, everything has to be consistent all this time scales otherwise you cannot utilize this scheme to the full potential, that is one thing which we need to understand here and of course, there is a critical voltage there is a critical polymer concentration. So, they have to go hand in hand, these are the few things which we fully appreciate and then we said that there is another new technique which is of course; we have differentiated between these forming of fibers or strands and forming of particles.

That is that we have done and what is this AC electrospinning and DC electrospinning, how one is forming a long fiber strand of smaller diameter and other is forming larger diameter, but producing opposite charges small elements of opposite charges forming a mesh, forming a membrane, forming a matrix. So, these we discussed and then we brought in a new brought in another idea which is discharge driven vertices. The where the use of electrode and use of this liquid pool by the using the, by manipulating this, by forming a plasma cloud, vortex is created within the liquid pool. And, its electrode is at the same time used for to pool the colloidal particles using D E P forces. And, so at the same time there is gravity which is always available.

So, these three forces could be manipulated to create the swirl, create the radial and azimuthal and all kinds of forces the way one wants. And, so, this gives a good potential to form the, this gives a good opportunity to trap or separate these biomolecules or biological particles in a microfluidic set up. So, the potential of this has been highlighted in this lecture. So, with that I conclude today’s lecture. Thank you very much.